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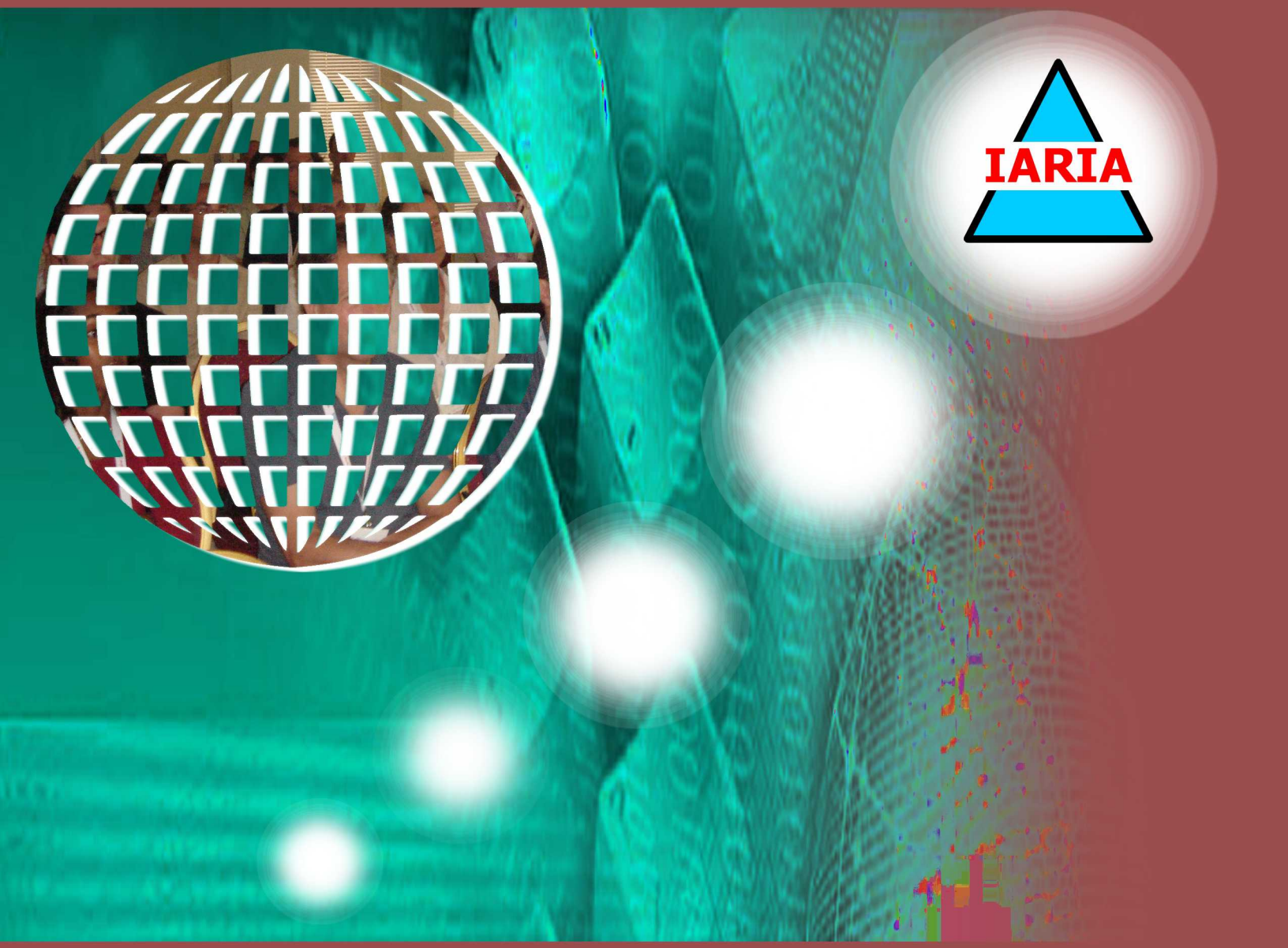

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An Empirical Evaluation of Simplified Function Point Measurement Processes

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Abstract— **Function Point Analysis is widely used, especially to quantify the size of applications in the early stages of development, when effort estimates are needed. However, the measurement process is often too long or too expensive, or it requires more knowledge than available when development effort estimates are due. To overcome these problems, simplified methods have been proposed to measure Function Points. We used simplified methods for sizing both "traditional" and Real-Time applications, with the aim of evaluating the accuracy of the sizing with respect to full-fledged Function Point Analysis. To this end, a set of projects, which had already been measured by means of Function Point Analysis, have been measured using a few simplified processes, including those proposed by NESMA, the Early&Quick Function Points, the ISBSG average weights, and others; the resulting size measures were then compared. We also derived simplified size models by analyzing the dataset used for experimentations. In general, all the methods that provide predefined weights for all the transaction and data types identified in Function Point Analysis provided similar results, characterized by acceptable accuracy. On the contrary, methods that rely on just one of the elements that contribute to size tend to be quite inaccurate. In general, different methods show different accuracy for Real-Time and non Real-Time applications. The results of the analysis reported here show that in general it is possible to size software via simplified measurement processes with an acceptable accuracy. In particular, the simplification of the measurement process allows the measurer to skip the function weighting phases, which are usually expensive, since they require a thorough analysis of the details of both data and operations. Deriving our own models from the project datasets proved possible, and yielded results that are similar to those obtained via the methods proposed in the literature.**

Keywords-Functional Size Measures; Function Points; Simplified measurement processes; Early&Quick Function Points (EQFP); NESMA estimated; NESMA indicative.

I. INTRODUCTION

The empirical evaluation of simplified Function Points processes [1] is motivated by the popularity of Function Points. In fact, Function Point Analysis (FPA) [2][3][4][5] is widely used. Among the reasons for the success of FPA is that it can provide measures of size in the early stages of software development, when they are most needed for cost estimation.

However, FPA performed by a certified function point consultant proceeds at a relatively slow pace: between 400 and 600 function points (FP) per day, according to Capers Jones [6], between 200 and 300 function points per day according to experts from Total Metrics [7]. Consequently, measuring the size of a moderately large application can take too long, if cost estimation is needed urgently. Also the cost of measurement can be often considered excessive by software developers. In addition, cost estimates may be needed when requirements have not yet been specified in detail and completely.

To overcome the aforementioned problems, simplified FP measurement processes have been proposed. A quite comprehensive list of such methods is given in [8]. Among these are the NESMA (NEtherland Software Metrics Association) indicative and estimated methods, and the Early & Quick Function Points method. Other methods were also proposed, including the Tichenor ILF Model [9] and models featuring fixed weights for the computation of size measures. These models are briefly described in Section II. The proposers of these methods claim that they allow measurers to compute good approximations of functional size measures with little effort and in a fairly short time.

The goal of the work reported here is to test the application of several simplified functional size measurement processes to real projects in both the "traditional" and Real-Time domains. Function Points are often reported as not suited for measuring the functional size of embedded applications, since FP – conceived by Albrecht when the programs to be sized were mostly Electronic Data Processing applications– capture well the functional size of data storage and movement operations, but are ill-suited for representing the complexity of control and elaboration that are typical of embedded and Real-Time software. However, it has been shown that a careful interpretation of FP counting rules makes it possible to apply FPA to embedded software as well [10].

In this paper, we apply the International Function Points User Group (IFPUG) measurement rules [4] to size a set of non Real-Time programs, and we apply the guidelines given in [11] (which are as IFPUG-compliant as possible) to measure a set of embedded Real-Time avionic applications. All these measures are used to test the *accuracy* of simplified functional size measurement processes. In fact, there is little doubt that the simplified Functional Size Measurement (FSM) methods actually allow for early and quick sizing; the real point is to evaluate to what extent the savings in time and costs are paid in terms of inaccurate size estimates. So, we concentrate on the assessment of the accuracy of size estimates, for both Real-

Time and embedded applications, as well as "traditional" business applications. Throughout the paper, by "accuracy" we mean the closeness of a size estimate to the real size measure, i.e., the size measured according to IFPUG rules by an experienced measurer.

In this paper, we enhance the work reported in [1] by using an extended dataset, and by testing the usage of additional simplified FSM techniques, not used in [1]. However, in the paper we do not just evaluate existing proposals for simplifying the functional size measurement process; instead, we produce our own simplified models for estimating the functional size of software applications. This is done using the same approaches already used to produce the existing simplified methods: in fact, we obtained models that are structurally similar to the existing ones, but featuring different parameters (e.g., weights for basic functional components).

All the methods –i.e., both those proposed in the literature and ours– are tested on a set of projects and the results are compared.

We also analyze the differences between Real-Time and non Real-Time applications, and derive a few considerations on what models are best suited to estimate the size of each class of applications.

The results of the measurements and analyses reported in the paper are expected to provide two types of benefits: on the one hand, they contribute to enhancing our understanding of functional size measurement processes and their suitability; on the other hand, we provide useful information and suggestions to the practitioners that have to decide whether to use simplified FSM methods, and which one to choose.

The paper is organized as follows: Section II briefly introduces the simplified FSM processes used in the paper. Section III describes the projects being measured and gives their sizes measured according to the full-fledged, canonical FPA process. Section IV illustrates the sizes obtained via simplified functional size measurement processes. Section V discusses the accuracy of the measures obtained via the simplified methods used and outlines the lessons that can be learned from the reported experiment. In Section VI, the dataset described in Section III is analyzed, in order to get simplified FSM models that are similar to those presented in Section II, but which rely on the measures of the considered projects. Section VII accounts for related work. Section VIII discusses the threats to the validity of the study. Finally, Section IX draws some conclusions and outlines future work.

Throughout the paper, we assume that the reader is familiar with the concepts of FPA and the IFPUG rules. Readers that need explanations and details about FP counting can refer to official documentation and manuals [4][5].

Throughout the paper, we refer exclusively to unadjusted function points (UFP), even when we talk generically of "Function Points" or "FP".

II. A BRIEF INTRODUCTION TO SIMPLIFIED SIZE MEASUREMENT PROCESSES

The FP measurement process involves (among others) the following activities:

- Identifying logic data;
- Identifying elementary processes;
- Classifying logic data as internal logic files (ILF) or external interface files (EIF);
- Classifying elementary processes as external inputs (EI), outputs (EO), or queries (EQ);
- Weighting data functions;
- Weighting transaction functions.

Simplified measurement processes allow measurers to skip –possibly in part– one or more of the aforementioned activities, thus making the measurement process faster and cheaper. Table III provides a quick overview of the activities required by FP measurement and estimation methods. Of course, the IFPUG method requires all the activities listed in Table III, while simplified methods require a subset of such activities.

A. Early & Quick Function Points

The most well-known approach for simplifying the process of FP counting is probably the Early & Quick Function Points (EQFP) method [12]. EQFP descends from the consideration that estimates are sometimes needed before requirements analysis is completed, when the information on the software to be measured is incomplete or not sufficiently detailed.

Since several details for performing a correct measurement following the rules of the FP manual [4] are not used in EQFP, the result is a less accurate measure. The trade-off between reduced measurement time and costs is also a reason for adopting the EQFP method even when full specifications are available, but there is the need for completing the measurement in a short time, or at a lower cost. An advantage of the method is that different parts of the system can be measured at different detail levels: for instance, a part of the system can be measured following the IFPUG manual rules [4][5], while other parts can be measured on the basis of coarser-grained information. In fact, the EQFP method is based on the classification of the processes and data of an application according to a hierarchy (see Fig. 1 [12]).

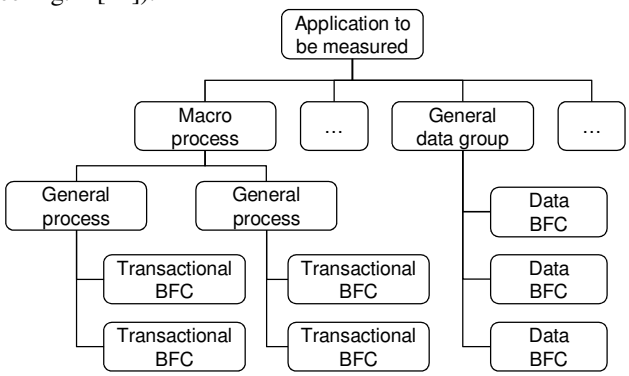

Figure 1. Functional hierarchy in the Early & Quick FP technique

Transactional BFC (Base Functional Components) and Data BFC correspond to IFPUG's elementary processes and LogicData, while the other elements are aggregations of processes or data groups. The idea is that if you have enough information at the most detailed level you count FP according to IFPUG rules; otherwise, you can estimate the size of larger elements (e.g., General or Macro processes) either on the basis of analogy (e.g., a given General process is "similar" to a known one) or according to the structured aggregation (e.g., a General process is composed of 3 Transactional BFC). By considering elements that are coarser-grained than the FPA

BFC, the EQFP measurement process leads to an approximate measure of size in IFPUG FP.

Tables taking into account the previous experiences with the usage of EQFP are provided to facilitate the task of assigning a minimum, maximum and most likely quantitative size to each component. For instance, Table I provides minimum, maximum and most likely weight values for generic (i.e., not weighted) functions as given in [12]. The time and effort required by the weighting phases are thus saved. Such saving can be relevant, since weighting a data or transaction function requires analyzing it in detail.

TABLE I. EQFP: FUNCTION TYPE WEIGHTS FOR GENERIC FUNCTIONS

Function type	Weight		
	Low	*Likely*	*High*
Generic ILF	7.4	7.7	8.1
Generic EIF	5.2	5.4	5.7
Generic EI	4	4.2	4.4
Generic EO	4.9	5.2	5.4
Generic EQ	3.7	3.9	4.1

The size of unspecified generic processes (i.e., transactions that have not been yet classified as inputs, outputs or queries) and unspecified generic data groups (i.e., logical files that have not been yet classified as ILF or EIF) as given in [12] are illustrated in Table II. When using this method, only the identification of logical data and elementary processes needs to be done: both the classification of data and transaction functions and their weighting are skipped. Consequently, sizing based on unspecified generic processes and data groups is even more convenient –in terms of time and effort spent– than sizing based on generic (i.e., non weighted) functions.

TABLE II. EQFP: FUNCTION TYPE WEIGHTS FOR UNSPECIFIED GENERIC PROCESSES AND DATA GROUPS

Function type	Weight		
	Low	*Likely*	*High*
Unspefied Generic Processes	4.3	4.6	4.8
Unspefied Generic Data Group	6.4	7.0	7.8

B. NESMA indicative and estimated methods

The Indicative NESMA method [13] simplifies the process by only requiring the identification of LogicData from a conceptual data model. The Function Point size is then computed by applying the following formulae –where #ILF is the number of ILF and #EIF is the number of EIF– whose parameters depend on whether the data model is normalized in 3rd normal form:

Non normalized model: FP = # ILF × 35 + # EIF × 15
Normalized model: FP = # ILF × 25 + # EIF × 10

The process of applying the NESMA indicative method involves only identifying logic data and classifying them as ILF or EIF. Accordingly, it requires less time and effort than the EQFP methods described above, in general. However, the Indicative NESMA method is quite rough in its computation: the official NESMA counting manual specifies that errors in functional size with this approach can be up to 50%.

The Estimated NESMA method requires the identification and classification of all data and transaction functions, but does not require the assessment of the complexity of each function: Data Functions (ILF and EIF) are all assumed to be of low complexity, while Transactions Functions (EI, EQ and EO) are all assumed to be of average complexity:

UFP = #EI × 4 + #EO × 5 + #EQ × 4 + #ILF × 7 + #EIF × 5

C. Other simplified FSM process proposals

1) Tichenor method

The Tichenor ILF Model [9] bases the estimation of the size on the number of ILF via the following formula for transactional system (for batch systems, Tichenor proposes a smaller multiplier):

UFP = #ILF × 14.93

This model assumes a distribution of BFC with respect to ILF as follows: EI/ILF = 0.33, EO/ILF = 0.39, EQ/ILF = 0.01, EIF/ILF = 0.1. If the considered application features a different distribution, the estimation can be inaccurate.

The fact that a method based only on ILF requires a given distribution for the other BFC is not surprising. In fact, the size of the application depends on how many transactions are needed to elaborate those data, and the number of transaction cannot be guessed only on the basis of the number of ILF, as it depend on the number of ILF just very loosely. Instead of allowing the user to specify the number of transactions that are needed, the Tichenor method practically imposes that the number of transactions complies with the distribution given above.

2) ISBSG distribution model

The analysis of the ISBSG dataset yielded the following distribution of BFC contributions to the size in FP:

ILF 22.3%, EIF 3.8%, EI 37.2%, EO 23.5%, EQ 13.2%

The analysis of the ISBSG dataset also shows that the average size of ILF is 7.4 UFP. It is thus possible to compute the estimated size on the basis of the number of ILF as follows:

UFP = (#ILF × 7.4) × 100 / 22.3

The same considerations reported above for the Tichenor model apply. If the application to be measured does not fit the distribution assumed by the ISBSG distribution model, it is likely that the estimation will be inaccurate.

3) Simplified FP

The simplified FP (sFP) approach assumes that all BFC are of average complexity [14], thus:

UFP = #EI × 4 + #EO × 5 + #EQ × 4 + #ILF × 10 + #EIF × 7

4) ISBSG average weights

This model is based on the average weights for each BFC, as resulting from the analysis of the ISBSG dataset [15], which contains data from a few thousand projects. Accordingly, the ISBSG average weights model suggests that that the average function complexity is used for each BFC, thus

UFP = #EI × 4.3 + #EO × 5.4 + #EQ × 3.8 + #ILF × 7.4 + #EIF × 5.5.

TABLE III. ACTIVITIES REQUIRED BY DIFFERENT SIMPLIFIED MEASUREMENT PROCESSES

Measurement activities	IFPUG	NESMA indic.	NESMA estim.	EQFP Generic func.	EQFP Unspec. generic func.	Tichenor ILF Model	ISBSG distribution	sFP	ISBSG average weights
Identifying logic data	✓	✓	✓	✓	✓	✓	✓	✓	✓
Identifying elementary processes	✓		✓	✓	✓			✓	✓
Classifying logic data as ILF or EIF	✓	✓	✓	✓		✓	✓	✓	✓
Classifying elementary processes as EI, EO, or EQ	✓		✓	✓				✓	✓
Weighting data functions	✓								
Weighting transaction functions	✓								

III. THE CASE STUDY

A. Real-Time projects

Most of the Real-Time projects measured are from a European organization that develops avionic applications, and other types of embedded and Real-Time applications. All the measured projects concerned typical Real-Time applications for avionics or electro-optical projects, and involved algorithms, interface management, process control and graphical visualization.

The projects' FUR were modeled using UML as described in [11], and then were measured according to IFPUG measurement rules [4]. When the Real-Time nature of the software made IFPUG guidelines inapplicable, we adopted ad-hoc counting criteria, using common sense and striving to preserve the principles of FPA, as described in [10]. The same projects were then sized using the simplified functional size measurement processes mentioned in Section II, using the data that were already available as a result of the IFPUG measurement.

Table IV reports the size in UFP of the measured projects, together with the BFC and –in parentheses– the number of unweighted BFC. For instance, project 1 involved 18 Internal Logic Files, having a size of 164 FP.

B. Non Real-Time projects

The considered non Real-Time projects are mostly programs that allow users to play board or card games vs. remote players via the internet; a few ones are typical business information systems.

The projects were measured –as the Real-Time ones– in two steps: the UML model of each product was built along the guidelines described in [16]; then, the function points were counted, on the basis of the model, according to IFPUG rules.

Table V reports the size in UFP of the measured projects, together with the BFC and –in parentheses– the number of unweighted BFC.

TABLE IV. REAL-TIME PROJECTS' SIZES (IFPUG METHOD)

Project ID.	ILF	EIF	EI	EO	EQ	UFP
1	164 (18)	5 (1)	90 (21)	8 (2)	22 (5)	289
2	56 (8)	0 (0)	21 (6)	18 (3)	6 (1)	101
3	73 (7)	0 (0)	12 (2)	47 (8)	4 (1)	136
4	130 (15)	15 (3)	44 (11)	0 (0)	6 (1)	195
5	39 (4)	0 (0)	28 (8)	39 (8)	0 (0)	106
6	71 (9)	5 (1)	8 (2)	139 (28)	0 (0)	223
7	7 (1)	0 (0)	3 (1)	5 (1)	0 (0)	15
8	21 (3)	0 (0)	4 (1)	8 (2)	0 (0)	33
9	21 (3)	0 (0)	7 (2)	16 (4)	0 (0)	44

TABLE V. NON REAL-TIME PROJECTS' SIZES (IFPUG METHOD)

Project ID.	ILF	EIF	EI	EO	EQ	UFP
1	45 (6)	7 (1)	34 (10)	6 (1)	0 (0)	92
2	28 (4)	20 (4)	37 (9)	5 (1)	4 (1)	94
3	21 (3)	5 (1)	27 (7)	8 (2)	18 (6)	79
4	31 (4)	0 (0)	49 (16)	13 (3)	3 (1)	96
5	24 (3)	0 (0)	45 (14)	21 (5)	0 (0)	90
6	49 (7)	0 (0)	36 (9)	0 (0)	6 (2)	91
7	21 (3)	0 (0)	31 (9)	14 (3)	14 (4)	80
8	42 (6)	5 (1)	35 (9)	17 (3)	10 (2)	109
9	21 (3)	0 (0)	38 (11)	15 (5)	8 (2)	82

IV. RESULTS OF SIMPLIFIED MEASUREMENT

Simplified measurement processes were applied following their definitions, which require data that can be easily derived from the tables above. So, for instance, the data required for Real-Time project 1 are the following:

- The NESMA indicative method requires the numbers of ILF and EIF. Table I shows that the number of ILF is 18, and the number of EIF is 1.
- Similarly, the Tichenor ILF model and the ISBSG distribution models just require the ILF number.
- The NESMA estimated method, the EQFP generic functions method, the sFP method and the ISBSG average weights method require the numbers of ILF, EIF, EI, EO, and EQ. Table I shows that the numbers of ILF, EIF, EI, EO, and EQ are, respectively, 18, 1, 21, 2, and 5.
- The EQFP unspecified generic functions method requires the numbers of data groups (that is, the number of ILF plus the number of EIF) and the number of transactions (that is, the sum of the numbers of EI, EO, and EQ). Table I shows that the number of data groups is 18+1 = 19, and the number of transactions is 21+2+5 = 28.

TABLE VI. SIZES OF REAL-TIME PROJECTS OBTAINED VIA THE NESMA METHODS

Project ID	IFPUG	NESMA indicative non normalized	NESMA indicative normalized	NESMA estimated
1	289	645	460	245
2	101	280	200	99
3	136	245	175	101
4	195	570	405	168
5	106	140	100	100
6	223	330	235	216
7	15	35	25	16
8	33	105	75	35
9	44	105	75	49

A. Applying NESMA indicative

The applications to be measured were modeled according to the guidelines described in [16]. The logic data files – modeled as UML classes– provide a data model that cannot be easily recognized as normalized or not normalized. Therefore, we applied both the formulae for the normalized and not normalized models.

The formulae of the NESMA indicative method were applied to the number of ILF and EIF that had been identified during the IFPUG function point counting process. The results are given in Table VI for Real-Time projects and in Table VII for non Real-Time projects.

B. Applying NESMA estimated

The formulae of the NESMA indicative method were applied to the number of ILF, EIF, EI, EO, and EQ that had been identified during the IFPUG function point counting process. The results are given in Table VI for Real-Time projects and in Table VII for non Real-Time projects.

TABLE VII. SIZES OF NON REAL-TIME PROJECTS OBTAINED VIA THE NESMA METHODS

Project ID	IFPUG	NESMA indicative non normalized	NESMA indicative normalized	NESMA estimated
1	92	225	160	92
2	94	200	140	93
3	79	120	85	88
4	96	140	100	111
5	90	105	75	102
6	91	245	175	93
7	80	105	75	88
8	109	225	160	106
9	82	105	75	98

C. Applying EQFP

As described in Figure 1. , the EQFP method can be applied at different levels. Since we had the necessary data, we adopted the BFC aggregation level. At this level it is possible to use the data functions and transaction functions without weighting them or even without classifying transactions into EI, EO, and EQ and logic data into ILF and EIF. In the former case (generic functions) the weights given in Table I are used, while in the latter case (unspecified generic functions) the weights given in Table II are used.

The results of the application of EQFP are given in Table VIII for Real-Time projects, and in Table IX for non Real-Time projects.

TABLE VIII. MEASURES OF REAL-TIME PROJECTS OBTAINED VIA THE EQFP METHOD

Project ID	IFPUG	EQFP – unspecified generic processes and data groups	EQFP –generic transactions and data files
1	289	262	262
2	101	102	106
3	136	100	108
4	195	181	182
5	106	102	106
6	223	208	229
7	15	16	17
8	33	35	38
9	44	49	52

TABLE IX. MEASURES OF NON REAL-TIME PROJECTS OBTAINED VIA THE EQFP METHOD

Project ID	IFPUG	EQFP – unspecified generic processes and data groups	EQFP –generic transactions and data files
1	92	100	99
2	94	107	99
3	79	97	92
4	96	120	118
5	90	108	108
6	91	100	100
7	80	95	92
8	109	113	113
9	82	104	103

TABLE X. MEASURES OF NON REAL-TIME PROJECTS OBTAINED VIA THE TICHENOR ILF MODEL, ISBSG DEISTRIBUTION, SFP AND ISBSG AVERAGE WEIGHTS METHODS.

Project ID	IFPUG	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
1	92	90	199	112	98
2	94	60	133	113	100
3	79	45	100	99	91
4	96	60	133	123	118
5	90	45	100	111	109
6	91	105	232	114	98
7	80	45	100	97	92
8	109	90	199	126	112
9	82	45	100	107	104

TABLE XI. MEASURES OF REAL-TIME PROJECTS OBTAINED VIA THE TICHENOR ILF MODEL, ISBSG DEISTRIBUTION, SFP AND ISBSG AVERAGE WEIGHTS METHODS.

Project ID	IFPUG	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
1	289	269	597	301	259
2	101	119	265	123	105
3	136	105	232	122	107
4	195	224	498	219	179
5	106	60	133	112	107
6	223	134	299	245	232
7	15	15	33	19	17
8	33	45	100	44	37
9	44	45	100	58	52

D. Applying Tichenor ILF Model

In order to apply the model we just had to multiply the number of ILF of each of our projects for the constant 14.93 suggested by Tichenor. The obtained results are illustrated in Table X and Table XI for non Real-Time and Real-Time projects, respectively.

When applying this method, it should be remembered that the results are likely to be incorrect if the distribution of BFC in the estimated application does not match the distribution observed by Tichenor. Accordingly, when applying the method, one should also check the distribution of BFC. Unfortunately, this implies making more work, namely, one should count the number of EIF, EI, EO, and EQ in addition to ILF. Even worse, one could discover that the distribution of his/her application is different from the distribution assumed by Tichenor, so that the estimated size is not reliable.

In our case, the projects do not appear to fit well in the distribution assumed by Tichenor: the *differences* between the measured ratios and the ratios expected by Tichenor are the following:

- For Real-Time projects: 14.3% for EI/ILF, 43.7% for EO/ILF, 3.9% for EQ/ILF, 7.9% for EIF/ILF.
- For non Real-Time projects: 96.7% for EI/ILF, 22.2% for EO/ILF, 27.3% for EQ/ILF, 14.7% for EIF/ILF.

In practice, our projects have a very different distribution of BFC sizes with respect to Tichenor expectations (for instance, in non Real-Time projects EI had often a larger size than ILF, while it is expected that the size of EI is about one third of the size of ILF). So, we must expect a quite poor accuracy from Tichenor estimates. This is actually confirmed by the data in Table XIV, Table XV and Table XVI.

E. Applying the ISBSG distribution model

We applied the formula UFP = (#ILF × 7.4) × 100 / 22.3 prescribed by the method. Then, we evaluated the *differences* between the measured percentage contribution of BFC and the ISBSG averages. The differences we found were relatively small:

- For Real-Time projects: 28.7% for ILF, 3.4% for EIF, 19.3% for EI, 21.3% for EO, 13.2% for EQ.
- For non Real-Time projects: 12% for ILF, 4.8% for EIF, 5.6% for EI, 15.4% for EO, 13.2% for EQ.

Accordingly, we expect that the ISBSG distribution model applies reasonably well to our dataset, especially as non Real-Time projects are involved.

The obtained size estimates are illustrated in Table X and Table XI for non Real-Time and Real-Time projects, respectively.

F. Applying the sFP and ISBSG average weights

The application of the sFP and ISBSG average weights methods was extremely similar to the application of the NESMA estimated and EQFP generic methods, only the values of weights being different.

The obtained results are illustrated in Table X and Table XI for non Real-Time and Real-Time projects, respectively.

V. SUMMARY AND LESSONS LEARNED

In this section, the results of our empirical analysis are reports. First we discuss the quantitative results, then we analyze the results from a more theoretical point of view.

A. Applying the sFP and ISBSG average weights

To ease comparisons, all the size measures of RT projects are reported in Table XII and those of non RT projects are reported in Table XIII.

TABLE XII. MEASURES OF REAL-TIME PROJECTS OBTAINED VIA THE VARIOUS METHODS

Proj ID	IFPUG	NESMA ind. non norm.	NESMA ind. norm.	NESMA estim.	EQFP unspec.	EQFP generic	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
1	289	645	460	245	262	262	269	597	301	259
2	101	280	200	99	102	106	119	265	123	105
3	136	245	175	101	100	108	105	232	122	107
4	195	570	405	168	181	182	224	498	219	179
5	106	140	100	100	102	106	60	133	112	107
6	223	330	235	216	208	229	134	299	245	232
7	15	35	25	16	16	17	15	33	19	17
8	33	105	75	35	35	38	45	100	44	37
9	44	105	75	49	49	52	45	100	58	52

TABLE XIII. MEASURES OF NON REAL-TIME PROJECTS OBTAINED VIA THE VARIOUS METHODS

Proj ID	IFPUG	NESMA ind. non norm.	NESMA ind. norm.	NESMA estim.	EQFP unspec.	EQFP generic	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
1	92	225	160	92	100	99	90	199	112	98
2	94	200	140	93	107	99	60	133	113	100
3	79	120	85	88	97	92	45	100	99	91
4	96	140	100	111	120	118	60	133	123	118
5	90	105	75	102	108	108	45	100	111	109
6	91	245	175	93	100	100	105	232	114	98
7	80	105	75	88	95	92	45	100	97	92
8	109	225	160	106	113	113	90	199	126	112
9	82	105	75	98	104	103	45	100	107	104

TABLE XIV. RELATIVE MEASUREMENT ERRORS (REAL-TIME PROJECTS)

Proj ID	NESMA ind. non norm.	NESMA ind. norm.	NESMA estim.	EQFP unspec.	EQFP generic	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
1	123%	59%	-15%	-9%	-9%	-7%	107%	4%	-10%
2	177%	98%	-2%	1%	5%	18%	162%	22%	4%
3	80%	29%	-26%	-26%	-21%	-23%	71%	-10%	-21%
4	192%	108%	-14%	-7%	-7%	15%	155%	12%	-8%
5	32%	-6%	-6%	-4%	0%	-43%	25%	6%	1%
6	48%	5%	-3%	-7%	3%	-40%	34%	10%	4%
7	133%	67%	7%	7%	13%	0%	120%	27%	13%
8	218%	127%	6%	6%	15%	36%	203%	33%	12%
9	139%	70%	11%	11%	18%	2%	127%	32%	18%

TABLE XV. RELATIVE MEASUREMENT ERRORS (NON REAL-TIME PROJECTS)

Proj ID	NESMA ind. non norm.	NESMA ind. norm.	NESMA estim.	EQFP unspec.	EQFP generic	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
1	145%	74%	0%	9%	8%	-2%	116%	22%	7%
2	113%	49%	-1%	14%	5%	-36%	41%	20%	6%
3	52%	8%	11%	23%	16%	-43%	27%	25%	15%
4	46%	4%	16%	25%	23%	-38%	39%	28%	23%
5	17%	-17%	13%	20%	20%	-50%	11%	23%	21%
6	169%	92%	2%	10%	10%	15%	155%	25%	8%
7	31%	-6%	10%	19%	15%	-44%	25%	21%	15%
8	106%	47%	-3%	4%	4%	-17%	83%	16%	3%
9	28%	-9%	20%	27%	26%	-45%	22%	30%	27%

TABLE XVI. MEAN AND STDEV OF ABSOLUTE RELATIVE ERRORS

	NESMA ind. non norm.	NESMA ind. norm.	NESMA estim.	EQFP unspec.	EQFP generic	Tichenor ILF model	ISBSG distrib.	sFP	ISBSG average weights
Mean (RT only)	127%	63%	10%	9%	10%	20%	112%	17%	10%
Stdev (RT only)	64%	44%	7%	7%	7%	16%	59%	11%	7%
Mean (non RT)	79%	34%	8%	17%	14%	32%	58%	23%	14%
Stdev (non RT)	56%	33%	7%	8%	8%	17%	50%	4%	8%
Mean (all)	103%	49%	9%	13%	12%	26%	85%	20%	12%
Stdev (all)	63%	40%	7%	8%	8%	17%	60%	9%	8%

The relative measurement errors are given in Table XIV and Table XV.

The obtained results show that we can divide the simplified FSM methods in two classes: those which base the size estimation exclusively on some measure of the data (like the NESMA indicative, the Tichenor and ISBSG distribution methods) and those which propose fixed weights for all the BFC of FPA.

The former methods yield the largest errors. Although it was expected that estimates based on less information are generally less accurate than estimates based on more information, the really important finding of our experimental evaluation is that the size estimates based on data measures feature quite often intolerably large errors, i.e., errors that are likely to cause troubles, if development plans were based on such estimates. For instance, let us consider the Tichenor method (which appears the best of those based on data measures) and assume that only size estimation errors not larger than 20% are acceptable: 10 estimates out of 18 would be unacceptable.

On the contrary, the methods that take into consideration all BFC and provide fixed weights for them yield size estimates that are close to the actual size. Among these methods sFP is an exception, since it regularly overestimates the size of projects, often by over 20%. This seems to indicate that "average" projects are characterized by data and/or transactions whose actual complexity is smaller than the complexity expected by the sFP method.

The accuracy of the used methods is summarized in Table XVI, where the mean and standard deviation of the *absolute* relative errors are given for Real-Time projects, for non Real-Time projects, and for the entire set of projects. The mean value of absolute relative errors is a quite popular statistic, often termed MMRE (Mean Magnitude of Relative Errors).

Table XVI shows that the NEMSA estimated, the two EQFP methods and the ISBSG average weights methods provide essentially equivalent accuracy. This is not surprising, given that these methods propose very similar weight values. The NESMA estimated method appears the best, but for Real-Time projects the EQFP methods perform similarly, often even better.

For Real-Time projects, EQFP (either in the unspecified or generic flavor) tends to provide the most accurate results, while the NESMA estimated method provides quite reasonable estimates.

It is worthwhile noticing that EQFP is more accurate than NESMA for Real-Time applications because it uses bigger weights, which suite better Real-Time application, which are more complex than non Real-Time applications.

B. Theoretical analysis

As mentioned in Section II, simplified FSM methods are based on skipping one or more phases of the standards Function Point measurement process (see Table III). It is reasonable to assume that the accuracy of the measure is inversely proportional to the number of phases not performed, hence to the amount of data not retrieved from the functional user requirements of the software to be measured.

To confirm such hypothesis, we have enhanced the information reported in Table III with the data concerning mean errors and error standard deviations: the result is given in Table XVII. The direct comparison of accuracy data with the information used for measurement makes the following observations possible.

Any simplified method that does not involve the weighting appears to be bound to a 10-15% mean absolute error.

It does not appear true that the more you measure, the best accuracy you get. For instance, EQFP considering unspecified generic functions appear more accurate than sFP, even though the former method does not involve classifying function types.

Among methods that use the same type and amount of data, there are relatively large differences in accuracy: for instance, the Tichenor ILF model appears more precise than both the NESMA indicative (with normalized data) and the ISBSG distribution.

The last two observations suggest that exploiting the knowledge provided by statistical analysis can be decisive for achieving accurate measures via simplified processes. For instance, the EQFP method considering unspecified generic functions is quite accurate because the likely complexity of data and transactions assumed by the method (see Table II) were derived via accurate statistical analysis. On the contrary, the complexity values assumed by the sFP method were chosen on the basis of expectations, not on rigorous statistical analysis.

The exploitation of statistical data is the base for the new methods described in the next section.

TABLE XVII. MEASUREMENT PROCESSES: REQUIRED DATA VS. ACCURACY

	IFPUG	NESMA indic. Norm.	NESMA estim.	EQFP Generic func.	EQFP Unspec. generic func.	Tichenor ILF Model	ISBSG distribution	sFP	ISBSG average weights
Identifying logic data	✓	✓	✓	✓	✓	✓	✓	✓	✓
Identifying elementary processes	✓		✓	✓	✓	(*)	(*)	✓	✓
Classifying logic data as ILF or EIF	✓	✓	✓	✓		✓	✓	✓	✓
Classifying elementary processes as EI, EO, or EQ	✓		✓	✓		(*)	(*)	✓	✓
Weighting data functions	✓								
Weighting transaction functions	✓								
Mean error	-	49%	9%	13%	12%	26%	85%	20%	12%
Error stdev	-	40%	7%	8%	8%	17%	60%	9%	8%

(*) required to verify applicability

VI. NEW SIMPLIFIED FSM MODELS

In this section, we derive simplified FSM models similar to those described in Section II, but based on the measures of our own applications (as reported in Table IV and Table V).

In Table XVIII we give the average weights of the BFC computed over all the measured applications. Note that the given averages are computed as the mean –at the dataset level– of the mean values computed for each application. In the table, the mean weights derived from our dataset are shown together with the weights proposed by other simplified FSM methods, for comparison. The fact that our EI and EO means are smaller than the values proposed by other methods, while the ILF and EIF means are very close to those proposed by other methods probably means that our applications were simpler than those considered in the definition of other methods.

TABLE XVIII. AVERAGE FUNCTION TYPE WEIGHTS FOR OUR DATASET

Function type	EQFP generic	NESMA Estim.	ISBSG average	sFP	Our dataset (all proj.)
ILF	7.7	7	7.4	7	7.4
EIF	5.4	5	5.5	5	5.3
EI	4.2	4	4.3	3	3.7
EO	5.2	5	5.4	4	4.6
EQ	3.9	4	3.8	3	4

In Table XIX we give the average values of weights derived from our dataset, distinguishing Real-Time and non Real-Time applications. We also give the average value of the

ratio between the number of ILF and the size in UFP. It is possible to note that the average number of UFP per ILF we found is quite larger than that found by Tichenor. This suggests that models based just on ILF can be hardly generalized.

Note that we computed also the weights for transaction functions (TF) and data functions (DF). These weights can be used in simplified measurement processes like the EQFP unspecified generic method.

TABLE XIX. MEAN AND MDEIAN WEIGHTS FOR THE PROJECTS IN OUR DATASET

	Mean (median) weight							
Dataset	**ILF**	**EIF**	**EI**	**EO**	**EQ**	**TF**	**DF**	**UFP/ #ILF**
All non RT proj	6.6	5.5	3.5	4.4	3.4	7.0	3.7	22.7
All RT proj	8.2	5.0	4.0	4.8	5.1	8.1	4.4	17.0
All proj	7.4	5.3	3.7	4.6	4.0	7.6	4.1	19.9

The values in Table XIX suggest that transactions were generally more complex in Real-Time applications than in non Real-Time applications. The latter are probably responsible for relatively smaller weights of transaction (EI, EO, and EQ) in Table XVIII.

Using the values in Table XIX it was possible to derive models that are similar to those described in Section II: they are described in Table XX and Table XXI.

TABLE XX. MODELS FOR NON RT PROJECTS.

Average weights (all BFC)	UFP = 6.6 #ILF+ 5.5 #EIF + 3.5 #EI + 4.4 #EO + 3.4 #EQ
Average weights (DF and TF)	UFP = 7.0 #TF + 3.7 #DF
ILF based model	UFP = 22.7 #ILF

TABLE XXI. MODELS FOR RT PROJECTS.

Average weights (all BFC)	UFP = 8.2 #ILF+ 5 #EIF + 4 #EI + 4.8 #EO + 5.1 #EQ
Average weights (DF and TF)	UFP = 8.1 #TF + 4.4 #DF
ILF based model	UFP = 17 #ILF

We used such models to estimate the size of the projects in our dataset. The results of the estimations are reported in Table XXII and Table XXIII for Real-Time and non Real-Time projects, respectively.

Table XXII and Table XXIII show a rather poor accuracy of the estimation based on ILF, with error greater than 20% for several projects.

On the contrary, the estimations based on average weights are reasonably accurate; the obtained results are particularly good for non Real-Time projects, with all the estimates featuring errors not greater than 10%.

The average values of the absolute relative errors are reported in Table XXIV together with the average values of the absolute relative errors obtained with the best among the other methods, for comparison.

It is easy to see that the estimates obtained using the average weights of the projects being estimated feature practically the same accuracy as the other methods.

TABLE XXII. ESTIMATES OF RT PROJECTS BASED ON MODELS USING THE PARAMETERS GIVEN IN TABLE XIX.

Proj. ID		**Average weights (all BFC)**		**Average weights (DF and TF)**		**ILF based model**	
	Actual size	***Est. size***	***% err***	***Est. size***	***% err***	***Est. size***	***% err***
1	289	273	-6%	277	-4%	306	6%
2	101	110	9%	109	8%	136	35%
3	136	109	-20%	105	-23%	119	-13%
4	195	187	-4%	198	2%	255	31%
5	106	104	-2%	103	-3%	68	-36%
6	223	223	0%	213	-4%	153	-31%
7	15	17	13%	17	13%	17	13%
8	33	39	18%	37	12%	51	55%
9	44	52	18%	51	16%	51	16%

TABLE XXIII. ESTIMATES OF NON RT PROJECTS BASED ON MODELS USING THE PARAMETERS GIVEN IN TABLE XIX.

Proj. ID		**Average weights (all BFC)**		**Average weights (DF and TF)**		**ILF based model**	
	Actual size	***Est. size***	***% err***	***Est. size***	***% err***	***Est. size***	***% err***
1	92	85	-8%	90	-2%	136	48%
2	94	87	-7%	97	3%	91	-3%
3	79	81	3%	84	6%	68	-14%
4	96	98	2%	102	6%	91	-5%
5	90	91	1%	92	2%	68	-24%
6	91	85	-7%	90	-1%	159	75%
7	80	79	-1%	79	-1%	68	-15%
8	109	98	-10%	101	-7%	136	25%
9	82	88	7%	88	7%	68	-17%

It is a bit surprising that in the literature a few models of type UFP = k × #ILF were proposed, while model of type UFP = k × #EP (where #EP is the number of elementary processes, i.e., #EI + #EO + #EQ) received hardly any attention. We computed the ratio UFP/#EP for each application, and used the average value k in models UFP = k × #EP, to estimate the size of the applications in our dataset. The obtained estimates were characterized by errors quite similar to those of ILF-based models (the average absolute error was 25% for Real-Time projects and 27% for non Real-Time projects). Accordingly, it seems that models of type UFP = k × #EP are not likely to provide good estimates.

TABLE XXIV. MEAN AND STDEV OF ABSOLUTE RELATIVE ERRORS

	Average weights, all BFC	Average weights, DF & TF	Average UFP / #ILF	NESMA estim.	EQFP unspec.	EQFP generic	ISBSG average weights
Mean (RT only)	10%	9%	26%	10%	9%	10%	10%
Stdev (RT only)	8%	10%	29%	7%	7%	7%	7%
Mean (non RT)	5%	4%	25%	8%	17%	14%	14%
Stdev (non RT)	3%	4%	22%	7%	8%	8%	8%
Mean (all)	8%	10%	31%	9%	13%	12%	12%
Stdev (all)	6%	6%	19%	7%	8%	8%	8%

VII. RELATED WORK

Meli and Santillo were among the first to recognize the need for comparing the various functional size methods proposed in the literature [17]. To this end, they also provided a benchmarking model.

In [18], van Heeringen et al. report the results of measuring 42 projects with the full-fledged, indicative and estimated NESMA methods. They found a 1.5% mean error of NESMA estimated method and a 16.5% mean error of NESMA indicative method.

Using a database of about 100 applications, NESMA did some research on the accuracy of the estimated and indicative function point counts. They got very good results (http://www.nesma.nl/section/fpa/earlyfpa.htm), although no statistics (e.g., mean relative error) are given.

In [19], Vogelezang summarized the two techniques to simplified measuring given in the COSMIC measurement manual: the approximate technique and the refined approximate technique. In the approximate technique, the average size of a functional process is multiplied with the number of functional processes the software should provide. The refined approximate technique uses the average sizes of small, medium, large and very large functional processes. The accuracy of the COSMIC-FFP approximate technique is good enough with less than 10% deviation on a portfolio and less than 15% on a project within a specified environment [19].

Popović and Bojić compared different functional size measures –including NESMA indicative and estimated– by evaluating their accuracy in effort estimation in various phases of the development lifecycle [20]. Not surprisingly, they found that the NESMA indicative method provided the best accuracy at the beginning of the project. With respect to Popović and Bojić, we made two quite different choices: the accuracy of the method is evaluated against the *actual* size of the software product and –consistently– all the information needed to perform measurement is available to all processes.

There is no indication that Real-Time projects were among those measured by van Heeringen et al. or by NESMA.

In [8], Santillo suggested probabilistic approaches, where the measurer can indicate the minimum, medium and maximum weight of each BFC, together with the expected probability that the weight is actually minimum, medium or maximum. This leads to estimate not only the size, but also the probability that the actual size is equal to the estimate.

VIII. THREATS TO VALIDITY

A first possible threat to the internal validity of the study is due to the relatively small datasets.

Another possible issue concerns the size and complexity of the applications. As far as the Real-Time applications are concerned, we measured real industrial projects. Accordingly, we are fairly sure that they represent a good benchmark for the considered simplified FSM methods. On the contrary, our non Real-Time projects are fairly small. However, the really important point for testing the adequacy of simplified FSM methods is not the size of the benchmark applications, but their complexity. It is possible that our non Real-Time projects are slightly less complex than average applications: this would explain why most simplified FSM methods overestimate them (see Table XV).

The fact that our datasets are not very homogeneous is actually not a problem; rather it is useful to challenge the proposed simplified FSM methods with different types of software applications.

IX. CONCLUSION

Sometimes, FPA is too slow or too expensive for practical usage. Moreover, FPA requires a knowledge of requirements that may not be available when the measures of size are required, i.e., at the very first stages of development, when development costs have to be estimated. To overcome these problems, simplified measurement processes have been proposed.

In this paper, we applied simplified functional size measurement processes to both traditional software applications and Real-Time applications.

The obtained results make it possible to draw a few relevant conclusions:

1. Some of the simplified FSM methods we experimented with seem to provide fairly good accuracy. In particular, NESMA estimated, EQFP, and ISBSG average weights yielded average absolute relative errors close to 10%. This level of error is a very good trade off, if you consider that it can be achieved without going through the expensive phase of weighting data and transactions.
2. Organizations that have historical data concerning previous projects can build their own models. We showed that with a relatively small number of projects it is possible to build models that provide a level of accuracy

very close to that of methods like NESMA estimated and EQFP.

3. The simplified FSM methods are generally based on average values of ratios among the elements of FP measurement. Accordingly, projects that have unusual characteristics tend to be ill suited for simplified size estimation. For instance, project 3 in our set of Real-Time projects is more complex than the other projects in the set, having most EI and EO characterized by high complexity. This causes most method to underestimate the size of the project by over 20%. Therefore, before applying a simplified FSM method to a given application, it is a good idea to verify that this application is not too much (or too less) complex with respect to "average" applications. Our Real-Time project 3 was characterized by the need to store or communicate many data at a time: this situation could have suggested that using average values for an early measurement leads to a rather large underestimation.

EQFP methods proved more accurate in estimating the size of Real-Time applications, while the NESMA estimated method proved fairly good in estimating both Real-Time and non Real-Time applications. However, the relatively small number of projects involved in the analysis does not allow generalizing these results.

Even considering the relatively small dataset, it is however probably not casual that the NESMA estimated method happened to underestimate all projects. Probably NESMA should consider reviewing the weights used in the estimated method, in the sense of increasing them.

When considering the results of our analysis from a practical viewpoint, a very interesting question is "what simplified method is the best one for my application(s)?". Table XIV and Table XV show that the methods that are better on average are not necessarily the best ones for a given project. To answer the question above it would be useful to characterize the projects according to properties not considered in FSM, and look for correlations with the measures provided by different simplified methods. This would allow selecting the simplified measurement method that provided the best accuracy for applications of the same type as the one to be sized. Unfortunately, it was not possible to analyze the possibly relevant features of the dataset described in Section III (we had no access to the code of Real-Time projects), thus this analysis is among future activities.

As already mentioned, the results presented here are based on datasets in which the largest project has size of 289 FP: further work for verifying the accuracy of simplified measurement methods when dealing with larger project is needed.

Among the future work is also the experimentation of simplified measurement processes in conjunction with measurement-oriented UML modeling [16], as described in [21].

The models described in Section II are generally derived in a rather naive way, i.e., simply computing averages of some elements that are involved in the measurement: e.g., the average ration between the measure of BFC and their number. Simplified measurement models should be better derived via regression analysis. Unfortunately, the relatively little number of applications in our datasets does not support this type of analysis, especially if multiple independent variables are involved, as in models of type UFP = f(EI, EO, EQ, ILF, EIF) or UFP = f(TF, DF). Performing this type of analysis is among our goal for future activities, provided that we can get enough data points.

ACKNOWLEDGMENT

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Basic Building Blocks for Column-Stores

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***Abstract*—A constantly increasing CPU-memory gap as well as steady growth of main memory capacities have increased interest in column store systems due to potential performance gains within the realm of database solutions. In the past, several monolithic systems have reached maturity in the commercial and academic spaces. However, a framework of low-level and modular components for rapidly building column store based applications has yet to emerge. A possible field of application is the rapid development of high-performance components in various data-intensive areas such as text-retrieval systems and recommendation systems. The main contribution of this paper is a column-store-tool-kit, a basic building block of low-level components for constructing applications based on column store principles. We present a minimal amount of necessary structural elements and associated operations required for building applications based on our column-store-kit. The eligibility of our toolkit is demonstrated subsequently in using the components of our toolkit for building different query execution plans. This part of work is a first step in our effort for the construction of a pure colmun-store based query optimizer.**

***Keywords*—Column store; basic components; framework; rapid prototyping; TPC-H benchmark; query-optimizer; query-execution plan.**

I. Introduction

Within database systems, values of a dataset are usually stored in a physically connected manner. A *row store* stores all column values of each single row consecutively (see Figure 1, bottom left). In contrast to that, within a *column store*, all values of each single column are stored one after another (see Figure 1, bottom right). In column stores, the relationship between individual column values and their originating datasets are established via Tuple IDentifiers (TID). The main advantage of column stores during query processing is the fact that only data from columns which are of relevance to a query have to be loaded. To answer the same query in a row store, all columns of a dataset have to be loaded, despite the fact, that only a small portion of them are actually of interest to the processing. On the other side, the column store architecture is disadvantageous for frequent changes (in particular insertions) to datasets. As the values are stored by column, they are distributed at various locations, which leads to a higher number of required write operations exceeding those within a row store to perform the same changes. This characteristic makes this type of storage interesting especially for applications with very high data volume and few sporadic changes only (preferably as bulk upload), as it is the case in, e.g., data warehouses, business intelligence systems or text retrieval systems.

In our previous work [1], we identified the basic building blocks of our Column Store ToolKit (CSTK) and its interfaces with respect to providing a toolkit for building column store-based applications. In this paper, we extend our formulated ideas with a number of experiments which demonstrate the suitability of our toolkit with regard to building a query optimizer for column stores and the general suitability for scientific questions in the field of column store research.

Interest in column store systems has recently been reinforced by steady growth of main memory capacities that meanwhile allow for main memory-based database solutions and, additionally, by the constantly increasing CPU-memory gap [2]. Today's processors can process data much quicker than it can be loaded from main memory into the processor cache. Consequently, modern processors for database applications spend a major part of their time waiting for the required data. Column stores and special cache-conscious [3] algorithms are attempts to avoid this "waste of time". A number of commercial and academic column store systems have been developed in the past. In the research area, MonetDB [4] and C-Store [5] are widely known. Open Source and commercial systems include Sybase IQ, Infobright, Vertica, LucidDB, and Ingres. All these systems are more or less complete database systems with an SQL interface and a query optimizer.

As column stores are a young field of research, numerous aspects remain to be examined. For example, separation of datasets into individual columns result in a series of additional degrees of freedom when processing a query. Abadi et al. [6] developed several strategies as to when a result is to be "materialized", i.e., at which point in time result tuples shall be composed. Depending on the type of query and selectivity of predicates, an early or late materialization may be reasonable. Interesting studies were published about compression methods [7], various index types as well as the execution of join operations, e.g., Radix-Join [2], Invisible Join [8] or LZ-Join [9]. In addition to that, there are attempts at creating hybrid approaches that try to combine the advantages of column and row stores. The main objective of this paper is to present a number of low-level building blocks for constructing applications based on column store systems. Instead of copy-

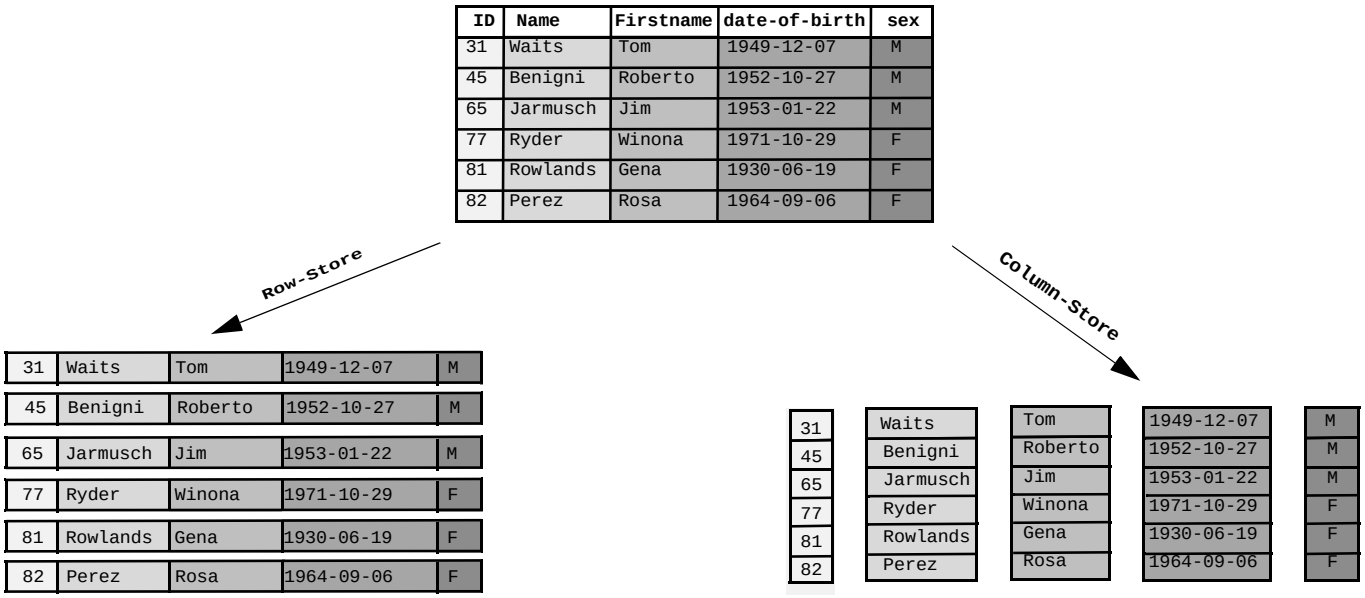

Fig. 1. Comparison of the layouts of a row store and a column store

ing the low-level constructs of existing sophisticated column stores, our research work is focused on identifying components and operations that allow for building specialized column store based applications in a rapid prototyping fashion. As our components can be composed in a "plug and compute"-style, our contribution is a column-store-tool-kit, which is a building block for experimental and prototypical setup of applications within the field of column stores. A possible field of application is the rapid development of high-performance components in various data-intensive areas such as text-retrieval systems.

This paper is structured as follows. In the next section, related work is mentioned. Then, in Section III, some basic considerations about column stores will be outlined. Afterwards, in Section IV and V the identified components and corresponding operations will be explained on a logical level. On this basis, various implementations of logical components and operations will be presented in Section VI. Finally, results will be summarized and an outlook will be given on future research activities.

II. Related Work

In the field of database systems, there are a number of related approaches. For example the C++-fastbit-library [10] provides a number of searching functions based on compressed bitmap indexes. Beside the low-level bitmap components, also a SQL interface exists in this library. The approach is comparable to the bitmap index in some relational database systems (i.e., Oracle, PostgreSQL). In contrast to these indexes, the fastbit bitmaps are compressed and therefore also usable for high cardinality attributes. The CSTK described in this paper can benefit from the compressed bitmap classes when implementing the *PositionLists* (see Section IV). Weather this implementation variant is advantageous depends on a number of factors. For details see [11]. In the field of query optimization there are a number of different tools, i.e., the Volcano project [12], developed by Goetz Graefe. Volcano is a optimizer generator, which means, that the source code of the optimizer is generated, based on a model specification which consists of algebraic expressions. The library itself contains modules for a file-system, buffer management, sorting, duplicate elimination, $B+$-trees, aggregation, different join implementations, set operations, and aggregation functions. Based on the experiences gained with Volcano, the Cascades framework [13] was started, which later forms the base for the SQL Server 7.0 query optimizer [14].

III. Column Store Principles

Nowadays, modern processors utilize one or more cache hierarchies to accelerate access to main memory. A cache is a small and fast memory that resides between main memory and the CPU. In case the CPU requests data from main memory, it is first checked, whether it already resides within the cache. In this case, the item is sent directly from the cache to the CPU, without accessing the much slower main memory. If the item is not yet in the cache, it is first copied from the main memory to the cache and then further sent to the CPU. However, not only the requested data item, but a whole cache line, which is between 8 and 128 bytes long, is copied into the cache. This prefetching of data has the advantage, that requests to subsequent items are much faster, because they already reside within the cache. Meanwhile, the speed gain when accessing a dataset in the first-level cache is up to two orders of magnitude compared to regular main memory access [15]. Column stores take advantage of this prefetching behavior, because values of individual columns are physically connected together and, therefore, often already reside in the cache when requested, as the execution of complex queries is processed column by column rather than dataset by dataset. This also means that the decision whether a dataset fulfills a complex condition is generally delayed until the last column is processed. Consequently, additional data structures are required to administrate the status of a dataset in a query. These data structures are referred to as *Position List*s. A *PositionList* stores the TIDs of matching datasets. Execution of a complex query generates

a *PositionList* with entries of the qualified datasets for every simple predicate. Then, the *PositionList*s are linked by *and*/*or* semantics. As an example, Figure 2 shows a possible execution plan for the following query:

```
select birthday, name
  from person
 where birthdate < '1960-01-01'
   and sex='F'
```

First, the predicates $birthdate$ <'1960-01-01' and sex ='F' must be evaluated against the correponding columns (birthdate and sex), which results in the *PositionList*s *PL1* and *PL2*. These two evaluations could also be done in parallel. Next, an *and*-operation must be performed on these two *PositionList*s, resulting in the *PositionList PL3*. As we are interested in the birthdate and name of the persons that fulfil the query conditions, we have to perform another two operations (extract), which finally returns the entries for the TIDs, specified by the *PositionList PL3*.

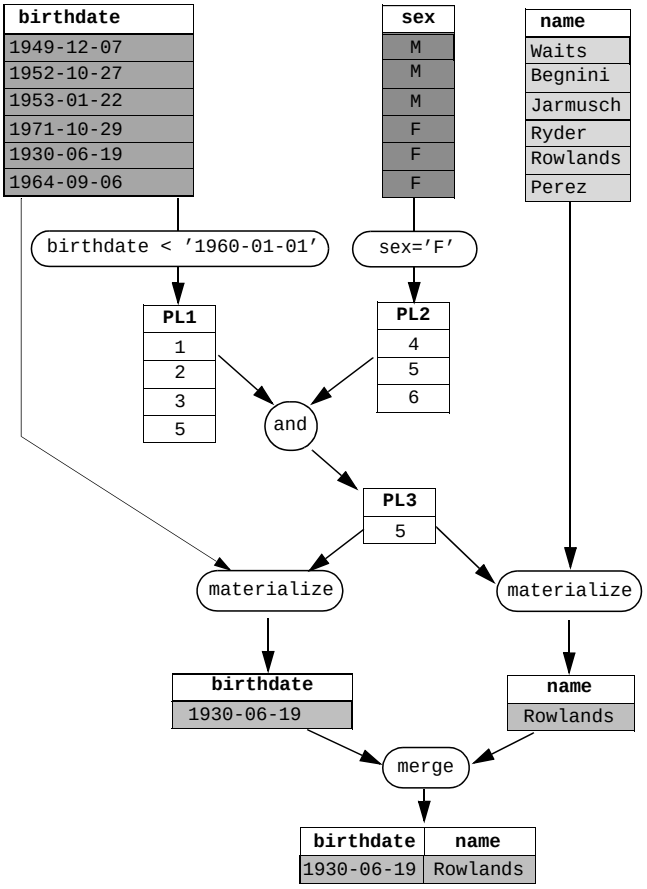

Fig. 2. Processing of a query with PositionLists

IV. Concept

The main focus of our components is to model the individual columns, which can occur both in the secondary store as well as main memory. Their types of representation may vary. To store all values of a column, for example, it is not necessary to explicitly store the TID for each value, because it can be determined by its position (dense storage). To handle the results of a filter operation however, the TIDs must be stored explicitly with the value (sparse storage). Another important component is the *PositionList* already mentioned in Section III. Just like columns, two different representation forms are available for main and secondary storage. To generate results or to handle intermediate results consisting of attributes of several columns, data structures are required for storing several values (so-called multi columns). These may also be used for the development of hybrid systems as well as for comparing the performance of row and column store systems. The operations mainly focus on writing, reading, merging, splitting, sorting, projecting, and filtering data. Predicates and/or *PositionList*s are applied as filtering arguments. Figure 3 illustrates a high level overview of the most important operations and transformations between the components. In Section V, they will be described in detail. Moreover, the components are to be developed for use on both secondary store and main memory as well as designed for maximum performance. This particularly implies the use of cache-conscious algorithms and structures.

V. Presentation of Logical Components

In the following sections, the aforementioned components will be presented together with their structure and their corresponding operations. Section VI will then outline potential implementations to reach highest possible performance.

A. Structure

1) ColumnFile: The *ColumnFile* serves to represent a column on the secondary storage. Supported primitive data types are: uint, int, char, date und float. Moreover, the composite type *SimpleStruct* (see V-A2) is supported, which may consist of a runtime definable list of the previously mentioned primitive data types. As a standard, the TID of a value in the *ColumnFile* is given implicitly by the position of the value in the file. If this is not the case, a *SimpleStruct* is used, which explicitly contains the TID in the first column.

2) SimpleStruct: SimpleStruct is a dynamic, runtime definable data structure. It is used within *ColumnFile* as well as within *ColumnArray*s (see below). The *SimpleStruct* plays a role in the following cases:

- Result of a filter query, in which the TIDs of the original datasets are also given.
- Combination of results consisting of several columns.
- Setup of hybrid systems having characteristics of both column and row stores. For example, it may be advantageous to store several attributes in a *SimpleStruct* that are frequently requested together.
- Representation of sorted columns, where TIDs are required. This is particularly reasonable for Join operators or a run-length-encoded compression on their basis.

3) ColumnArray and MultiColumnArray: A *ColumnArray* represents a column in main memory, which consists of a flexible number of lines. The data types correspond to those of the previously defined *ColumnFile*. If the data type is a *SimpleStruct*, it is referred to as *MultiColumnArray*. In addition to the actual column values, the TIDs of the first and last dataset

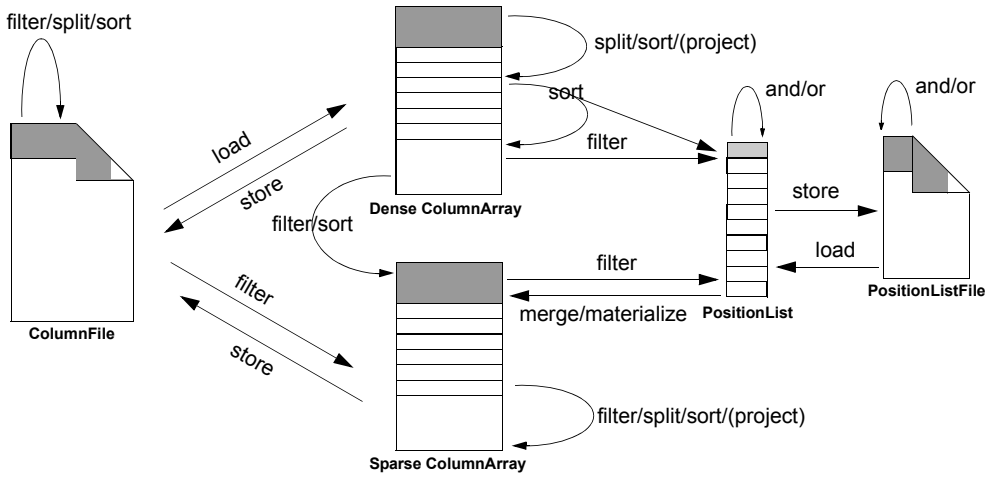

Fig. 3. Components and Operations

and the number of datasets stored are given in the header of the *(Multi)ColumnArray*. Two types of representations are distinguished:

- **Dense:** The type of representation is dense, if no gaps can be found in the datasets, i.e., if the TIDs are consecutive. In this case, the TID is given virtually by the TID of the first data set and the position in the array and does not have to be stored explicitly (see Figure 4, left side). This type of representation is particularly suited for main memory-based applications, in which all datasets (or a continuous section of them) are located in main memory.
- **Sparse:** This type of representation explicitly stores the TIDs of the datasets (see Figure 4, right). The primary purpose of a sparse *ColumnArray* is the storage of (intermediate) results. As will be outlined in more detail in Section V, it may be chosen between two physical implementations depending on the concrete purpose.

4) ColumnBlocks and MultiColumnBlocks: Apart from the *(Multi)ColumnArray*s of flexible size, *(Multi)ColumnBlocks* exist, which possess a arbitrary, but fixed size. They are mainly used to implement ColumnArrays with their flexible size. In addition, they may be applied in the implementation of an custom buffer management as a transfer unit between secondary and main memory and as a unit that can be indexed.

5) PositionList: A *PositionList* is nothing else than a *ColumnArray* with the data type *uint(4)* as far as structure is concerned. However, it has a different semantics. The *PositionList* stores TIDs. A *PositionList* is the result of a query via predicate(s) on a *ColumnFile* or a *(Multi)ColumnArray*, where the actual values are of no interest, but rather the information about the qualified data sets. *Position List*s store the TIDs in ascending order without duplicates. This makes the typical and/or operations very fast, as the cost for both operations is $O(|Pl_1|+|Pl_2|)$. As will be outlined in Section VI, various types of implementations may be applied. Analogously to the *(Multi)ColumnArray*, there is a representation of the *PositionList* for the secondary store, which is called *PositionFile*.

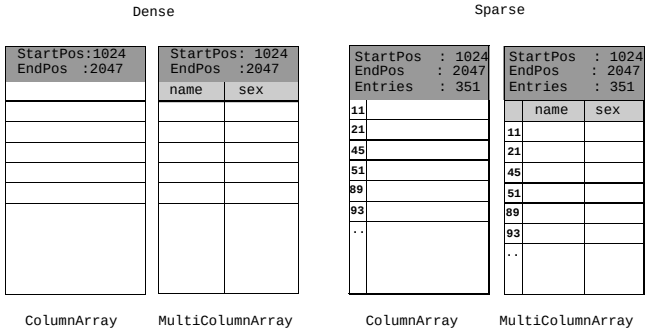

Fig. 4. Types of ColumnArrays

B. Operations

1) Transformations on ColumnFiles: Several operations are defined on *ColumnFile*s. A filter operation (via predicate and/or PositionList) can be performed on a *ColumnFile* and the result can be written to another *ColumnFile* (with or without explicit TIDs). Other operations are the splitting of a *ColumnFile* as well as sorting among different criterias (see Section V-B6) with and without explicitly storing the TID.

2) Transformations between ColumnFile and (Multi)-Column-Array: ColumnFiles and *(Multi)ColumnArray*s are different types of representation of one or more logical columns. Physically, ColumnFiles are located in the secondary storage, while *ColumnArray*s are located in main memory. Consequently, both types of representations can also be transformed into each other using the corresponding operators.

A *ColumnFile* can be transformed completely or partially into a dense *(Multi)ColumnArray*. If not all, but only certain datasets that match special predicates or *PositionList*s are to be loaded into a *(Multi)ColumnArray*, this can be achieved using filter operations that generate a sparse *(Multi)ColumnArray*. A sparse *(Multi)ColumnArray* may also be transformed into a *ColumnFile*. In this case, the TIDs are stored explicitly in combination with the values. Other operations refer to the insertion of new values and the deletion of values. An outline of the most important operations of *ColumnFile*s is given in Table I.

TABLE I. OUTLINE OF OPERATIONS ON COLUMNFILES

Operation	Result type
read(ColumnFile)	ColumnArray (dense)
read(ColumnFile, start, length)	ColumnArray (dense)
filter(ColumnFile, predicate)	ColumnArray (sparse)
filter(ColumnFile, predicate-list)	ColumnArray (sparse)
filter(ColumnFile, positionlist)	ColumnArray (sparse)
filter(ColumnFile, positionlist-list)	ColumnArray (sparse)
filter(ColumnFile, predicate-list, positionlist-list)	ColumnArray (sparse)
fileFilter(ColumnFile, predicate)	ColumnFile (explicit TIDs)
fileFilter(ColumnFile, predicate-list)	ColumnFile (explicit TIDs)
fileFilter(ColumnFile, positionlist)	ColumnFile (explicit TIDs)
fileFilter(ColumnFile, positionlist-list)	ColumnFile (explicit TIDs)
fileFilter(ColumnFile, predicate-list, positionlist-list)	ColumnFile (explicit TIDs)
split(ColumnFile, predicate)	ColumnFile, ColumnFile
split(ColumnFile, position)	ColumnFile, ColumnFile
merge(ColumnFile-list, predicate-list)	MultiColumnArray (sparse),
sort(ColumnFile, column(s), direction)	ColumnFile
sort(ColumnFile, Orderlist)	ColumnFile
mapSort(ColumnFile)	ColumnFile, Orderlist
mapSort(ColumnFile)	ColumnArray, Orderlist
insert(ColumnFile, value)	Tupel-ID
insert(MultiColumnFile, $value_1, \ldots$)	Tupel-ID
delete(ColumnFile, Tupel-ID)	boolean
delete(ColumnFile, Positionlist)	integer
delete(ColumnFile, predicate)	integer
delete(ColumnFile, predicate-list)	integer

3) Operations on ColumnArrays: Filter operations can be executed on *(Multi)ColumnArray*s using predicates and/or *PositionList*s. This may result in a sparse *(Multi)ColumnArray* or a *PositionList*. Furthermore, *ColumnArrays* may also be linked with each other by and/or semantics. If the *(Multi)ColumnArray*s have the same structure, the result also possesses this structure. The results correspond to the intersection or union of the original datasets. The result is a sparse *(Multi)ColumnArray*. If *(Multi)ColumnArray*s of differing structure are to be combined, only the and operation is defined. The result is a *(Multi)ColumnArray* that contains a union of all columns of the involved *(Multi)ColumnArrays* and returns the values for the datasets having identical TIDs. If the *(Multi)ColumnArray*s used as input are dense and if they have the same TID interval, the resulting *MultiColumnArray* is also dense. An outline of the most important operations of *ColumnArray*s is given in Table II. *ColumnArray* may also refer to a *MultiColumnArray*. A *MultiColumnArray*, however, only refers to the version having several columns.

4) Transformation from PositionList to ColumnArray: If the column values of the stored TIDs inside a *PositionList* are needed, an *extract* operation must be performed. Input to this operation is a *PositionList* as well as a *dense (multi) ColumnArray*. The result is a *sparse (Multi) ColumnArray*.

5) Operations between PositionLists: Several *PositionList*s may be combined by *and*, *or* semantics, with the result being a *PositionList*. The result list is sorted in ascending order corresponding to the TIDs. In addition, operations exist to load and store *PositionList*s. An outline of operations of *PositionList*s can be found in Table III.

6) Sorting: One basic operation on *(Multi) ColumnArray*s as well as *ColumnFiles* is sorting. Beside the obvious task to bring the result of a query in a specific order, sorting also plays an important role regarding performance considerations. For the elimination of duplicates, for join operations and for compression using run-length encoding, previous sorting can dramatically improve performance. As a consequence of sorting, the natural order is lost. This is critical for dense columns with implicit TIDs, because the relation to the other column values is lost. The problem can be solved by an additional data structure, similar to a *PositionList* that contains the mapping information to the original order of the datasets. Figure 5 gives an example of this situation. The *Multi ColumnArray* on the left side is to be sorted according to the column "name". Additionally to the sorting of the *MultiColumn* (top right), a list is generated which holds the information about the original positions (down right). The list can then be reused by applying it as a sorting criterion to other columns later, as shown in Figure 6.

TABLE II. OUTLINE OF OPERATIONS ON *ColumnArrays*

Operation	Result type
filter(ColumnArray, predicate)	ColumnArray (sparse)
filter(ColumnArray, predicate-list)	ColumnArray (sparse)
filter(ColumnArray, positionlist)	ColumnArray (sparse)
filter(ColumnArray, positionlist-list)	ColumnArray (sparse)
filter(ColumnArray, predicate-list, positionlist-list)	ColumnArray (sparse)
filter(ColumnArray, predicate)	PositionList
filter(ColumnArray, predicate-list)	PositionList
filter(ColumnArray, positionlist)	PositionList
filter(ColumnArray, positionlist-list)	PositionList
filter(ColumnArray, predicate-list, positionlist-list)	PositionList
and(ColumnArray, ColumnArray)	ColumnArray
or(ColumnArray, ColumnArray)	ColumnArray
and(ColumnArray, ColumnArray)	PositionList
or(ColumnArray, ColumnArray)	PositionList
project(MultiColumnArray, columns)	(Multi)ColumnArray
asPositionList(ColumnArray, column)	PositionList
split(ColumnArray, predicate)	ColumnArray (sparse) ColumnArray (sparse)
sort(ColumnArray)	ColumnArray
sort(ColumnArray, Orderlist)	ColumnArray
mapSort(ColumnArray)	ColumnArray, Orderlist
split(ColumnArray(dense), position) ColumnArray (dense)	ColumnArray (dense)
split(ColumnArray (sparse), position) ColumnArray (sparse)	ColumnArray (sparse)
merge(ColumnArray-list (sparse), predicate-list)	MultiColumnArray (sparse)
store(ColumnArray (dense))	ColumnFile
store(ColumnArray (sparse))	ColumnFile (explicit TIDs)

TABLE III. OUTLINE OF OPERATIONS ON *PositionList*S

Operation	Result type
load(ColumnFile)	PositionList
store(PositionList)	ColumnFile
and(PositionList, PositionList)	PositionList
or(PositionList, PositionList)	PositionList
materialize(PositionList, ColumnArray, ...)	ColumnArray
materialize(PositionList, ColumnFile, ...)	ColumnArray
read(PositionListFile)	PositionList
store(PositionList)	PositionListFile

7) Compression: Compression plays an important role in column stores [7], as it reduces the data volume that needs to be loaded. Nevertheless, we decided not to include compression in the first prototype and to concentrate on the interfaces of the components. To a certain extent, this constraint can be compensated by the use of dictionary-based compression [16], which will be implemented above the basic components. In later versions, various compression methods will be integrated, so first of all run-length encoding (RLE) [17].

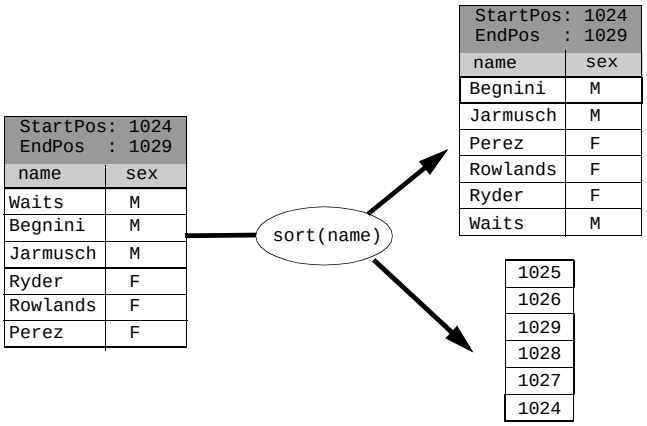

Fig. 5. Sorting with explicit generation of an additional mapping list

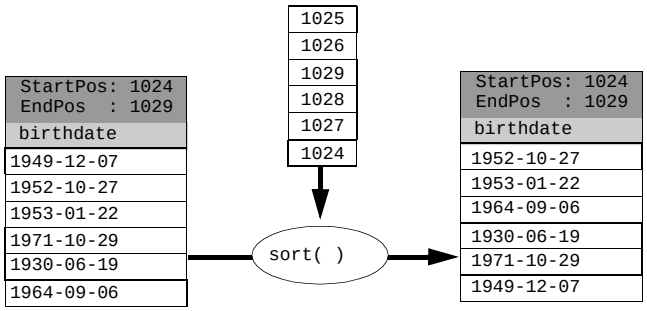

Fig. 6. Sorting with explicit given sort-order

VI. Implementation-specific Considerations

After presenting the logical structure and the required operations, this section will now focus on considerations for achieving a performance-oriented implementation. Due to the constantly increasing CPU-memory gap, cache-conscious programming is indispensable. For this reason, the implementation was made in C/C++. All time-critical parts were implemented in pure C using pointer arithmetics. The uncritical parts were implemented using C++ classes. The *ColumnBlock* was established as a basic component of the implementation. It is the basic unit for data storage. Its size is defined at creation time and it contains the actual data as well as information on its structure and the number of datasets. The structurization options correspond to those of the *(Multi)ColumnArray*. The *ColumnBlock* also handles all queries by predicates and/or *PositionList*s. A *(Multi)ColumnArray* consists of n *ColumnBlock* instances. All operations on a *(Multi)ColumnArray* are transferred to the underlying *ColumnBlock*s.

*PositionList*s play a central role in column store applications. One important point is the size of a *PositionList*. If the *PositionList*s are short (i.e., if they contain a few TIDs only), representation as *ColumnArray* is ideal. Four bytes are required per selected entry. If the lists are very large, however, memory of 400 MB is required for ten million entries, for instance. In this case, a bit vector is recommended for representation. This bit vector uses for each dataset a bit at a fixed position to indicate whether a dataset belongs to the set of results or not. If, for example, 10 million data sets exist for a table, only 1.25 MB are required to represent the *PositionList* for certain selectivities. Moreover, the two important operations *and* and *or* can be mapped on the respective primitive processor commands, which makes the operations extremely fast. If *PositionList*s are sparse, bit vectors can be compressed very well using run-length encoding (RLE) (e.g., to a few KB in case of 0.1% selectivity). The necessary operations can be performed very efficiently on the compressed lists, which further increases the performance. An implementation based on the word-aligned hybrid algorithm [18] with satisfactory compression for medium-sparse representations was developed within the framework of the activities reported here [19], [20].

Figure 7 gives an overview of the memory consumption for different implementations of a *PositionList*. Here, we compare the behavior of a dynamic array containing 4-byte TIDs with a plain uncompressed bitvector and different implementations (32, 64 bit) of the Word Aligned Hybrid (WAH) algorithm [18], both compressed and uncompressed. As we can see in the figure, the behavior of the dynamic array implementation is quite good for very small selectivities, but changes for the worse for medium and high densities. Uncompressed bitmaps (plain bitvector or WAH uncompressed) behave independently for all densities. Their size is determined by the number of tuples in a table only. Compressed bitmaps show a very good behavior for all densities. If selectivities become low, they behave like uncompressed bitmaps (compared to a pure uncompressed implementation of a bitvector, there will be a slight overhead of 1/32. resp. 1/64.). From a selectivity of about 3%, the array has a higher memory consumption than the uncompressed bitvector. Beside the memory consumption, also the runtime behavior of the different implementation variants plays a very important role. In [21], an elaborate analysis of the memory consumption and runtime behavior of different implementation variants (array, bitvector, compressed bitvector) for positionlists can be found. The bottom line of this paper is that the choice of the right implementation variant is not a trivial task and depends heavily on the selectivity of the predicates. The differences in the runtime behavior are over two orders of magnitude for typical *PositionList* operations.

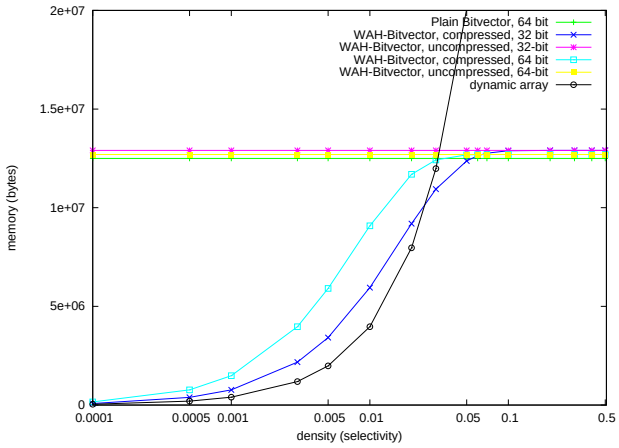

Fig. 7. Comparison of the memory consumption for different implementation variants of *PositionLists*

*MultiColumnArray*s may exist in two different physical layouts. In the first version, the n values are written in a physically successive manner and correspond to the classical n-ary storage model (NSM). This type of representation is

particularly suited, if further queries are to be performed on this *MultiColumnArray* with predicates on the respective attributes. The individual values of a dataset are stored together in the cache and all attribute values are checked simultaneously rather than successively with the help of additional *PositionLists* (see Figure 8, left). The second type of representation corresponds to the PAX format [22]. Here, every column is stored in a separate *ColumnArray*. In addition, a *PositionList* is stored, which identifies the datasets (see Figure 8, right). This type of representation is recommended, for instance, for collecting values for subsequent aggregation functions. Several *(Multi)ColumnArrays* may share a single *PositionList*.

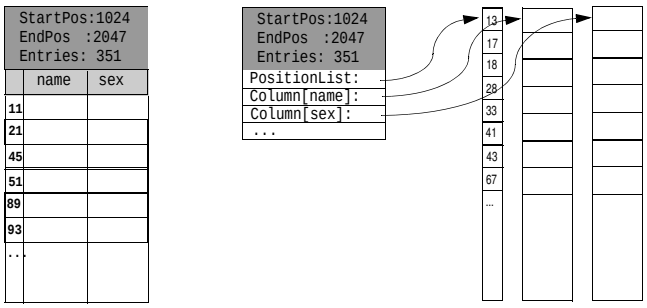

Fig. 8. Comparison of storage formats for ColumnArrays

VII. USE CASES

In this section, we want to deal with the usage of the CSTK-components. We will present the general mechanism for building complex queries from the components, demonstrate the suitability of our components for scientific questions in the field of column store research and present an execution plan and the runtime behavior for a typical data warehouse query from the TPC-H [23] benchmark. The aim of this experiment is to gain further insight into the costs of the different operations and to derive rules for a query optimizer for column stores [24].

A. Usability of the Components

1) Materialization: In [6], Abadi et al. propose different strategies to construct the final result sets from the intermediate *PositionLists*. This step is called "materialization". One strategy is to keep the *PositionList* values as long as possible and to only materialize the attribute values in a very last step. This is called "late materialization". On the other hand, "early materialization" means that the values should already be extracted in every selection step. The quintessence of the paper is that the superiority of any strategy depends on the characteristic of the query.

In the paper, Abadi et al. identified four different datasource operators (DS1, .., DS4) from which data could be read from disk or main memory. Additionally, they identified the *AND* operator for *PositionLists* and two more tuple construction operators, *MERGE* and *SPC* (Scan, Predicate, and Construct) for the construction of result tuples.

Based on these operators, they formed different query plans to implement early and late materialization strategies. Figure 9 shows the different execution plans for the following query, implementing an early materialization strategy (a, b) or a late materialization strategy (c, d).

```
SELECT l_shipdate, l_linenum
  FROM lineitem
 WHERE l_shipdate < C1
   AND l_linenum  < C2
```

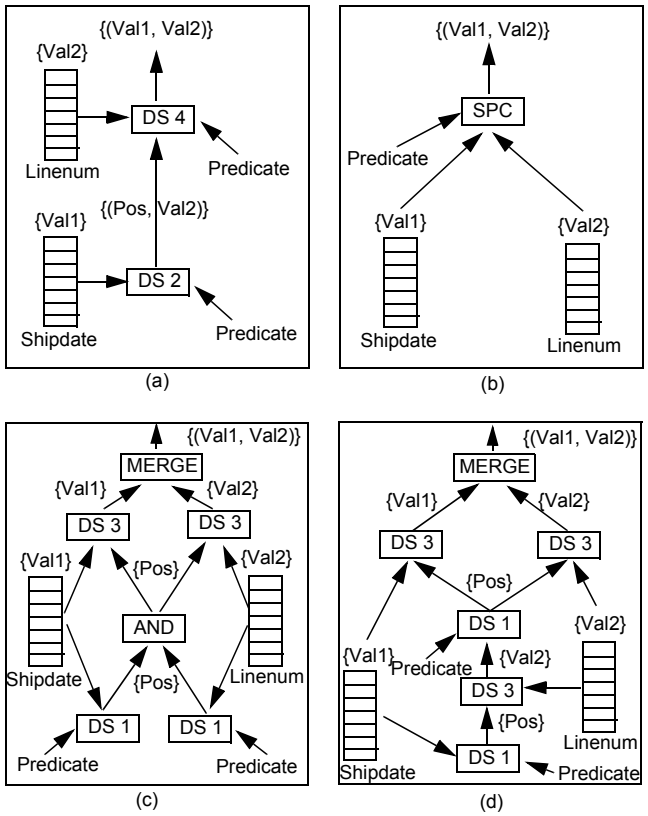

Fig. 9. Different query-plans from [6]

Using the components from the CSTK, these query plans can easily be rebuilt, using the operations from Tables I, II, and III. This is shown in Figure 10. In contrast to the original execution plans, which do not distinguish between file and main memory representation in each case, this is done with the execution plans built with the CSTK.

2) Complex Queries: In the following, a step-by-step explanation of a join operation is performed based on an example. The underlying dataset is from TPC-H benchmark (*lineitem* and *partkey* table).

The SQL query is the following:

```
SELECT p_name, l_quantity
  FROM part
  JOIN lineitem
    ON p_partkey = l_partkey
 WHERE l_orderkey = 34
```

Figure 11 shows the corresponding operations on the required columns. First, the *WHERE*-clause on the *l_orderkey* column is executed (1) to get the corresponding TIDs (l_TID) from the *lineitem* table. The extracted TIDs (5,6,7) are then used to read the corresponding values (883, 894, 169) from the *l_partkey* column of the *lineitem* table (2). Next, the (*l_TID*, *l_partkey* tuples are sorted based on their *l_partkey*

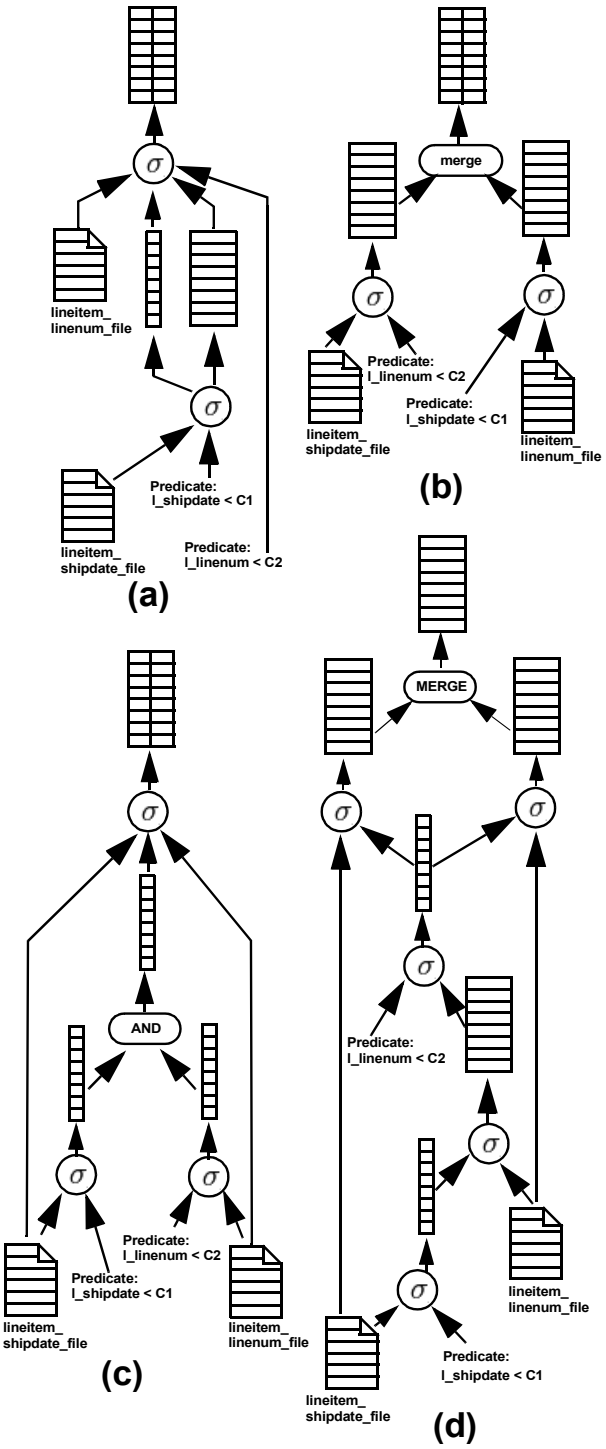

Fig. 10. Different materialization strategies from [6] using the CSTK components

values (3). The resorted tuples can then be merged with the sorted *p_partkey* column of the *partkey* table (5), which has to be sorted priorly (4) and enriched with the *p_TID* column, which was implicitly given by the position of the values in the unsorted *p_partkey* column.

The result of the merge operation are tuples of the form (*l_TID*, *p_TID*). They represent the result of the join operation

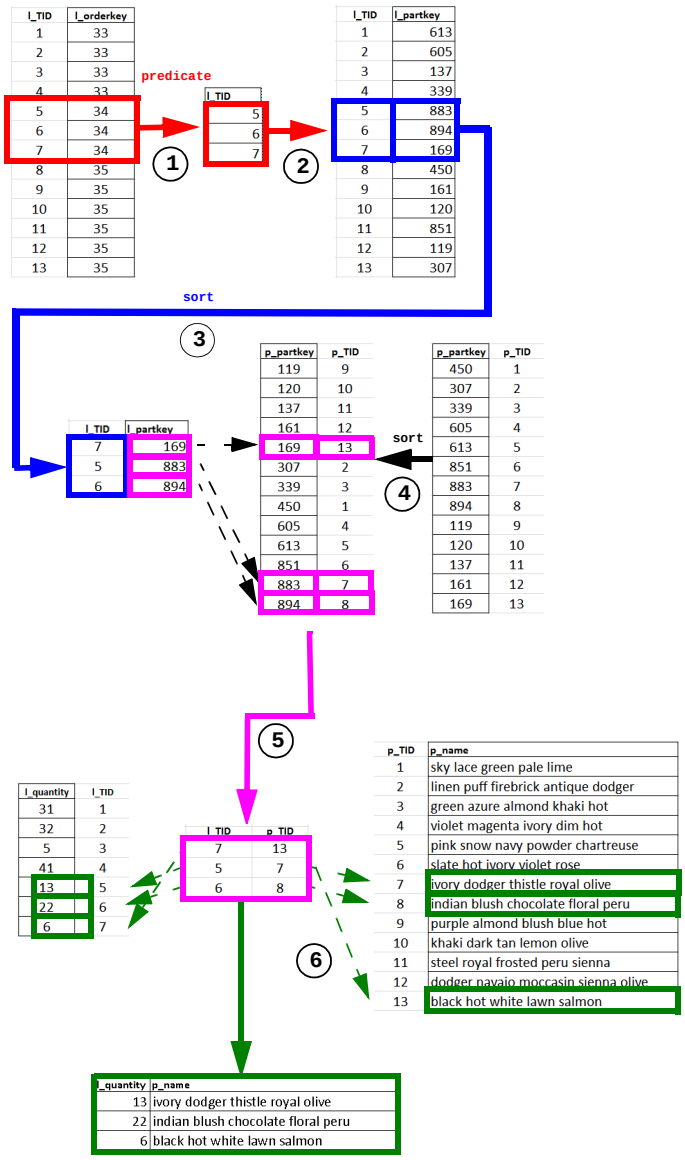

Fig. 11. Join-Operation with the Column-Store-Tool-Kit

between the *lineitem* and *partkey* table on the *partkey* column. In the last step, the materialization (6) takes place. The *l_TID* and *p_TID* values are replaced by their corresponding values from the *p_name* and *p_quantity* columns.

After demonstration of a CSTK-Join on a concrete example, the principle data flows, based on the operations on Tables I, II, and III are shown. Figure 12 shows an execution plan performing the following SQL query:

```
SELECT *
  FROM orders o
  JOIN lineitem l
    ON l_orderkey=o_orderkey
```

In the current execution plan, a sort-merge join is performed. As a first step, the entries in the two column files *orders_orderkey_file* and *lineitem_orderkey_file* must be sorted (remember: in the files, the TIDs are implicit given by the

position of the values in the file). This is done with the *mapSort*-operation. The *mapSort* operation sorts the column values and provides an additional data structure *pl_o* and *pl_l*, which contains the TIDs for each sorted value. The structure is similar to a *PositionList*, but the TIDs are no longer sorted.

After the preparatory sorting step, the values in the columns are compared position by position (operation *cmp*). For each matching value from the two columns, the corresponding entries in the previously generated *PositionList pl_o* and *pl_l* are taken and written into the joined *PositionList* (*pl_o',pl_l'*). In a final step (not shown in Figure 12), the joined *PositionList* is materialized.

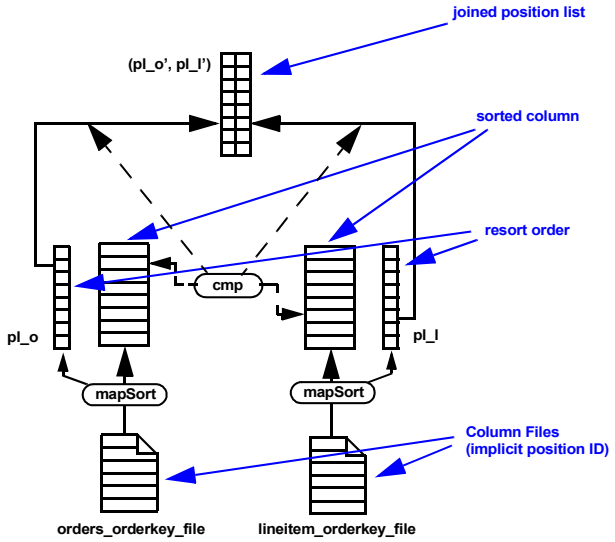

Fig. 12. Join-Operation with the Column-Store-Tool-Kit

An additional *WHERE* clause (see below) leads to the execution plan in Figure 13.

```
SELECT *
  FROM orders o
  JOIN lineitem l
    ON l_orderkey=o_orderkey
 WHERE o_orderdate= '1992-01-13'
```

The evaluation of the condition on the *orders_orderdate_file* generates a *PositionList* (pl_o), which acts as a filter criterion for the *orders_orderkey_file*. After filtering, the *PositionList* also represents the TIDs for the *orders_orderkey* column. In the subsequent *mapSort* operation, the *orders_orderkey* column is resorted along its values and the corresponding TIDs in the *PositionList* pl_o get resorted, respectively (pl_o'). The rest of the join operation is similar to that already described in Figure 12.

B. Performance Tests

To complete our case study concerning our toolkit, we present a more complex query from the TPC-H repository (Query 3). We model an execution plan using our components and run some performance tests, which we compare with MySQL and Infobright.

The SQL query we use is the following:

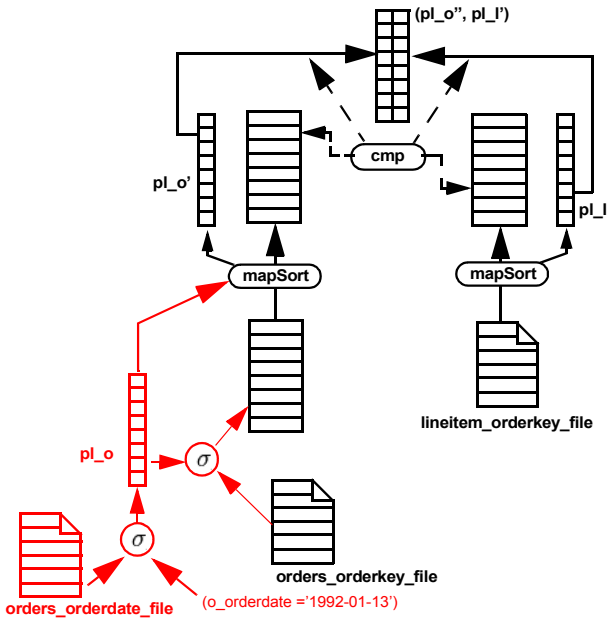

Fig. 13. Join-Operation with the Column-Store-Tool-Kit

```
select l_orderkey,
       sum(l_extendedprice*(1-l_discount))
                                  as revenue,
       o_orderdate,
       o_shippriority
  from customer,
       orders,
       lineitem
 where c_mktsegment = 'BUILDING'
   and c_custkey = o_custkey
   and l_orderkey = o_orderkey
   and o_orderdate < date '1995-03-15'
   and l_shipdate > date '1995-03-15'
 group by l_orderkey,
       o_orderdate,
       o_shippriority
 order by revenue desc,
       o_orderdate
```

A possible corresponding execution plan for this query using late materialization is shown in Figure 14. Beside the used operations and the intermediate results. shown. The input consists of about 6 million lineitem tuples, 727 thousand orders and over 30 thousand customers from the TPC-H benchmark dataset. The machine settings are the following: Intel® Core™ i7-3520M CPU, 2.9 GHz processor with 2 physical cores, 8 GB main memory, running Windows 7 Enterprise, 64 bit. The cache sizes are: First level cache: 128KB, second-level cache: 512KB, third-level cache: 4MB.

The operation mainly consists of a join over the three tables and a subsequent grouping according to three columns. The overall execution time is about 1.107 sec. About 20% of the overall time is spent reading the needed columns from file and performing the selections based on predicates or *PositionLists*. The most expensive operations are the *mapSort*-operations, which take about 25% of the execution time. The subsequent sorting of the corresponding *PositionLists* takes another 15%.

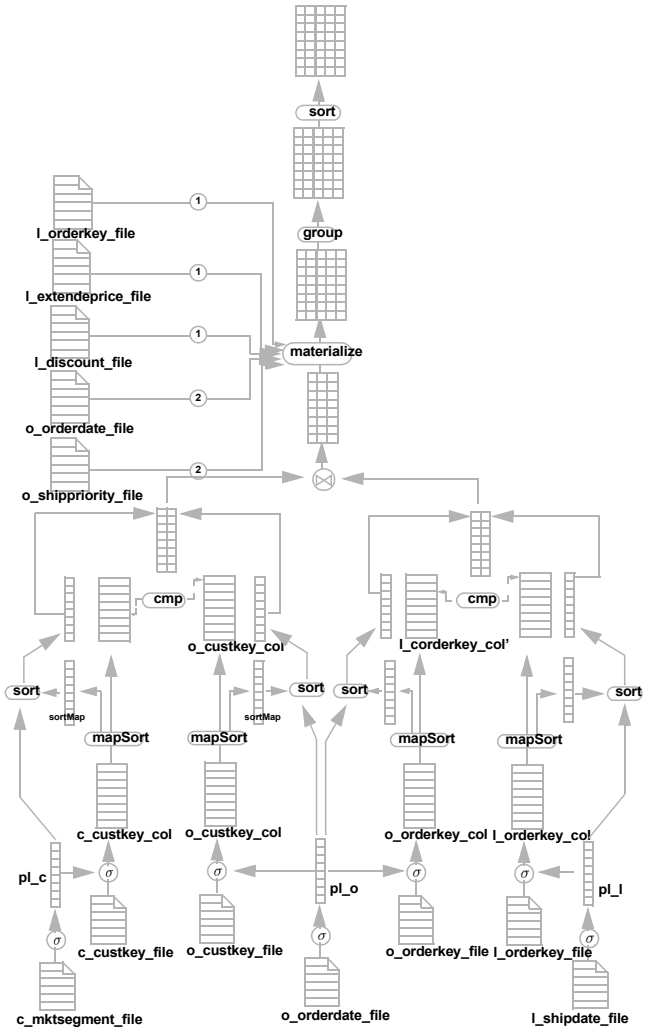

Fig. 14. TPC-H Query 3, execution plan and time behavior with CSTK components

Currently, we use a standard quicksort implementation without any optimizations. By exchanging the sorting algorithm with a more sophisticated version, we expect a further improvement of the runtime behavior. After sorting of the columns, we can use a merge-join implementation, which performs its task in about 0.03 seconds for an input cardinality of over 3.2 million tuples (lineitem datasets) and 727 thousand tuples (order datasets).

About one third of the complete execution time is spent accessing files on disk. Using a main-memory implementation could further reduce the overall execution time significantly. In comparison, the execution time of the same query using MySQL (with indexes on all foreign keys as well as on the columns which are predicated) takes about 116 seconds (cold start) with empty cache and about 13 seconds for repeated executions. Infobright [25], a column store-based version of MySQL, takes about 3 seconds to execute the query.

VIII. Conclusion

This paper presented a collection of basic components to build column store applications. The components are semantically located below those of the existing column store database implementations and are suited for building experimental (distributed) systems in the field of column store databases.

As a proof of concept, we used these components to retrace the materialization experiments carried out by Abadi et al. [6]. Additionally, we show that typical operations like joining tables and grouping results can be carried out. Finally, we construct an execution plan from the TPC-H benchmark and point out that the performance is quite good, compared to existing column store databases. It is planned to use these components to obtain further scientific findings in the area of column stores and to develop data-intensive applications.

IX. Future Work

A first version of the column store tool kit is available without support for compression. The next steps planned are the integration of compression and the use in concrete areas, such as text retrieval systems. A future activity will be the implementation of a scripting language interface for the components. With the help of this interface, it will be possible to assemble the developed components more easily without losing the performance of the underlying C/C++ implementation. In this case, the scripting language act as glue between the components, allowing the developer to build up complex high performance applications with very little effort [26]. As an alternative, a custom domain-specific language (DSL) [27] may be used for building column store applications. A bachelor's thesis [28] focused on the extent to which various degrees of flexibility regarding the structure of *MultiColumnArray*s and expression of the predicates affect the performance. According to the thesis, the structural definition at compilation time is of significant advantage compared to the structural definition at runtime. If the implemented flexibility of the *SimpleStruct* is not required at runtime, an alternative implementation may be used. It may be realized by defining a language extension for C/C++, for example. Thus, the respective structures and operations can be defined using a simple syntax. With a number of macros of the C++ preprocessor or a separate inline code expander [29], these could then be transformed into valid C/C++ code.

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Theoretical and Practical Implications of User Interface Patterns Applied for the Development of Graphical User Interfaces

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Abstract — **We address current research concerning patterns dedicated to enable higher reusability during the automated development of GUI systems. User interface patterns are promising artifacts for improvements in this regard. Both general models for abstractions of graphical user interfaces and user interface pattern based concepts such as potential notations and model-based processes are considered. On that basis, the present limitations and potentials surrounding user interface patterns are to be investigated. We elaborate what theoretical implications emerge from user interface patterns applied for reuse and automation within user interface transformation steps. For this purpose, formal descriptions of user interface patterns are necessary. We analyze the capabilities of the mature XML-based user interface description languages UIML and UsiXML to express user interface patterns. Additionally, we experimentally investigate and analyze strengths and weaknesses of two general transformation approaches to derive practical implications of user interface patterns. As a result, we develop suggestions on how to apply positive effects of user interface patterns for the development of pattern-based graphical user interfaces.**

Keywords — graphical user interface development; model-based software development; HCI patterns; user interface patterns; UIML; UsiXML

I. INTRODUCTION

Interactive systems. Interactive systems demand for a fast and efficient development of their graphical user interface (GUI), as well as its adaptation to changing requirements throughout the software life cycle. In this paper, E-Commerce software serves as a representative of these interactive systems. Currently, these are a fundamental asset of modern business models providing B2C interaction via online-shops. In many cases, such systems are offered as standard software, which allows several customization options after installation. In this context, they are differentiated into the application kernel and a GUI system.

The application kernel software architecture relies on well-proven and, partially, self-developed software patterns. Thus, it offers a consistent structure with defined and differentiated types of system elements. So, the design has a positive influence on the understanding of the modular functional structures as well as their modification options.

Limited customizability of GUIs. Contrary to the application kernel, the customization of the GUI is possible only with rather high efforts. An important reason is that software patterns do not cover all aspects needed for GUIs. These patterns have been commonly applied for GUIs [2][3], but in most cases they are limited to functional and control related aspects [4]. The visual and interactive components of the GUI are not supported by software patterns yet. Furthermore, the reuse of GUI components, e.g., layout, navigation structures, choice of user interface controls (*UI-Controls*) and type of interaction, is only sparsely supported by current methods and tools. For each project with its varying context, those potentially reusable entities have to be implemented and customized anew, leading to high efforts.

Moreover, the functional range of standard software does not allow a comprehensive customization of its GUI system. The GUI requirements are very customer-specific. In this regard, the customers want to apply the functionality of the standard software in their individual work processes along with customized dialogs. However, due to the characteristics of standard software, only basic variants or standard GUIs can be offered. So far, combinations of components of the application architecture with a GUI are too versatile for a customizable standard product.

User interface patterns. Along with other researchers [5] [6] [7] [8] [9], we propose an approach to this problem through the deployment of User Interface Patterns (UIPs). These patterns offer well-proven solutions for GUI designs [10], which embody a high quality of usability [11]. So far, UIPs usually have not been considered as source code artifacts, in contrast to software patterns. Current UIPs and their compilations mostly reside on an informal level of description [5]. The research towards formal pattern representations is still in progress.

A. Objectives

In this paper, we elaborate that formal UIPs can assist in raising effectiveness and efficiency of the development process of a GUI system. For a start, we present and analyze conceptual models for the GUI development to valuate and position UIPs as unique artifacts. In this regard, we describe, from a theoretical point of view, how reuse and automation within GUI transformation steps can be established by the deployment of UIPs.

This is a revisited and substantially augmented version of "Development of Graphical User Interfaces based on User Interface Patterns", which appeared in the in Proceedings of The Fourth International Conferences on Pervasive Patterns and Applications (PATTERNS 2012) [1].

Moreover, we present and review current approaches concerning the definition, formalization, and deployment of UIPs within model-based software development processes dedicated to GUI-systems. On this basis, we discuss the limitations and possibilities of transformations into executable GUIs. For that purpose, two different transformation approaches have been experimentally investigated. These approaches will be assessed facing two different GUI dialog examples. As a result, we derive practical implications of UIPs and develop suggestions, how the positive effects of UIPs for the development of GUIs can be applied. Finally, influences resulting from the use of UIPs in the development process are discussed.

B. Structure of the Paper

In Section II, selected state of the art and related work according to general applicable models for the GUI development are presented. The next section is dedicated to the current state of concepts and processes already applying UIPs as software artifacts. Both parts of related work are assessed according to our objectives in Sections IV and VI respectively. Subsequently, the theoretical implications of UIPs on the development process for GUIs are elaborated in Section V. Afterwards, Section VII presents our two approaches for the transformation of formal UIPs into source code. The practical implications of UIPs resulting from their application in experimental transformations are presented in Section VIII, which also combines the findings of Sections V and VII for discussion. Finally, our conclusions are drawn and future research options are outlined in Section IX.

II. Related Work: GUI Development Processes

The development of GUI systems still remains a challenge in our days. To discuss the activities and potentials of UIPs independently from specific software development processes and requirement models, we refer to generic model concepts. In the following sub-sections, we present two models, which describe activities and capture work products of the GUI specification process. Additionally, an early generation concept for GUI systems is presented.

A. GUI Specification Process and Model Transformations

A general GUI specification model. In reference [12], Ludolph elaborates the common steps of a GUI specification process. To master the complexity that occurs when deriving GUI specifications from requirement models, Ludolph proposes four model layers and corresponding transformations built on each other. Three of them, being relevant in our context, are depicted in Figure 1.

Essential model. By the *essential model*, all functional requirements and their structures are described. This information consists of the core specification, which is necessary for the development of the application kernel. Examples for respective artifacts are *use cases*, domain models and the specification of *tasks* or functional decompositions. These domain-specific requirements are abstracted from the realization technology, and thus, from the GUI system [12].

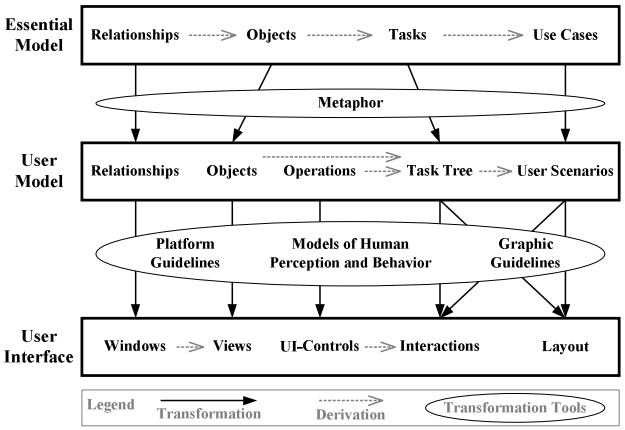

Figure 1. Model transformations of the GUI development process based on [12]

Consequently, a GUI specification must be established to bridge the information gap between requirements and a GUI system.

User model. A first step in the direction of GUI specification is prepared by the *user model*. With this model, the domain-specific information of the *essential model* is picked up and enhanced by so-called *metaphors*. The latter symbolize generic combinations of actions and suitable tools, which represent interactions with a GUI. Examples of *metaphors* would be indexes, catalogues, help wizards or table filters. The principal action performed by these examples is a search for objects. How this action is carried out may differ, since the respective *metaphors* embody varying functionality to be accessed by the user in order to find objects.

The *tasks* of the *essential model* have to be refined and structured in *task trees*. For each *task* of a certain refinement stage, *metaphors* are assigned, which will guide the GUI design for this part of the process. In the same manner, *use cases* can be supplemented with these new elements in their sequences to describe *user scenarios*.

User interface. This model is used for establishing the actual GUI specification. Through the three parts rough layout, interaction design and detailed design [12], the appearance and behavior of the GUI system are concretized. The aim is to set up a suitable mapping between the elements of the *user model* and *views*, *windows*, as well as *UI-Controls* of the *user interface*. For the *metaphors* chosen before, graphical representations are now to be developed. The *objects* to be displayed, their attributes and the relations between them are represented by *views*. Subsequently, the *views* are arranged in *windows* according to the activities of the *user scenarios*, or alternatively, to the structure of the more detailed *task trees*. In these steps, there are often alternatives, which are influenced by style guides or the used GUI library and especially by the provided *UI-Controls*. At the same time, generic interaction patterns are applied as transformation tools, which also have an impact on the choice of *UI-Controls*.

B. Cameleon Reference Framework

User interface challenges. In reference [13], Vanderdonckt presents a GUI specification and development model, which is more concerned with handling environmental and non-functional requirements of GUI systems. The challenges to overcome are represented by different user skills and cultures. In addition, a user interface should be aware of different usage contexts and respective user intentions as well as working environments and individual capabilities of devices the user interface is running on.

Need for automation. GUI development is tedious when facing the above mentioned challenges, and thus, Vanderdonckt states in [13] that normally, GUIs would have to be developed for each context or device separately. A reason is given by the difficulty to source common or shared parts of the user interfaces. Since architectures and final code or frameworks have a great impact on the final shape of the certain user interfaces, the potential reuse is largely limited. Finally, advice is given to employ model-driven software development techniques within a GUI development environment.

To approach a solution, which copes with both the challenges and need for model-driven development, Vanderdonckt proposes a methodology, which consists of GUI modeling abstractions or steps besides a method and tool support. The proposed four modeling steps [13], originated from [14], are described in the following paragraphs:

Task & Concepts (T&C). The *tasks* to be performed by the user, while interacting with the GUI-system, are specified during this step. Additionally, *domain concepts* relevant to those *tasks* are specified as well.

Abstract UI (AUI). With the AUI, *tasks* are being grouped and structured by Abstract Interaction Objects (AIOs): *Individual Components* and *Abstract Containers* are both sub-types of AIOs and form the main elements of an AUI. These resemble rather abstract entities serving for definition and structuring purposes only. Thus, AIOs come without any technical appearance or other format of imagination, since the options to shape them are very different during the next two modeling steps and should be preserved for developers. Besides the structuring of AIOs, an AUI specifies very basic interaction information such as input, output, navigation and control [5], which is defined independently from modality. Finally, the AUI acts as a "canonical expression of the rendering of the domain concepts and tasks" [13].

Concrete UI (CUI). The CUI refines the elements of an AUI to a complete but platform-independent user interface model. In this regard, Concrete Interaction Objects (CIOs) refine the AIOs of the AUI. CIOs resemble a chosen set of both *UI-Controls* or containers and their respective properties. While resembling an abstraction, the CUI "abstracts a FUI into a UI definition that is independent of any computing platform" [13].

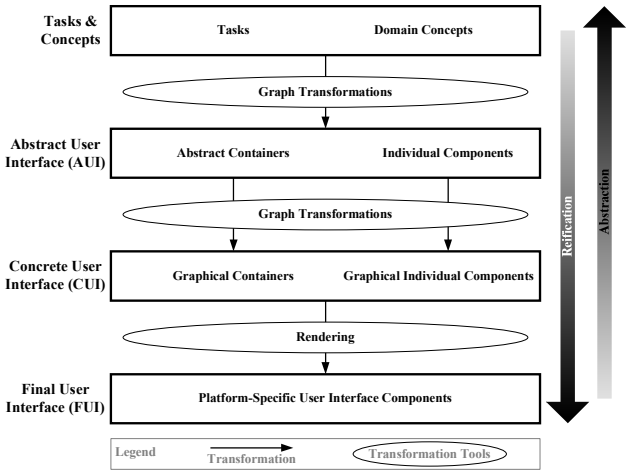

Figure 2. Modeling steps of the Cameleon Reference Framework based on [13] and implemented by UsiXML [15]

Final UI (FUI). As the last refinement, the FUI represents a certain device or platform specific user interface model. So, it embodies the final user interface components running in that specific environment.

The above described modeling steps are depicted by Figure 2, which is focused on graphical user interface implementations, as this is the case for its source [13].

UsiXML. To express the occurring models within these modeling steps, the GUI specification language UsiXML (user interface extensible markup language) [15] has been developed. Concerning the modeling facilities for the CUI step, UsiXML offers a specific set of CIOs sourced from common UI toolkits or frameworks. Therefore, the available modeling elements represent an intersection set of common GUI element sets.

C. Generators for graphical User Interfaces

To raise efficiency in GUI development, concepts and frameworks have been invented, which are able to generate complete GUI applications based on a partly specification of the application kernel or comparative model bases. Here, Naked Objects [16] and JANUS [17] can be mentioned. Both rely on an object-oriented domain model, which has to be a part of the application kernel. Based on the information provided by this model, standard dialogs are being generated with appropriate *UI-Controls* for the repetitive *tasks* to be carried out in conjunction with certain *objects.* For instance, to generate an *object* editor for entities like product or customer, certain text fields, lists or date pickers are selected as *UI-Controls*, which match the domain data types of the selected domain *object* for editing.

III. Related Work: User Interface Patterns

In this part of related work, we present definitions, notations and concepts that address or employ patterns specific for model-based user interface development.

A. User Interface Pattern Definition and Types

Current research has been discussing Human-Computer-Interaction (HCI) patterns [18] and especially User Interface Patterns (UIPs) for a longer period [19] [5] now. A UIP can be defined as a universal and reusable solution for common interaction and visual structures of GUIs. UIPs are distinguished by two types according to Vanderdonckt and Simarro [5]:

Descriptive UIPs. Primarily, UIPs are provided by means of verbal and graphical descriptions. In this context, UIPs are commonly specified following a scheme similar to the one used for design patterns [20]. By reference [21], a specialized language for patterns was proposed, which is named PLML (pattern language markup language). Details about the language structure can be found in [22] as well as its XML DTD in [5]. A practical application of its descriptive capabilities for several types of patterns, which may occur in conjunction with the Cameleon Reference Framework, is also outlined in [5].

UIP-Libraries. UIP libraries such as [23], [24], and [25] provide numerous examples for descriptive UIPs. Based on the presented categories, concepts about possible UIP hierarchies and their collaborations can be imagined.

Formal UIPs. Generative UIPs [5] are presented rarely. In contrast to descriptive UIPs, they feature a machine-readable form and are regarded as formal UIPs accordingly. The format for storing such UIPs may constitute of a graphic, e.g., UML [19] or XML based notation [26] [8] [9]. The formal UIPs are of great importance, since they can be used within development environments, especially for automated transformations to certain GUI-implementations.

B. Formalization of User Interface Patterns

In order to permit the processing of descriptive UIPs, they have to be converted to formal UIPs. Possible means for this step can be provided by formal languages applied for specifying GUIs. These languages, however, have been designed for the specification of certain GUIs and were not intended for a pattern-based approach in the first place. Until now, there is no specialized language available for formalizing UIPs.

UsiXML and UIML. In our preparation, we conducted an extensive investigation on formal GUI specification languages and their applicability for UIPs. As result, two languages with an outstanding maturity have been identified.

Intentionally, the XML-based languages UsiXML [15] and UIML [27] were developed for specifying a GUI independently from technology and platform specifics. However, such languages may be applicable for UIPs. One the one hand, UIML offers templates and associated parameters for reusing pre-defined structures and behavior of GUI components. On the other hand, UsiXML is designed to implement the Cameleon Reference Framework, which already propagated higher reuse by its abstractions of GUI modeling steps as well as automated processing by model-driven software development techniques. Moreover, both indeed have been applied in model-based processes or have been extended for that context. More information on that is provided in Section III.C.

IDEALXML. To raise the efficiency of GUI development environments, tools are necessary that facilitate formal specifications of UIPs with regard to language definitions and rules. A widespread tool concept for UsiXML is presented with IDEALXML [13] [5]. By using the various models defined by UsiXML as an information basis, many aspects of a GUI and additionally the applied domain model of the application kernel are included in the GUI specification. As a result, a detailed and comprehensive XML specification for the GUI can be created. Many aspects of the *user model* from [12] are already included.

C. Model-based Processes with User Interface Pattern Integration

The pattern conception emerged from the HCI research has already been taken into consideration for model-based software development of GUI-systems. Researchers have introduced several model frameworks and notations to express generative UIPs, and thus, enable formalization facilities for descriptive UIPs. A common basis assumed for all different processes is a task based *user model* that is exploited to derive dialog and navigation structures of the user interface. Yet, all approaches have not reached a sufficient maturity level according to the available publications. They still were drafting or enhancing their processes, tools or notations as they had been by challenged relevant issues surrounding generative pattern definition and application.

Queen's University Kingston. Zhao et al. [6] proposed the detailed modeling of tasks in order to be able to group them into segments, which are being transformed to dialogs displaying the associated data or contained sub-tasks.

As challenges for future work, two main aspects remained: the evaluation of achieved usability by the pattern application and the extension of customization abilities of the underlying framework to allow the definition of specific *UI-Controls* and even patterns to be integrated into the established process were suggested in [28]. In addition, the integration of more user interface patterns along with guidelines for final UI design as well as an enhancement of the task analysis to exploit more information relevant for UI generation were outlined in [6] as future work.

University of Rostock. Radeke et al. [29] presented a modeling framework that would be capable of employing patterns for all involved models (task, dialog, presentation and layout). Since the approach was focused on task modeling and respective patterns, the derivation of dialog structures was a main outcome. In order to enhance their capabilities towards pattern application for CUI models, UsiPXML (user interface modeling pattern language) was introduced in [26] as a notation to express all kinds of involved patterns. Being based on UsiXML as well as PLML, the new notation incorporated enhancements like structure attributes and variables to allow for a context-specific instantiation of a defined pattern.

However, future challenges were stated as follows. The need for enhanced tool support and the definition of more complex patterns was raised in [30]. Moreover, the pattern representation on the CUI level with UsiXML should be

revised as well according to [31]. Lastly, the expansion of the set of available patterns and the concept of pattern inter-relationships were relevant considerations in [26]. For the latter, the research question about how task and dialog patterns would influence other patterns situated on lower levels is left open.

University of Augsburg. An alternative modeling framework integrating patterns on selected model stages was suggested by Engel and Märtin in [8]. Rooted in principles on the structuring of pattern languages [32], the main emphasis was laid on the hierarchy of patterns and their notation [33], which was based on a custom XML DTD for the generative part.

For the encountered challenges, future activities were considered, which would enrich the implementation aspects of pattern descriptions [34] and deliver concepts of pattern relationships. In the focus of transformations, future work was seen for the derivation of concrete UI models from abstract ones [35].

University of Kaiserslautern. Starting with criticism of recent approaches of other researchers, Seissler et al. [9] proposed a third modeling framework with comparative models and patterns, but they employed different notations and introduced a suggestion for a classification of pattern relationships. Additionally, the need for runtime adaptation of user interfaces was considered [36] as well as the concept of encapsulation of UIML fragments [9] within their notation to express user interface patterns.

They emphasized on tool support for pattern instantiation or the adaptation of patterns to different contexts of use that may even change at runtime [36]. Moreover, a proper tool for pattern selection and integration as well as the refinement of inter-model pattern relationships were stated as future challenges in [9]. The latter was considered to reflect the relations between pattern of different abstractions in order to offer better modularization and provide options for patterns that may be better suited for a specific context. Finally, Seissler et al. recognized in [9] that their future work should extend the pattern language for further testing of their notation approach.

IV. Model Considerations for Deploying User Interface Patterns

This section is intended to discuss the first part of related work presented in Section II. Before the more advanced concepts of Section III are addressed, the transition of traditional GUI specification and development towards a pattern-based solution shall be attended to. In this context, we outline the possible deployment of UIPs in development processes referring to both conceptual models elaborated by Ludolph and Vanderdonckt.

A. Review of the GUI Specification Model by Ludolph

Model transformations as described by Ludolph [12] illustrate a detailed account of relevant model elements for the GUI specification of the covered domain. However, any transformations are carried out manually. Besides that, no automation and only few options for reuse are mentioned.

However, artifact dependencies are detailed and the transformation of *essential model* requirement elements to certain *user interface* model elements is outlined. For the final transformation, Ludolph suggests manual and cognitive means of transformation, which lead to clearly defined dependencies between *user model* and *user interface* entities. These prerequisites are ideal to be considered in the discussion on how UIPs influence artifacts. Particularly, it is of interest, how a GUI specification can be developed starting from a basis of functional requirement artifacts and using UIPs as bridging elements for transformations.

B. Review of the Cameleon Reference Framework

Relevance. From our point of view, the Cameleon Reference Framework as presented in [13] resembles a valuable model foundation or mental concept for UIPs, since it addresses the following two aspects. Firstly, GUI development activities and related tool support to decide on automation steps are covered. Secondly, pattern deployment possibilities and related abstractions may be derived. In this regard, a developer can decide on the granularity, reach and modularization of potential patterns while having the four segregated modeling steps on his mind. However, the latter aspect was not met by the original source and is only inspired.

GUI development aspect. As far as the first aspect is addressed, the proposed model abstractions or steps resemble UI concerns applicable to a wide range of different domains. The model abstractions make sense as they address the elaborated challenges in [13] by a separation of concerns. The four steps have been introduced to handle the various challenges or requirements by sharing or distributing them across the abstractions. Consequently, the separation of models enables different grades of reuse and an isolation of particular challenges, as they are no longer bound to single GUI models but to a set of models as proposed.

To approach the modeling steps, a strict top-down decomposition procedure is not required. In contrast, the entry point is variable so that one can start with an AUI or CUI without tasks modeling at all. A user interface may be subsequently abstracted or refined across the proposed reification model stages.

Moreover, the steps aid both in forward and reverse engineering, since they demand for explicitly capturing implicit knowledge applied in both model transformation paths: the refinement towards a FUI can be approached by subsequent increase in detail, which is stored in segregated models and their elemental notations. As the reification of an AUI towards CUI is progressing, the elementary concepts embodied by AIOs of different dialogs can be lined up to identify reoccurring structures. In this respect, AIOs are an abstraction and so they do share the commonalities of certain GUI structures. Consequently, identified AIO structures offer potentials to discover UIPs for the particular domain during the transition to the CUI.

Concerning reverse engineering, the abstraction of a given FUI or CUI model to abstract grouped tasks embodied by AIOs is also supported. The derived AUI may be reified to another platforms' CUI. If an AUI was already created by

forward engineering, a modeling step could be avoided for the migration to other platforms or devices.

For practical implementation, transformation means or tools mentioned as in the Ludolph model are missing. Although the models used for implementing the four steps are closely related to the UsiXML language, the associated metamodel as a potential implementation is still work in progress. At usixml.org, no current version could be consulted. Therefore, no detailed mappings like in the Ludolph model could be depicted.

Pattern incorporation aspect. As respective implementations of the Cameleon modeling steps, the presented models in [13] and [5] currently do not outline the reuse or modularization of artifacts. A proper pattern-based view to overcome the manual "translation" [13] process between available models still has to be invented. At last, models or fragments of them can only be reused in their completeness and are not abstracted further. Patterns may be instantiated at various modeling steps (e.g., AUI, CUI) as suggested in [5], but can hardly be adapted to other contexts without manual re-modeling. To conclude, an additional abstraction inside modeling steps, which allows for pattern definition and instantiation, is missing and is not provided by the available sources.

As far as UIPs are concerned, these patterns should not be associated to the AUI, since the latter is too abstract for UIPs. Certain UI-Controls cannot be modeled or imagined on the AUI level, so that a great portion of an individual UIP's characteristics cannot be expressed. The resulting refinement work to "reify" [13] an AUI based UIP towards a CUI representation would denote a considerable effort. For instance, whenever a selection AIO is encountered inside a UIP definition, there would be more than one possible reification available like a combobox, listbox or a radio group. Therefore, it could be implied that the model-to-model transformation between AUI and CUI relied on extensive manual configuration or intervention, as the CUI does possess much more detail than the AUI. Otherwise, strict rules to enable automated graph transformation may prevent the expression of particular UIPs. Lastly, for the particular domain addressed here, UIPs rely on the WIMP (windows, icons, menus and pointer) paradigm, so AUI considerations will not merit extensive reuse as this would be permitted by a CUI model.

With respect to the CUI modeling stage, the applied notation like UsiXML would have to reflect a chosen set of *UI-Controls*, events and containers as well as their chosen set of properties. These sets may already limit the expressiveness of UIPs or an issue would be the integration of new types or properties. Due to the fact that particular UIPs may exclusively address certain devices or platforms or that other classifications of UIPs may restrict their reusability to a certain domain [37], even the CUI level would be too abstract to allow for an exact representation. If this aspect would not pose an issue in a certain development environment, UIPs clearly are to be settled on the CUI level, since there are several advantages for keeping UIPs on that particular abstraction level:

As mentioned in [13], a notation like UsiXML or even UIML could be used to express UIPs on the CUI level leading to the benefits of these languages. Firstly, for the machine-readable XML languages no programming skills would be needed. Secondly, with XML as a basis, the notation would posses a standard format and vast tool support (parsers, editors). Thirdly, "cross-toolkit development" [13] would be possible and UIP sources could be kept independently from changing GUI platforms or frameworks and lastly, programming languages.

C. Exertion of Ludolph and Cameleon Models

Current state of the art has proposed own specific model frameworks as mentioned in Section III.C. These approaches neither have achieved a truly reusable pattern-based solution yet, nor have they positioned UIPs in relation to generally applicable fundamentals. Since the transformations by Ludolph or the Cameleon model have been formulated from different perspectives, but still embody general concepts, we take them into consideration to derive theoretical and practical implications of UIPs.

Different focus. The model by Ludolph is focused on particular artifacts, their transformations and related measures. In contrast, the Cameleon Reference Model by Vanderdonckt presents abstractions to treat environments, devices, portability, and most notably, the software production environment, as XML and automation or model-driven software development are of the essence.

GUI transformations by Ludolph. The model established by Ludolph can be considered as a refinement of the *Tasks & Concepts* as well as the CUI level for graphic user interfaces, since most artifacts can be allocated to one of these levels. An AUI level is actually missing and only implicitly established by the augmentation of *user model* elements with *metaphors*. The final stage of the Ludolph model can be defined in terms of the CUI when specification notations like UIML or UsiXML-CUI are being used.

Cameleon. The Cameleon Reference Model is the more abstract model as its details are to be defined by the implementation language, especially by UsiXML, and the particular context of use or domain. Due to the defined modeling stages, pattern deployment and modularization concerns can be approached more gentle rather than being trapped in discussions of how to structure a pattern language for certain artifacts [38].

Shared limitation. Both models do not feature a clearly distinguished pattern dimension.

Reuse may be already addressed by Ludolph for GUI structures within a certain project. For instance, the *views* associated to certain *objects* may experience reuse in each *task* they are handled by different operations. However, *objects* tend to change in the face of different contexts, domains, users and thus, real pattern-based reuse across different projects is missing.

Although the pattern support for the UsiXML metamodel was already inspired by Vanderdonckt as a "Translation" [13] of models to different contexts and PLML-patterns in the environment of IDEALXML [5], it has not been implemented in the main language facilities of UsiXML yet.

Exertion. The model by Ludolph is already detailed concerning domain artifacts. Therefore, it will be used to discuss both the theoretical and practical implications of UIPs on artifact development stages. Nevertheless, it is not suitable to position UIPs without the conception of a pattern language or hierarchy. Märtin et al. [32] [33] support a fine-grained structure, which is clearly neglected by Seissler et al. [9]. Furthermore, pattern relations are still to be outlined in most model-based approaches as mentioned in Section III.C. Assuming that a pattern language with appropriate pattern relationships would have been elaborated, Ludolph's model may be customized for the particular domain, as it already holds artifacts typical for business information systems.

The Cameleon Reference Framework will be taken into consideration to position UIPs concerning their practical implications. In this context, the abstraction level of UIPs has to be discussed, i.e., how concrete UIPs should be compared to implementation level GUI elements. Additionally, technical considerations should be addressed like the coupling to GUI frameworks and programming languages. The most important fact is the positioning of UIPs in the light of potential notations, which have been introduced in Section III.B.

D. Limitations of GUI-Generators

In contrast to IDEALXML, which enables the extensive modeling of the GUI, GUI-generators may generate executable GUI code but they lack such a broad informational basis. Therefore, GUI-generators have two essential weaknesses:

Limited functionality. The information for generating the GUI is restricted to a domain model and previously determined dialog templates along with their *UI-Controls*. Hence, their applicability is limited to operations and relations of single domain *objects*. When multiple and differing domain *objects* do play a role in complex *user scenarios* [12], the generators can no longer provide suitable dialogs for the GUI application. Moreover, extensive interaction flows require hierarchical decisions, which have to be realized, e.g., by using wizard dialogs. In this situation, GUI generators cannot be applied. The connection between dialogs and superordinate interaction design still has to be implemented manually.

Uniform visuals. A further weakness is related to the visual GUI design. Each dialog created by generators is based on the same template for the GUI-design. Solely the contents which are derived from the application kernel are variable. Both *layout* and possible *interactions* are fixed in order to permit the automatic generation. The uniformity and its corresponding usability have been criticized for Naked Objects [39]. Assuming the best case, the information for GUI design is based on established UIPs and possesses their accepted usability for certain *tasks*. Nevertheless, the generated dialogs look very similar and there is no option to select or change the UIPs incorporated in the GUI design.

V. THEORETICAL IMPLICATIONS OF USER INTERFACE PATTERNS

In this section, the theoretical implications of UIPs are derived on the basis of considered models of Section IV and the following scenario serving as a background.

A. Application Scenario: GUI Customization of Standard Software

On the basis of the customization of GUIs for standard software and the model transformations described in Section II.A, the theoretical implications of UIPs are to be considered. To present an example of standard software, we refer to e-commerce software, which usually offers both a front-end system for online-shopping and a back-end system to manage orders and stock.

Common essential model. This kind of standard software fulfils the functional requirements of a multitude of users at the same time. Therefore, these systems share a well-defined *essential model* that specifies their functional range and has many commonalities along existing installations. Standard software implements the *essential model* through different components of the *Application Kernel* as shown in Figure 3. Each installation consists of a configuration for the *Application Kernel*, which includes many already available and little custom components in most cases. In this context, the *User Interface* acts as a compositional layer that combines *Core* and *Custom Services* together with suitable dialogs for the user.

Individual GUIs for eShops. Concerning eShops, the visual design of the GUI is of special relevance, since the user interface is defined as a major product feature that differentiates the competitors on the market. Hence, the needs of customers and users are vitally important in order to provide them with the suitable and individual dialogs. In this regard, the proportions of components related to the whole system are symbolized by their size in Figure 3.

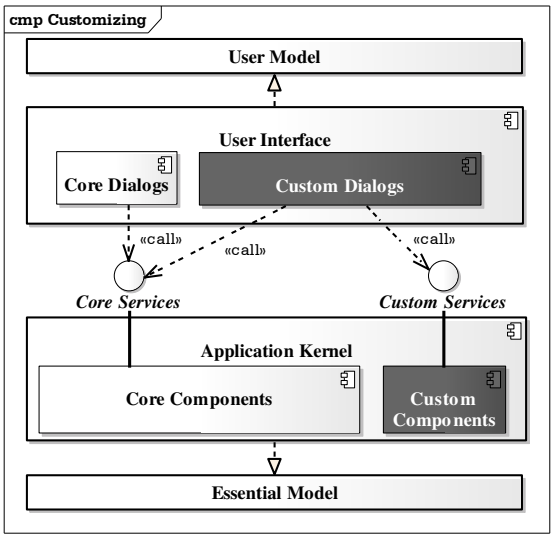

Figure 3. Components involved in the customization of standard software

In comparison to the *Custom Components* of the *Application Kernel* the *Custom Dialogs* represent the greater part of the *User Interface* and the customization accordingly. Along with the customization of the application kernel there is a high demand for an easy and vast adaptability of the GUI.

GUIs for custom services. The customization of the GUI system is needed, as elements of the *essential model* tend to be very specific after extensive customization or maintenance processes. Thus, the standard *user model* as well as the *user interface* can no longer be used for the customized services. In this case, models have to be developed from scratch and a corresponding solution for the GUI has to be implemented.

Usability. The development of GUIs is caught in a field of tension between an efficient design and an easy but extensive customization. High budgets for the emerging efforts have to be planned. Additional efforts are needed for important non-functional requirements such as high usability and uniformity in interaction concepts and low-effort learning curve during the customization process of GUIs. For realizing these requirements, extensive style guides and corresponding *user interface* models often need to be developed prior to the manual adaptation of the GUI. These specifications will quickly lose their validity as soon as the GUI-framework and essential functions of the *Application Kernel* change.

B. Model Aspects of User Interface Patterns

With the aid of UIPs the time-consuming process of GUI development and customizing can be increased in efficiency. To prove this statement, the influences of UIPs on the common model transformations of the Ludolph model from Section II.A are examined in the next step. In Section V.C potentials for improvements are derived from these influences.

Metaphors and UIPs. *Metaphors* act as the sole transformation tool between *essential model* and *user model*. Since they lack visual appearances as well as concrete interactions, the mapping of *metaphors* to the elements of the *essential model* is very demanding. *Metaphors* will not be visualized by GUI sketches prior to the transformation of the *user model*.

Since UIPs are defined more extensively and concretely, they can be applied as a transformation tool instead of using *metaphors*. Descriptive UIPs feature a pattern-like description scheme that, for example, is provided in the catalogues in [23] and [24]. Thus, they offer much more information and sometimes even assessments, which can inspire the GUI specification. In addition, descriptive UIPs do already possess visual designs that may be exemplary, or in the worst-case, abstract.

With the *user model*, operations on *objects* have to be specified. The *metaphors* do not provide enough information for this step. In contrast, UIPs are definitely clearer concerning these operations since they group *UI-Controls* according to their *tasks* and do operationalize them in this way. Interaction designs and appropriate visuals are presented along with UIPs. These aspects would have to be defined by on behalf of the developer using only the *metaphor*.

When UIPs are used in place of *metaphors* for formalization, these new entities can be integrated in the tools for specifications. Concerning UsiXML, UIPs could describe the CUIM. *Task-Trees* are already present in UsiXML, so this concept of specification partly follows the modeling concepts in [12] and thus may be generically applicable.

User model and UIPs. With regard to the *user model*, the numerous modeling steps no longer need to be performed with the introduction of UIPs. Instead, it is sufficient to derive the *tasks* from the *use cases* within the *essential model* and allocate UIPs for these. Detailed *task-trees* no longer have to be created, since UIPs already contain these operations within their interaction design. Nevertheless, *tasks* have to provide a certain level of detail to derive navigation structures [29].

Interactions can already be specified in formal UIPs. Later on, this information can directly be used for parts of the presentation control of *views* or *windows*. As a result, an extensive *user scenario* also is obsolete, as it was originally needed for deriving the more detailed *task-tree*. Now it is sufficient to lay emphasis on expressing the features of UIPs and their connection to the *tasks* defined by the *essential model*. The *objects* are also represented within the UIPs in an abstract way. With the aid of placeholders for certain domain data types, adaptable *views* for *object* data can already be prepared in formal UIPs. Finally, much of the afore-mentioned information of the *user model* now will be provided by completely specified UIPs.

User interface and UIPs. UIPs provide the following information for the *user interface*: *Layout* and *interaction* of the GUI will be described by a composition of a hierarchy of UIPs that is settled on the level of *views* and *windows*. When creating the UIP-hierarchy, a prior categorization is helpful, which features the distinction between *relationship*, *object* and *task* related UIPs. This eases the mapping to the corresponding model entities.

For *interactions*, the originally applied *Models of Human Perception and Behavior* of Figure 1 are no longer explicitly needed since they are implicitly incorporated in the interaction designs of the UIPs. In this context, suitable types of *UI-Controls* are already determined by UIPs. Nevertheless, a complete and concrete GUI-design will not be provided by UIPs, since the number, ordering and contents of *UI-Controls* depend on the context and have to be specified by the developer with instance parameters accordingly. In the same way, *Platform* and *Graphic Guidelines* act as essential policies to adapt the UIPs to the available GUI-framework and its available *UI-Controls*.

Conclusion. We explained that UIPs might cover most parts of the *user model* as well as numerous aspects of the *user interface*. By using UIPs in the modeling process, these specification contents can be compiled based on the respective context without actually performing the two transformations from Figure 1 explicitly. Basically, the transformation to the target platform remains as depicted in Figure 4.

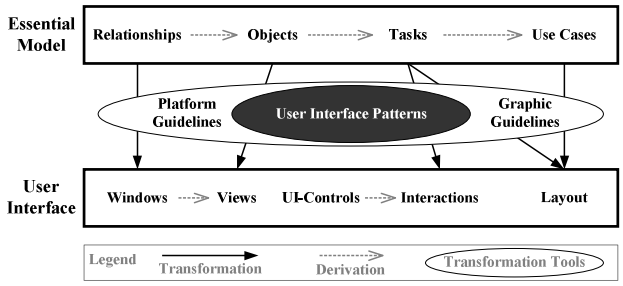

Figure 4. GUI transformations with the aid of UIPs and automation

C. Influence of User Interface Patterns on GUI-Transformations

In this section, the potentials of UIPs related to the GUI specification process are summarized from a theoretical perspective.

Reuse. By means of UIPs, the transformational gap between *essential model* and *user interface* can be bridged more easily since reuse of many aspects will be enhanced significantly. Thereby UIPs are not the starting point of model transformations; they rather serve as a medium for conducting needed information for the transformations. The information originally included in the *user model* and parts of the *user interface* are now extracted from the selection and composition of UIPs.

Layout and *interaction* of *windows* as well as the interaction paradigm of many parts of the GUI can be determined by a single UIP configuration on a high level in hierarchy. This superordinate GUI design can be inherited by a number of single dialogs without the need for deciding about these aspects for each dialog in particular.

Many interaction designs can be derived from initial thoughts about GUI design for the most important *use cases* and their corresponding *tasks*. When a first UIP configuration has been created, the realization of the *Graphic* and *Platform Guidelines* therein can be adopted for other UIP-applications since the target platform is the same for each dialog of a system. Especially when *user scenarios* overlap, meaning they partly use the same *views* or *windows* as well as *object* data, UIPs enable a high grade of reuse. UIP assignments, already established for other *tasks,* can be reused with the appropriate changes.

E-commerce software tends to use many application components together although they are offered by different dialogs as illustrated in Figure 3. UIPs can contribute to a higher level of reuse in this context. Depending on the possible mapping between *Application Kernel* components and UIP-hierarchy, new dialogs can be formed by combining the views of certain services which are determined by their assigned UIPs.

Reuse and usability. Besides reuse, UIPs ensure that multiple non-functional requirements will be met. As proven solutions for GUI designs their essential function is to enable a high usability by the application of best-practices or the expression of design experiences. In this context, they facilitate the adherence of style guides by means of their hierarchical composition.

Technically independent essential model. It is a common goal to keep elements of the *essential model* free from technical issues. Thus, the *essential model* has no reference to the GUI specification. Therefore, it is not subject to changes related to new requirements, which the user may incorporate for the GUI during the lifecycle of the system. User preferences often tend to change in terms of the visuals and *interactions* of the GUI. Concerning *use cases*, this rule of thumb is elaborated in [40] and [41]. Technical aspects and in particular the GUI specification are addressed in separate models such as *user model* and *user interface* according to [12]. After changes, these models have to be kept consistent what results in high efforts. For instance, a new or modified step within a *use case* scenario has to be considered in the corresponding *user scenario*, too.

By assigning UIPs to elements of the *essential model*, explicit *user models* and the prior checking of consistency between these models both become obsolete. Instead, *user models* will be created dynamically as well as implicitly by an actual configuration of UIPs and *essential model* mapping. The approach of Zhao et al. [6] strictly follows this concept. A technical transformation to the source code of the GUI that relies on the concrete appearances of the UIPs remains as shown in Figure 4. By modeling assignments between UIP and *task* or between UIP and *object*, the number of *UI-Controls*, the hierarchy and *layout* of UIPs, sufficient and structured information on the GUI system is provided. Subsequently, a generator will be able to compile the GUI suited for the chosen target platform. These theoretical influences enable an increased independence from the technical infrastructure, since the generator can be supplied with an appropriate configuration to instantiate the UIPs compatible to the target platform and its specifics.

Modular structuring of *windows* and *views*. Common to software patterns, UIPs reside on different model hierarchies. Dialog navigation, frame and detailed *layout* of a dialog can be characterized by separate UIPs. The *views* of a *window* can be structured by different UIPs on varying hierarchy levels. Thus, a modular structure of dialogs is enabled. In addition, versatile combinations, adaptability and extensibility of building blocks of a GUI will be promoted.

VI. Review of UIP Notations and Applications

In this section, both potential notations and applications of UIPs are reviewed.

A. Review Criteria for XML GUI Specification Languages

Both languages are to be assessed by the following criteria:

Pattern variability criterion. The main criterion to be supported by a formalization language is the ability to allow the developer to abstract certain model structures to patterns. Each pattern embodies some points of variability to express a solution that is applicable and adaptable to a number of contexts. For instance, Figure 5 displays on the upper right hand side two exemplary UIP sketches. On the lower left hand side of Figure 5 possible UIP applications are drafted.

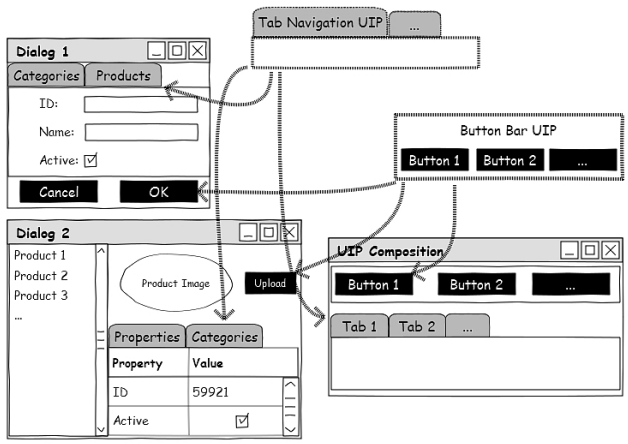

Figure 5. Schematic UIP examples and instances used in GUI dialogs

An apparent variability point of each illustrated UIP is the number of elements of the defined structure, e.g., how many buttons will appear in a certain UIP instance.

Content criteria. Besides the pattern abstraction criterion, three additional criteria are relevant for UIPs to be formalized. Firstly, the visuals to appear in the pattern structure have to be specified. In some cases certain *UI-Control* types make up the main impact of a certain UIP. For instance, the patterns "Collapsible Panels", "Carrousel", "Fly-out Menu" and the "Retractable Menu" sourced from [23] require certain *UI-Controls* that enable animation effects. It is important for the formalization to express *UI-Controls* that enable the desired *interaction* as close as possible while retaining a CUI level specification. Secondly, the layout of modeled structures has to be defined. Thirdly, stereotype behavior that is represented by the UIP has to be expressed.

B. UsiXML User Interface Pattern Abstraction Capability

Issues. The assessment of UsiXML is not an easy task compared to UIML. This is due to the facts that UsiXML is a far more complex language supporting most levels of Cameleon and it is not documented by a comprehensive specification with integrated examples as this is the case for UIML. At the time of writing, only older metamodels [42] of UsiXML and the W3C submission [43] of the AUI model [44] were available, possibly not reflecting new features.

Variability points. At its current state, whenever a pattern is to be expressed in UsiXML CUI, the variability points have to be avoided and specified directly. More precisely, it is only possible to specify a certain button bar or tab navigation instance with UsiXML. As far as we know, there is no way to parameterize the number of desired buttons or tabs. Thus, the described user interface structure looses on genericity [5]. Only the generativity [5] for a certain context and the platform- or device independence of the pattern remains on the CUI model of UsiXML. Other variability points for behavior and layout may be identified and reviewed. Unfortunately, this basic variability concern is a knock-out criterion.

IDEALXML. According to IDEALXML and its pattern expression capabilities [5], it was not mentioned how UIPs are being expressed in models such as the AUI or CUI model as reusable artifacts. Thus, it seems the patterns being modeled with the IDEALXML environment are always special instances to be manually adapted to new or changing contexts.

AUI patterns. Nevertheless, the AUI model and IDEALXML tool still might be mighty assets for pattern formalization. Following this thought, a developer would have to create AIOs of desired facets to model certain portions of a pattern, e.g., a single control facet for the button bar UIP or a single navigation facet for the tab navigation UIP of Figure 5. The modeling would solely be based on abstract structuring and interaction definition, as there would be no visual impressions of the final user interface. Later on, the instantiation of an AUI model pattern towards a CUI model would be prone to demand for fine-grained information, as each AIO would have to be configured individually to represent a specific set of CIOs and thus *UI-Controls*. In addition, language facilities would be needed to determine if an AIO was to be instantiated once or several times for a CUI. In any case, the modeling of UIPs with the UsiXML AUI model does not seem to be practical feasible, since user interface engineers would have a hard time to imagine the results. Finally, UIPs from public or corporate libraries could not be modeled with an adequate level of detail with respect to content criteria introduced in the previous section.

C. UIML User Interface Pattern Abstraction Capability

Reuse by templates. The UIML language facilities may enable the storing of UIPs. More precisely, UIML provides templates for the integration and reuse of already defined structures in new GUI formalizations [45]. The templates even may be parameterized, hierarchically nested and incorporated in the same way as ordinary <part> or <structure> elements [45]. Additionally, UIML templates may be used to restructure present <part> elements within a UIML document by the mechanisms of replace, union and cascade [45].

Sourcing of templates. UIML templates can only be sourced by concrete UIML structures, e.g., an existing <structure> or <part> element. The final element that incorporates any template must define certain values per <template-parameters> tag, which holds constants for the parameters of sourced templates [45].

Variability points. For UIPs to be stored inside a UIML document variability points need to be maintained. Therefore, it would be necessary to nest templates up to the structure root. In other words, the resulting main UIML document would have to resemble another template itself.

In this regard, even parameterized templates do not seem to be able to store UIPs deployable for varying contexts, since the respective parameters would have to be provided in the main UIML document. Unfortunately, a main UIML specification cannot be defined as a template that incorporates other templates and defines their variability point parameters, which would govern the elements of child

templates. In detail, it is not allowed for <structure> to define parameters on that root level. Neither <interface>, <structure> or <part> tags can define own parameters to be processed by a pattern instantiation wizard [29] or similar tool.

Separation of instances and templates. To resolve this issue, a separation of UIML document types could be attempted where UIP definition and UIP instantiation are segregated. The UIML templates stand alone as separate files and may promise some reuse. Those templates can be sourced from the same or other UIML files. However, there are some restrictions as follows. As stated in the UIML 4.0 specification [45], <part> tags can only source <part>-based templates and <structure> tags <structure>-based templates respectively. Possible scenarios, which can be derived from this approach, are explained in the following sub-sections.

1) Sourcing several <part>-based Templates

In this approach, several UIML documents would each specify a certain UIP with (hierarchical) templates and respective parameters, repeated parts and maybe restructuring actions or behavior as additional options. A schematic example for this kind of solution related to the tab UIP and "Dialog 1" of Figure 5 is provided by Figure 6.

Definition of placeholders. As shown on the right hand side of Figure 6, one major UIML document would have to define the particular UIP instance or complete dialog ("Dialog 1") to be rendered. Separate container elements would have to be defined in the main UIML document serving as placeholders to be merged with the sourced template by either the replace, union or cascade options. In this regard, template parameters of UIML reside on the child node level as outlined on the right hand side of Figure 6. This implies that concrete parameters have to be passed to included templates and consequently, the final UIML document describing the UIP instances would have to be created for each application or dialog separately. In this way, the UIP instance document would be sourcing several smaller templates as lower level hierarchy <part> elements within their <structure>.

Separate definition of individual UIP instances. Finally, parameters would have to be provided and kept in the UIML UIP instance document as shown in Figure 6. Therefore, each UIP instance would have to be specified at root node level separately. The main UIML document would have to define the panels or containers to include UIPs into the hierarchy of the virtual tree. This is due to the fact that UIML template parameters may only be applied for root and child node level.

2) Sourcing nested <part>-based Templates

The reuse of several <part>-based templates could be approached, but contained structures would build a strict hierarchy. As depicted on the left hand side of Figure 6, for <part>-based templates only one root level container would be possible, which combines several nested <part> elements into the same sub-tree. Hence, the incorporation of two UIPs at the same time would result in a "virtual tree" [45] with equally ranked or nested elements inside the same container. The main UIML document could only source both UIPs within this strictly defined hierarchy and thus, the developer would replace a <part> with both UIPs at once. According to Figure 5, the tab UIP would be directly followed by the button UIP inside the same panel and the dialog data contents would be situated at the bottom differing from the actual desired layout depicted in Figure 5.

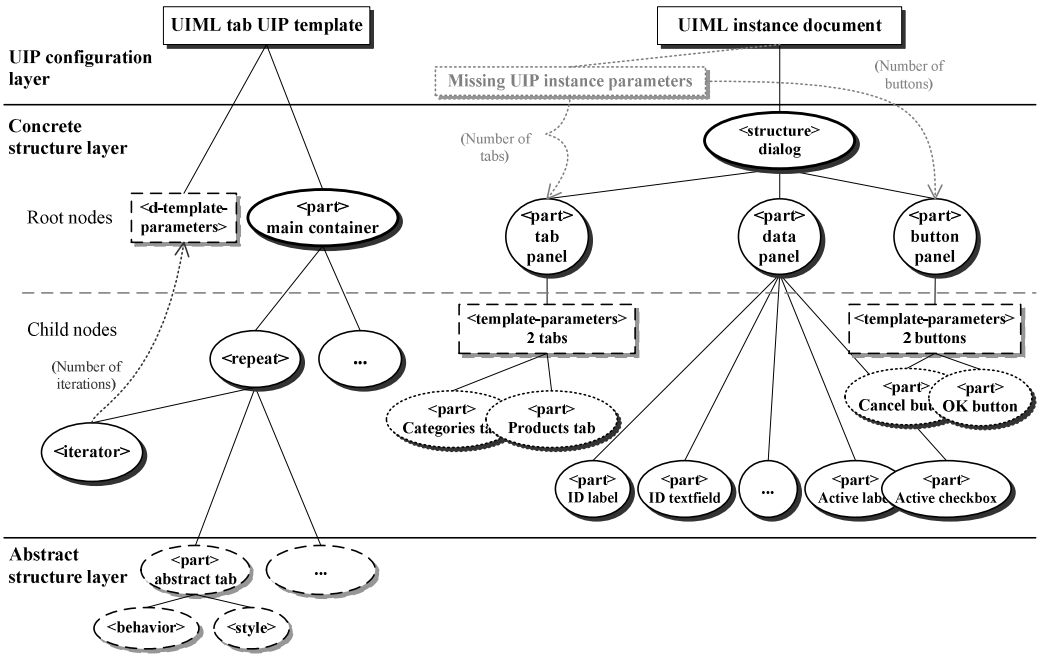

Figure 6. Schematic UIML <part>-based template and its sourcing inside a UIML document

3) Sourcing <structure>-based Templates

UIP compositions. Complex UIPs or their compositions like in Figure 5, forming entire new UIP units of reuse, could be specified with <structure>-based templates and hierarchical <part> elements. Following this approach, parameters could be applied to denote the iterators for each <part> at root node level included in the <structure>-based template. This variant is illustrated in Figure 7. Additionally, the cascade merging strategy could be used to preserve elements not to be replaced and the main UIML document would have to maintain a similar naming for <part> elements to be replaced by the template. In Figure 7, the <part> elements of both the template and UIML instance document are named equally.

However, these kinds of templates can only replace, cascade or union with one main <structure> element. Finally, this implies that only one template can be included in a UIML document using union or cascade at once. There is no sourcing of multiple <structure>-based templates possible.

Limitations of UIML instance documents. The current UIML template facilities are not a suitable solution for UIPs, since a strong tool support should define an instantiation configuration at design-time to raise efficiency and not the UIML document itself. With UIML as the basic configuration document there would be no overview about required parameters and no checking of constraints, e.g., the minimum, maximum or optional occurrence of elements), as there is even no definition of them inside the UIML document. UIML offers no visual aids in defining a UIP-instance. To conclude, reuse would still be limited to certain portions and GUI specification as well as configuration would pose high efforts.

Moreover, the above discussed strategies for applying UIML templates have another considerable drawback. The <d-template-parameters> definitions only allow for flat parameter structures. According to the presented examples, only the number of occurrences of child elements can be specified in the template and thus, configured in the UIML instance document. We cannot think of a way how to configure <style> information such as the label names for the given UIPs.

Summary. To draw a conclusion, UIML offers rich facilities like templates and restructuring mechanisms to manipulate a "virtual tree" structure [45] of a CUI model. Nevertheless, these capabilities are only valid for structure elements enumerated and defined concretely. There is no sufficient solution for the usage of a template, <repeat> or <restructure> for abstract elements with variable occurrences.

Currently, it seems that primitive UIPs may be defined via <part>-based templates, but the template has to be incorporated into a full UIML document and thus, variables have to be defined concretely. In addition, the limitations of parameter definition have to be taken into account.

In the following we provide a summary of current UIML shortcomings.

4) Current UIML Limitations

No meta-parameters for UIML documents. UIML provides no means to parameterize templates or UIML documents even further; meaning the introduction of meta-templates is not possible. UIML documents do not allow variables to govern nested templates. A higher level UIP configuration layer is missing, as indicated on the upper right hand side of in Figure 6. Such a layer could compensate for missing pattern support and allow nested parameterization for the final UIML document.

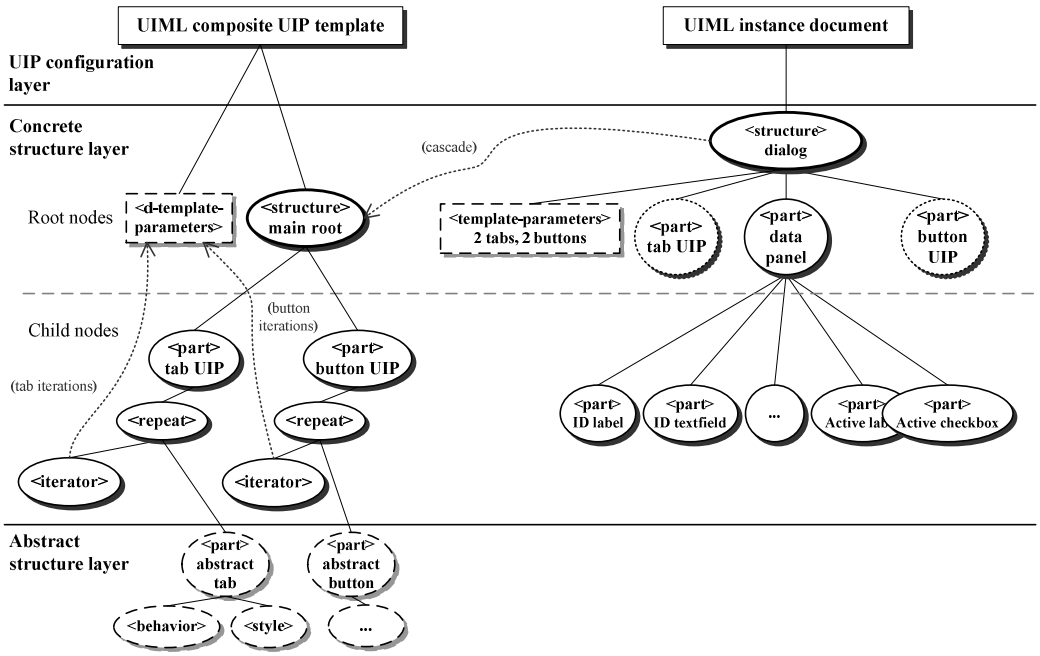

Figure 7. Schematic UIML <structure>-based template and its sourcing inside a UIML document

```
<!ELEMENT template (behavior| d-class| d-
component| constant| content| interface| logic|
part| layout| peers| presentation|
property| restructure| rule| script| structure|
style| variable| d-template-parameters)>
```

Figure 8. UIML 4.0 DTD [45] template tag definition

This way, the number of embedded template elements or respective sub-ordinate UIP instance could be governed. Currently, there is no reuse possible concerning root node structure elements with UIML, since the root elements are defined by the UIML UIP instance document itself. A developer would need to use UIML for defining final dialogs in detail this way.

Referencing abstract elements. Structure elements that are sourced from templates need to be referenced explicitly as this is needed for <style> and <behavior> sections for example. Therefore, a developer cannot specify the <behavior> or <style> of abstract elements or those yet to appear or being instantiated at design- or run-time inside a UIML document.

UIML DTD. Concerning the current UIML 4.0 XML DTD [45] as listed in Figure 8, the definition of templates may be faulty, since only one child element is currently allowed.

For instance, that means either <structure>, <part> or <d-template-parameters> are allowed as the solely child. Restrictions limit reuse to certain UIP combinations: Either one <structure>-based template in union or cascade as well as multiple <part>-based templates inside separately defined container elements are allowed. So a developer cannot specify how many template instances would be needed. Meta-parameters that would govern the individual template-specific parameters are not yet supported.

UIPs already instantiated. In the end, UIML itself is not capable of expressing complex UIPs. Only concrete template instances can be used, as they are configured concretely per <template-parameters> tag.

D. Review of Content Criteria

***UI-Control* types of UsiXML.** According to *UI-Controls,* UsiXML defines precisely which types of *UI-Controls* are available and what properties they can possess. An additional mapping model would have to be created in order to assign these elements to the entities of the target platform.

***UI-Control* types of UIML.** In comparison to UsiXML, UIML offers a more flexible definition of *UI-Controls*, since custom *UI-Controls* as well as their properties can be declared freely in the structure- or respective style-sections [45] without the need to define them beforehand. To map these structure parts to technical counterparts of the implementation, UIML offers a peer-section. This separate section can be used to specify a mapping between the parts defined within the structure and any target platform GUI component. The mapping to the GUI-framework can be altered afterwards without the need for changing the already defined UIPs. In addition, standard mappings can be defined and reused for a certain platform. However, the type safety like in UsiXML is not given. Thus, a homogenous usage of types and their pairing with properties has to be ensured by the developer and is not backed by the language specification like this is the case for UsiXML.

***Layout* definition of UsiXML.** Concerning *layout*, UsiXML uses special language elements to set up a GridBagLayout.

***Layout* definition of UIML.** UIML offers two variants for *layout* definition: Firstly, it is possible to use containers as structuring elements along with their properties. The containers have information attached that governs the arrangement of their constituent parts. Secondly, UIML provides special tags used for the *layout* definition. In comparison to UsiXML, UIML has a more flexible solution by defining *layouts* with containers that can be nested arbitrarily.

Behavior definition. Related to behavior, both languages define own constructs. Nevertheless, complex behavior is difficult to master without clear guidelines for both.

E. Summary of XML GUI Specification Languages Review

Besides the considered criteria for review, the two languages differ in indirect, supportive categories like framework and tool support or documentation. Additional comparison criteria and results of our evaluation are presented by TABLE I.

UsiXML and UIML may express structures similar to UIPs to some extent, but these resemble already instantiated patterns or their fragments. In fact, UIML may even express assorted UIPs through its template facilities. Nevertheless, these features are not sufficient for most UIP applications. In sum, both languages are missing the capability to specify UIPs properly.

F. Valuation of model-based Processes

Referring to the related work in Section III.C, promising solutions that enable higher reuse through the selection and instantiation of UIPs during specification and development of GUI systems are in reach. However, the presented approaches partly face the same challenges:

Common challenges. On the conceptual level, they need to review pattern relationships, enhance notations or probe the expression of more complex patterns or extend the set of supported patterns. For public evaluation, working examples of UIP instantiated to a certain context should be provided. Concerning tool support, researchers have to develop or enhance tools that aid in selection of appropriate patterns under consideration of possible relations among them. Moreover, tools are needed to guide the instantiation or configuration of selected patterns for a given context. Therefore, a solution finally adequate to fulfill each individual project's goals seems to be ahead of elaborate work in the future.

Common issues. In sum, we see some issues relevant to limit the effectiveness of further progress as follows.

Firstly, no detailed requirements or project goals have been communicated along with the presentation of concepts.

TABLE I. UIML AND USIXML IN COMPARISON

	UIML	**UsiXML**
language base	XML	XML
application	platform-independent user interface specification	device-, modality- and platform-independent user interface specification
reuse of code parts	by templates with assigned parameters	no
more than one user interface structure in one document	yes	no
manipulation of interface structures	through behavioral rules and replacement mechanisms of code parts	no, only method calls can be described
dynamic creation of interface structures	referenced through the use of variables	no, only static description
language documentation	extensive, with detailed language specification 4.0 [45] supplemented by descriptions and examples	2012: relative short, meta model described by class diagrams and short descriptions, no examples 03/2013: no updated meta model available
corresponding specification method and modeling framework	no, focused on implementation and prototyping	yes, implementation of Cameleon Reference Model (Task, Domain, AUI, CUI models), IDEALXML both as method and tool
tool support	GUI designer only	vast selection of tools (GUI designer, renderer, modeling framework, …)
rendering	XSL transformation, or compilation by own development	XSL transformation, rendering tools (XHTML, XUL, Java)

This hinders the evaluation of given approaches, and thus, their own justification and comparison to other approaches is hampered. More precisely, the UIPs defined as generative patterns and their capabilities remain a vague concept. Another considerable set-back is due to the fact that no detailed code examples or notation details have been presented yet.

Secondly, the general modeling framework and approach have been outlined as main assets, but no detailed architecture or transformations to code or final artifacts to be interpreted have been discussed so far. Up to now, the readiness of the approaches for practice or even their invented notations has to be questioned. For a more precise analysis of considered model-based processes reference [46] may be consulted.

VII. EXPERIMENTAL APPLICATION OF UIPS IN GUI-MODEL-TRANSFORMATIONS

Up to now, there have been no reports about experiences in the practical application of formal UIPs. The particular steps to be performed for a model-to-code-transformation and the shape as well as the outline of a formalization of UIPs are analyzed in the following sections.

A. Approach

To gain further insights about the practical implications of UIPs, they have been experimentally applied by two different prototypes. Similar to the probing of software patterns, selected UIPs were instantiated for simple example dialogs. These are illustrated in Figure 9.

Sketched examples. On the one hand, the examples consisted of a *view* fixed in shape that contained the UIP „Main Navigation“ [23] on the upper part. On the other hand, the lower part shows two variants for a *view* whose visuals are dependent on the input of the user.
Thereby, the UIP „Advanced Search“ [23] was applied. This UIP demands for a complex presentation control and is characteristic for E-commerce applications. Depending on the choice of the user, the *view* and *interactions* are altered. The search criteria can be changed, deleted and added as depicted in Figure 9 by two possible states. Both example dialogs should have been realized by formalized UIPs and one prototype.

Influences. Based on the current state-of-the-art concerning potential UIP notations, model-based processes employing generative patterns and the chosen example, we opted for two considerable different approaches and architectures.

Firstly, the potential GUI specification languages turned out not being capable of storing UIPs in a satisfactory manner. Only UIML was able to specify selected UIPs at design-time.

Secondly, the available sources of existing approaches provide no details about practical considerations and architectures related to UIP instantiation. In addition, they are affected by missing requirements for a definition and vagueness concerning the notation format of UIPs.

Lastly, the chosen dialog examples pointed out, that certain CUI models statically exists at specification time and others are due to change at runtime. Thus, a dynamic reconfiguration of a CUI model has to be considered.

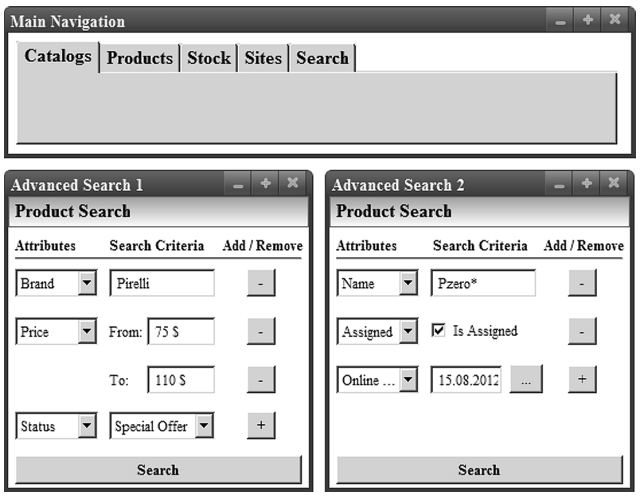

Figure 9. Example dialogs used for prototypes

Seissler et al. [36] also have outlined this aspect, but have not provided details yet. Finally, XML language capabilities will not be sufficient to provide proper formalization for dynamic user interfaces, as static user interfaces are already restricted.

Generation at design time. To test the formalization of simple UIPs and the generation of code for the examples, a solution, which generates the GUI dialogs at design time, was chosen. In general, the possibility to generate an executable GUI with the aid of UIPs had to be proven. The UIPs had to be completely defined at design time. Testing of the prototype had to be conducted after the GUI system was fully generated.

Choice of UIP notation. Regarding the structure of a GUI-specification, UsiXML proposes numerous models in order to separate the different information concerns *domain objects*, *tasks* and *user interface* as required by the underlying Cameleon Reference Framework. Not all the models were mandatory in terms of the example, since no explicit *essential model* was given. On the contrary, UIML operates with few sections within one XML-document. This is because the UIML format was easier to handle and learn with respect to the simple example. With UIML we could focus on the CUI to FUI transformation only.

In addition, on the basis of our review in Section VI UIML proved to be better suited for the specification of UIPs. Firstly, UIML is more compact in structure and enables a higher flexibility for shaping the formalization. Secondly, many of the language elements and models from UsiXML were not actually needed for the UIP „Main Navigation“. Thirdly, even the „Advanced Search“ example could not profit from the vast language range of UsiXML, since all possible variants for search criteria could not have been formalized or even enumerated. At least UIML offered the possibility to rely on templates in order to define all possible lines of search criteria composed of simple UIPs. UsiXML turned out to be too complex for these simple UIPs. Due to the limitations in documentation and the metamodel, it was not clear whether UsiXML permits the reuse of already specified UIPs at the time of our experiments. So we decided to apply UIML for the example dialogs.

Generation at runtime. The dynamic dialog *Advanced Search* could not be realized by the first approach. Thus, a solution had to be found that enables the instantiation of UIPs at runtime. Thereby, it was of importance to keep the platform independency of the UIML or respective CUI level specification. The formal UIPs had to be processed directly during runtime without binding them to a certain GUI-framework.

In the following analysis, we mainly concentrate on the latter approach where the instantiation of UIPs is executed at runtime. In contrast, the generation at design time is an often applied variant with respect to available approaches outlined in Section III.C. This particular approach strongly relies on the employed formalization language for UIPs. In fact, this major asset is still challenged as seen in Section VI.F. Therefore, we can not provide further advances by practical application.

B. *Generation at Design Time*

Foremost, the simple UIP *Main Navigation* was realized. This informally specified UIP was formalized using the chosen XML language. By means of a self-developed generator, a model-to-code-transformation was performed to create an executable dialog. Subsequently, the complete GUI system was started without any manual adaptations to the code.

Realization of „Main Navigation“. Java Swing was chosen as target platform. For the UIML <peer> section we decided to map the elements of „Main Navigation“ to horizontal JButtons instead of tabs.

In the formalization, the mandatory parameters for number, order and naming of *UI-Controls* were specified. As result, the UIP was described as an instance. The architecture was structured following the MVC-pattern [1]. The sections of UIML were assigned to components like this is illustrated by Figure 10.

<Structure> and <style> were processed within the object declarations (*UI-Controls*) of the *View* and its constructor. Based on the <behavior> section, *EventListeners* were generated acting as presentation controllers. For the *Model* the <content> section was assigned. Hence, the UIP “Main Navigation” formalized with UIML was transformed to source code.

Realization of „Advanced Search“. Even by using the UIML templates, this complex dialog could not be realized by a generation at design time. It was not possible to instantiate the formalized UIPs that were depending on the choice of attributes at runtime.

Results. The prototype primarily was intended to prove feasibility. This is because we chose a simple architecture and did not incorporate a *Dialog Controller* for controlling the flow of dialogs. The control was restricted to the scope of the *UI-Controls* of the respective UIP. Thus, the behavior only covered simple actions like the deactivation of *UI-Controls* or changing the text of a label. Complex decisions during the interaction process like the further processing of input data and the navigation control amongst dialogs could not be implemented.

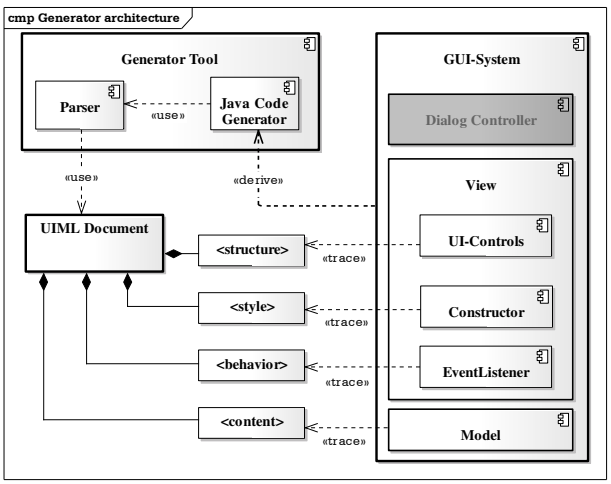

Figure 10. Architecture applied for code generation

A corresponding superordinate control could have been realized through a UIP-hierarchy in combination with appropriate guidelines for the formalization of control information. Despite the simplicity of the prototype, the following insights could be gathered:

Informal UIPs could be converted to formal UIP instances by using UIML as a formal language. Certain guidelines needed to be defined for this initial step. The *layout* of the example was specified by using containers for the main *window* and their properties. As a result, the *UI-Controls* were arranged according to these presets.

Nested containers and complex *layouts* have not yet been used for the experiment in this way. The <style> also was described concretely within the UIML document as well as the number and order of *UI-Controls*. The mapping of a formal UIP to a software pattern was described according to the scheme in Figure 10. Concerning the example *Advanced Search*, only fixed variants or a default choice of criteria could have been formalized. The generator could have created static GUIs accordingly without realizing the actual dynamics of this particular UIP.

C. Generation at Runtime

Since the *Advanced Search* UIP was very versatile and could not be formalized with all its variants with a single CUI model, the *layout* of the dialogs was fragmented.

By the means of a superordinate UIP the framing *layout* of the *view* was specified in a fixed manner at design time. In detail, the headline, labels and the three-column structure of the *view* appropriate to a table with the rows of search criteria were defined.

The mandatory but unknown parameters that determine the current choice of criteria and UIPs had to be processed at runtime. Accordingly, a software pattern had to be chosen that is able to instantiate UIP representations along with their behavior. This pattern had to act similarly to the builder design pattern [20], which enables the creation and configuration of complex aggregates. In [47] a suitable software pattern was discovered, which is explained shortly in the following paragraph and depicted in Figure 11:

Quasar VUI. The Virtual User Interface (VUI) is an early concept included in Quasar (quality software architecture) [48]. The VUI pattern follows the intention of programming dialogs in a generic way. This means that the dialog and its events are implemented via the technical independent, abstract interfaces *WidgetBuilder* and *EventListener* rather than using certain interfaces and objects of a GUI-framework directly. By means of this concept, the GUI-framework is interchangeable without affecting existing dialog implementations. Solely the component *Virtual User Interface (VUI)* depends on technological changes. Upon such changes, its interfaces would have to be re-implemented.

We are inclined that the VUI pattern implements some aspects symbolized by the CUI Cameleon step. Rather than specifying a certain CUI at design time and statically storing this as a source, the VUI creates a *Dialog* in an imperative way based on CUI level interface operation sequences.

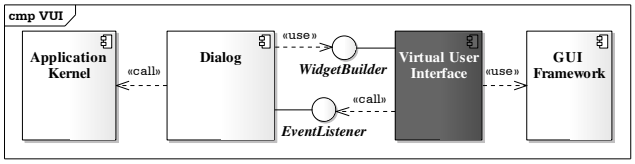

Figure 11. Virtual user interface architecture derived from [47]

By using the interface *WidgetBuilder*, a dialog dynamically can adapt its *view* at runtime. For instance, the *Dialog* delegates the *VUI* to create and configure a new *window* containing certain *UI-Controls*.

The *VUI* notifies the *Dialog* via the interface *EventListener* when events have been induced by *UI-Controls*. Both interfaces have to be standardized for a GUI system of a certain domain. This is essential to enable the reuse of reoccurring functionality such as the building of *views* and association of *UI-Controls* with events without regarding the certain technology or platform specifics being used. In short, an abstraction comparative to the CUI level and its advantages are enforced.

VUI for UIPs. The concept, the *VUI* is based on, can be adapted to the requirements of the UIP *Advanced Search*. The idea is to instantiate complete *view* components with UIP definitions besides simple *UI-Controls*. The *Dialog* is implemented by using generic interfaces, which enable the instantiation of UIPs, changing their *layout* and their association with events. In Figure 12 our refinement of the original *VUI* is presented.

To enable the implementation of UIP fragments, the *VUI* for UIPs is based on our previously described generator solution. Each possible variation of *UI-Controls* matching the attributes of the domain *objects* for *Advanced Search* has been formalized before. Hence, the search criteria rows of the dialog were visualized by different UIP fragments. Concerning the formal UIPs, the proper implementations for the chosen GUI-framework were generated as stated in Section VII.B. The previously mentioned generator was integrated in the component *UIP Implementations*. These implementations of UIPs located within *VUI* are based on the interfaces and objects of the GUI-framework. In analogy to the *UI-Controls* already implemented in the GUI-framework, the available UIP instances were provided via the interface *UIPBuilder* and could be positioned with certain parameters.

VUI at runtime. The *VUI* builds the *view* or a complete *window* as requested by the *Logical View.* Furthermore, the *VUI* provides information about the current composition and the *layout* of the *Dialog*. This information can be used by the *Logical View* for parameters to adapt the current *view* by delegating the *VUI* respectively. The *Dialog* coordinates the structuring of the *view* with the component *Logical View* and implements the application specific control in the *Dialog Controller* as well as dialog data in the *Model*.

Initially, events are reported to the *VUI* via *API-Events*. The *VUI* only forwards relevant events to the *Logical View*. When the respective event is solely related to properties of a *UI-Control* or a UIP instance, it is directly processed by the *Logical View* which delegates the *VUI* when necessary.

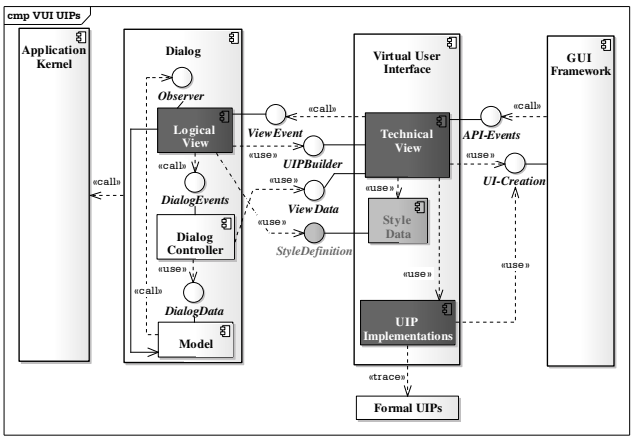

Figure 12. Virtual user interface architecture for UIPs

If the *Logical View* cannot process the particular event on its own, it will be forwarded to the *Dialog Controller*. For instance, this occurs when the user presses the button *Search* and a new *view* with the search results has to be loaded. The *Dialog Controller* collects the search criteria via the interface *ViewData* and sends an appropriate query to the *Application Kernel*. The result of the query will be stored as dialog data in the *Model*.

Results. For realizing *Advanced Search* with UIPs, a complex architecture had to be developed. Details like the connection of UIP instances to the *Dialog* data model as well as the automation potentials of the *Dialog Controller* could not yet be analyzed.

The UIPs had to be specified in a concrete manner like in Section VII.B. The prototype was not mature enough to handle abstract UIP specifications. The style of the *UI-Controls* was also described concretely, so the control of style by a component of the *VUI*, as depicted in Figure 12, has not yet been realized.

Through the *VUI,* the versatile combinations of *Advanced Search* could be realized according to the example at runtime. The VUI constitutes of a component-oriented structure related to the software categories of Quasar [48]. Accordingly, it possesses its virtues like the division of application and technology, separation of concerns therein and encapsulation by interfaces. Despite its challenging complexity, a flexible and maintainable architecture for dynamic GUI systems has been created. Finally, the formalized UIP fragments could be maintained at CUI level.

VIII. Practical Implications of User Interface Patterns

The reflection of both the theoretical implications of UIPs on GUI transformations and the results of our experiments led us to the following findings.

A. Formalization of UIPs

Reflection of results. By experimentally evaluating the model-to-code-transformation of formal UIPs, we came to the conclusion that the generation of a GUI is not the complicated part of the process. Instead, the formalization and the occurring options in this step lead to the main problem. Primarily, the preconditions to benefit from the positive influences of the UIPs on the GUI development process have to be established by the formalization.

The generator solution was well suited for stereotype and statically defined UIML contents. In this context, *layout*, number and order as well as style of UIPs have been specified concretely. This led us to a static solution that can be applied at design time. But the UIP *Advanced Search* could not be realized by following this approach.

Parameters for UIPs. In order to overcome this static solution, a parameterization of formal UIPs has to be considered. Via parameters the number, order, ID, *layout* and style of *UI-Controls* within UIPs specifications have to be determined to provide a more flexible solution. Especially the number and order of *UI-Controls* have to be abstractly specified in the first place. In this way, UIPs can be applied in varying contexts. In place of a concrete declaration of style for each UIP, a global style template has to be kept in mind. By using this template, dialogs could be created with uniform visuals and deviations are avoided. For this purpose, the *VUI* incorporated the *Style Data* component. It is intended to configure the visuals of UIP instances and *UI-Controls* globally. The configuration is used for the instantiation of these entities by the *Technical View*. Consequently, style information from single UIP specifications could be avoided and the UIPs would receive a more universal format.

The model-based processes have already approached the formalization issues. In fact, they have detailed the parameterization of presented XML languages UsiXML and UIML for their custom modeling frameworks. However, we could not rely on their findings, as both detailed information was missing and considerable future work in the line of improvements was outlined. Yet, a more sophisticated solution has still to be invented. This conclusion is backed by our subsequent work to derive detailed requirements on the definition and application of generative UIPs [46].

B. Generation at Design Time

In principle, complex UIPs or UIP-hierarchies can be realized with the generation at design time. The easiest cases are elementary or invariant UIPs like calendar, fixed forms or message windows. These examples can be generated with ease, since they do not need parameters besides a data model. For UIPs, which require parameters such as hierarchical UIP structures, an additional transformation is needed prior to the generation of source code.

Transformation of abstract UIPs. Firstly, the UIP is abstractly specified along with all parameter declarations needed and placeholders for nested UIPs. Subsequently, these parameters have to be specified via a context model, which adapts the UIP to a certain application. Based on the abstract UIP specification and the context model, a model-to-model-transformation is performed in order to generate concrete UIP specifications like they were used in our examples. In this state, all required information is available for the generation of the GUI system. The described model-to-code-transformation can be performed as a follow-up step.

It has to be analyzed whether a suitable format is available to realize this approach, by means of UsiXML or IDEALXML and the respective AUI and CUI models.

C. Generation at Runtime

Regarding the UIP *Advanced Search*, it is clear that a large gap has to be bridged between the *essential model* and the *user interface*. A *use case*, which demands for such dynamic UIPs, hides a whole variety of different GUI-designs and thus CUI level models. Consequently, one static *user interface* cannot always be established for the elements of the *essential model*. However, even for these dynamic GUIs UIPs can serve as media to enable reuse of numerous aspects directly by generation along with a composition at runtime. The combined application of both our approaches can provide a feasible solution. Concerning the example from Figure 9, the previously generated *layouts* actually were reused for the *Advanced Search window* and the *views* of search criteria. By instantiation of matching UIPs, even the interactions respectively the presentation control was reused.

Generation of dialogs. As shown with our example, the current VUI is capable of the instantiation and composition of single parts of a certain *Logical View*. The generation of complete *Logical Views* on the basis of formal UIPs and their hierarchy could possibly be realized with the VUI architecture. The model describing the *Logical View* has to refer to the standardized interfaces of the VUI and a common UIP catalog.

To formally specify the UIPs to be used in this environment, only UIML currently seems to be suitable. Firstly, an analysis of the required and reused elementary UIPs as well as the relevant *UI-Controls* has to be conducted in order to populate the basic level in the hierarchy of UIPs. Next, these UIPs have to be formalized with UIML along with their required data types and invariant behavior that acts as a basis for presentation control within the *VUI*. Furthermore, the interaction and *layout* within the *Logical View* have to be specified using UIML as well. This is because UIML already offers templates that can be parameterized and thus used for the composition of several UIP-documents into one master document establishing a UIP of higher level. Concerning UsiXML, one dialog can only be specified by a single AUI or respective CUI model.

To complete the *Dialog*, meaning *Dialog Controller* and *Model*, relevant information on *tasks* and data *objects* has to be included into a formal model. The research on the collaboration between adaptable UIPs and these logical aspects already has advanced [6] [26] [29] [31].

D. Limitations through the Application of UIPs

Individualization. Using UIPs instead of time-consuming manual transformations, a compromise is being contracted: A full individualization of the GUI is not possible with UIPs, since the customization is conducted within the limits of available and formalized UIPs reside on a CUI level of abstraction. Nevertheless, UIPs can embody a further building block of standard software. Customization will be facilitated by defined parameters and automation.

Metamodels. The application of UIPs demands for clear guidelines for modeling of the *essential model*, which result in a second limitation. The rules for this model need to define stereotype element types and their delimitations. The definition of the *essential model* should be governed by a metamodel to ensure the uniformity of defined model instance elements. In this respect, it will be defined what types and refinements of *tasks*, *domain objects* and domain data types do exist in order to assign them homogenously to certain UIP categories. This concept is essential for the proposal of suitable UIPs for the automated development of GUI systems.

The proposing system needs to work in two ways: On the one hand, the GUI developer asks for a suitable selection of UIPs for a certain part of the *essential model* at design time. On the other hand, users need to be provided with suitable UIPs in dynamic dialogs at runtime based on their current inputs. The mechanisms can only work if a uniform *essential model* with clearly defined abstractions derived from fixed guidelines is available as fundamental information.

IX. Conclusion and Future Work

A. Conclusion

We theoretically and experimentally elaborated that UIPs do have numerous positive influences on the GUI development process. UIPs integrate well in the common GUI transformations and respective models. Therefore, our findings are not restricted to the domain of E-commerce software, but rather can be adapted to other standard software such as enterprise resource planning systems. Even for individual software systems, UIPs can be of interest in case that numerous GUI aspects are similar and their reuse appears reasonable.

Currently, adaptability and reuse of UIPs are limited due to inadequate formalization options. Mostly invariant UIP and simple flat structures can be described by available template facilities of UIML. UIP compositions could only be created by manual implementation. We pointed to the limitations of current UIP specification format options and presented architectural solutions for their practical application. Above all, the upstream transformation of the abstract UIP description into UsiXML or UIML is worth to be considered, since one could use their strength in concretely specifying user interfaces. As an alternative to attempt to fully define UIPs in a single model, the approach to generate complete CUI level models on the basis of either UsiXML or UIML should be considered. Afterwards, the generation of GUIs based on this information would pose a minor issue.

B. Future Work

Formalization. For future work, we primarily see the research in formalizing UIPs. An important goal is to enable UIPs to act as real patterns that are adaptable to various contexts. The synthesis of a UIP-description model is the next step to determine properties and parameters of UIPs exactly and independently from GUI specification languages. Consequently, it can be more accurately assessed whether

future UIML or UsiXML versions are able to express the description model and thus UIPs completely. The independence from the platform can be achieved by both languages. However, it was not possible to specify context independent UIPs besides invariant or concrete UIPs. In this regard, the composition of UIPs, to form structured and modular specifications, remains unsolved, too.

Paradigm. Another open issue exists in the field of interaction paradigms [12] and the applicability of UIPs. With respect to the procedural paradigm, processes are defined, which exactly define the single steps of a *use case* scenario. To provide a matching *user interface* for this case, additional information needs to be included in the formalization of UIPs. For instance, the process or *task* structures have to be specified by UIPs on a high level of hierarchy. These UIPs possess little visual content, maybe a framing *layout* for *windows*, and mainly act as entities for controlling the application flow. The *Dialog Controller* from Figure 10 and Figure 12 could be based on such a UIP. In this paper, no information for these components was integrated in the formal UIPs. So these components had to be implemented manually. For example, the *Dialog Controller* opens a new *window* with search results for the *Advanced Search,* controls the further navigation and delegates the structuring of the next or previous *windows*. In this context, our *VUI* solution is a compromise between automation and the reuse of elementary and invariant UIPs through manual configuration of the *Dialog Controller* and the delegated *Logical View*. A full automation needs further research and the consideration of the achievements other researchers have gathered so far in the field of task pattern modeling.

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Message-Passing Interface for Java Applications: Practical Aspects of Leveraging High Performance Computing to Speed and Scale Up the Semantic Web

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***Abstract*—The age of Big Data introduces a variety of challenges in how to store, access, process, and stream massive amounts of structured and unstructured data effectively. Among those domains that are impacted by the Big Data problem at most, the Semantic Web holds a leading position. By current estimates, the volume of Semantic Web data is exceeding the order of magnitude of billions of triples. Using High Performance Computing infrastructures is essential in dealing with these massive data volumes. Unfortunately, the most Semantic Web applications are developed in Java language, which makes them incompatible with the traditional high performance computing software solutions, which are tailored for compiled codes developed in C and Fortran languages. The known attempts to port existing parallelization frameworks, such as the Message-Passing Interface, to the Java platform have proved either a poor efficiency in terms of performance and scalability, or a limited usability due to a considerable configuration and installation overhead. We present an efficient porting of Java bindings based on Open MPI - one of the most popular Message-Passing Interface implementations for the traditional (C, C++, and Fortran) supercomputing applications.**

Keywords-High Performance Computing, Big Data, Semantic Web, Performance, Scalability, Message-Passing Interface, Open MPI.

I. Introduction

The data volumes collected by the Semantic Web have already reached the order of magnitude of billions of triples and is expected to further grow in the future, which positions this Web extension to dominate the data-centric computing in the oncoming decade. Processing (e.g., inferring) such volume of data, such as generated in the social networks like Facebook or Twitter, or collected in domain-oriented knowledge bases like pharmacological data integration platform OpenPHACTS, poses a lot of challenges in terms of reaching the high performance and scalability by the software applications. As discussed in our previous publication [1], while there is a number of existing highly-scalable software solutions for storing data, such as Jena [2], the scalable data processing constitutes the major challenge for data-centric applications. This work is discussing application of the techniques elaborated in the previous paper to the Big Data application domain. In the literature, it is often referred as "Big Data" a set of issues related to scaling

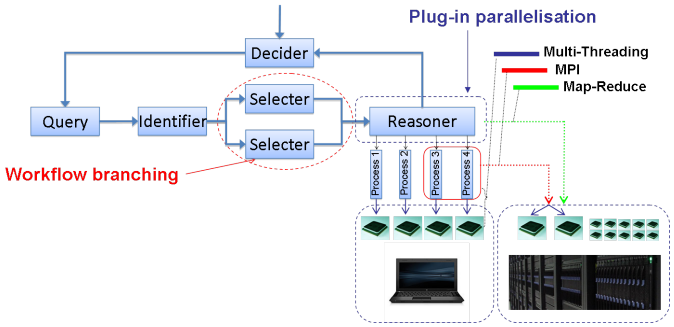


Figure 1. Parallelization patterns in a Reasoning application's workflow.

existing processing techniques to large amounts of data, for which standard computing platforms have proved inefficient [3]. Among those data-centric communities that address the Big Data, the Semantic Web enjoys a prominent position. Semantic Data are massively produced and published at the speed that makes traditional processing techniques (such as reasoning) inefficient when applied to the real-scale data. It is worth mentioning that the typical Semantic Web application workflows are highly parallel in their nature (see Figure 1) and are well-suited to run in high performance computing environments.

The data scaling problem in the Semantic Web is considered in two its main aspects - horizontal and vertical scale. Horizontal scaling means dealing with heterogeneous, and often unstructured data acquired from heterogeneous sources. The famous Linked Open Data cloud diagram [4] consists of hundreds of diverse data sources, ranging from geo-spatial cartographic sources like *Open Street Map*, to governmental data, opened to the publicity, like *data.gov*. Vertical scaling implies scaling up the size of similarly structured data. Along the open government data spawns over 851,000 data sets across 153 catalogues from more than 30 countries, as estimated in [5] at the beginning of 2012. Processing data in such an amount is not straightforward and challenging for any of the currently existing frameworks and infrastructures. Whereas there are some known algorithms dealing with the horizontal scaling complexity, such as

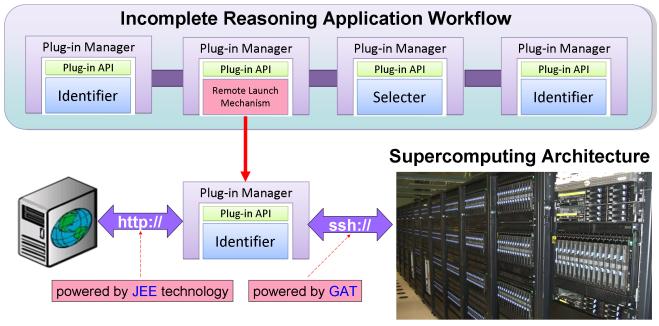


Figure 2. Execution of a reasoning application's workflow on a high performance computing system.

identification of the information subsets related to a specific problem, i.e., subsetting, the vertical scaling remains the major challenge for all existing algorithms.

Another essential property of the Big Data is complexity. Semantic applications must deal with rich ontological models describing complex domain knowledge, and at the same time highly dynamic data representing recent or relevant information, as produced by streaming or search-enabled data sources. A considerable part of the web data is produced as a result of automatic reasoning over streaming information from sensors, social networks, and other sources, which are highly unstructured, inconsistent, noisy and incomplete.

The availability of such an amount of complex data makes it attractive for Semantic Web applications to exploit High Performance Computing (HPC) infrastructures to effectively process the Big Data. There have been several pilot research projects aiming to enable the potential of supercomputing infrastructures to the Semantic Web application development. One of the prominent examples of such projects is the Large Knowledge Collider (LarKC), which is a software platform for large-scale incomplete reasoning. In particular, LarKC provides interfaces for loading off the computation-intensive part of a reasoning application's workflow to a supercomputing infrastructure (see Figure 2).

Both commodity and more dedicated HPC architectures, such as the Cray XMT [6], have been held in focus of the data-intensive Web applications. The XMT dedicated system, however, has proved successful only for a limited number of tasks so far, which is mainly due to the complexity of exploiting the offered software frameworks (mainly non-standard pragma-based C extensions).

Unfortunately, most Semantic Web applications are written in the Java programming language, whereas current frameworks that make the most out of HPC infrastructures, such as the Message Passing Interface (MPI), only target C or Fortran applications. MPI is a process-based parallelization strategy, which is a de-facto standard in the area of parallel computing for C, C++, and Fortran applications. Known alternative parallelization frameworks to MPI that conform with Java, such as Hadoop[7] or Ibis [8], prove to be scalable though but are not even nearly as efficient or well-developed as numerous open-source implementations of MPI, such as MPICH or Open MPI[9].

The implementation in Java has prevented MPI to be adopted by Semantic Web applications. However, given the vast data size addressed by the modern Web applications, and given the emergence of the new communities interested in adopting MPI, it seems natural to explore the benefits of MPI for Java applications on the HPC platforms as well. Introducing MPI to Java poses several challenges. First, the API set should be compliant with the MPI standard [9], but not downgrade the flexibility of the native Java language constructions. Second, the hardware support should be offered in a way that overcomes the limitation of the Java run-time environment, but meet such important requirements as thread-safety. Third, MPI support should be seamlessly integrated in the parallel application's execution environment. All of these three issues of functionality, adaptivity, and usability must complexly be addressed to make the use of MPI in Java applications practical and useful.

We look how to resolve the above-mentioned issues in a way that leverages the advances of the existing MPI frameworks. We present and evaluate our solution for introducing Java support in Open MPI [10], which is one of the most popular open source MPI-2 standard's implementations nowadays. Our approach is based on the integration of Java MPI bindings developed for mpiJava [11] directly in the native C realization of Open MPI, thus minimizing the bindings overhead and leveraging the Open MPI's run-time and development environment to ensure the high scalability of the Java parallel application. We also give examples of successful pilot scenarios implemented with our solution and discuss future work in terms of the development, implementation, and standardization activities.

II. Related Work

There are only a few alternatives to MPI in introducing the large-scale parallelism to Java applications. The most promising among those alternatives in terms of the performance and usability are solutions offered by IBIS/JavaGAT and MapReduce/Hadoop.

IBIS [12] is a middleware stack used for running Java applications in distributed and heterogeneous computing environments. IBIS leverages the peer-to-peer communication technology by means of the proprietary Java RMI (Remote Memory Invocation) implementation, based on GAT (Grid Application Toolkit) [13]. The Java realization of GAT (JavaGAT) is a middleware stack that allows the Java application to instatiate its classes remotely on the network-connected resource, i.e., a remote Java Virtual Machine. Along with the traditional access protocols. e.g., telnet or ssh, the advanced access protocols, such as ssh-pbs for clusters with PBS(cluster Portable Batch System)-like job

scheduling or gsissh for grid infrastructures are supported. IBIS implements a mechanism of multiple fork-joins to detect and decompose the application's workload and execute its parts concurrently on distributed machines. While [8] indicates some successful Java applications implemented with IBIS/JavaGAT and shows a good performance, there is no clear evidence about the scalability of this solution for more complex communication patterns, involving nested loops or multiple split-joins. Whereas IBIS is a very effective solution for the distributed computing environments, e.g., Grid or Cloud, it is definitively not the best approach to be utilized on the tightly-coupled productional clusters.

The MapReduce framework [14] and its most prominent implementation in Java, Hadoop, has got a tremendous popularity in modern data-intensive application scenarios. MapReduce is a programming model for data-centric applications exploiting large-scale parallelism, originally introduced by Google in its search engine. In MapReduce, the application's workflow is divided into three main stages (see Figure 3): map, process, and reduce. In the map stage, the input data set is split into independent chunks and each of the chunks is assigned to independent tasks, which are then processed in a completely parallel manner (process stage). In the reduce stage, the output produced by every map task is collected, combined and the consolidated final output is then produced. The Hadoop framework is a service-based implementation of MapReduce for Java. Hadoop considers a parallel system as a set of master and slave nodes, deploying on them services for scheduling tasks as jobs (Job Tracker), monitoring the jobs (Task Tracker), managing the input and output data (Data Node), re-executing the failed tasks, etc. This is done in a way that ensures a very high service reliability and fault tolerance properties of the parallel execution. In Hadoop, both the input and the output of the job are stored in a special distributed file-system. In order to improve the reliability, the file system also provides an automatic replication procedure, which however introduces an additional overhead to the inter-node communication. Due to this overhead, Hadoop provides much poorer performance than MPI, however offering better QoS characteristics related to the reliability and fault-tolerance. Since MPI and MapReduce paradigms have been designed to serve different purposes, it is hardly possible to comprehensively compare them. However they would obviously benefit from a cross-fertilization; e.g., MPI could serve a high-performance communication layer to Hadoop, which might help improve the performance by omitting the disk I/O usage for distributing the map and gathering the reduce tasks across the compute nodes.

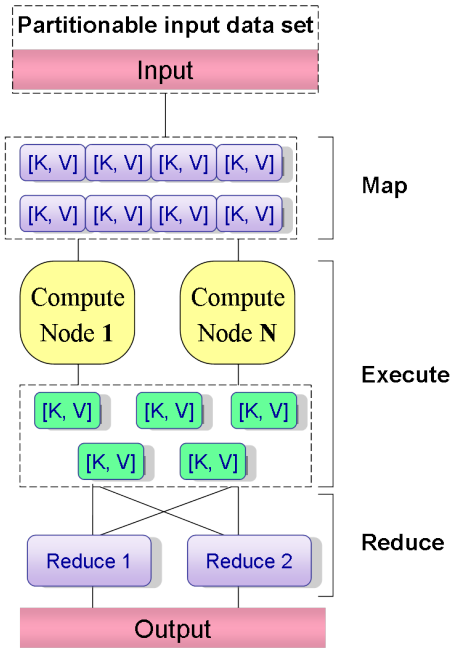


Figure 3. MapReduce processing schema.

III. Data-Centric Parallelization and MPI

By "data-centric parallelization" we mean a set of techniques for: (i) identification of non-overlapping application's dataflow regions and corresponding to them instructions; (ii) partitioning the data into subsets; and (iii) parallel processing of those subsets on the resources of the high performance computing system. For Semantic Web applications utilizing the data in such well-established formats as RDF [15], parallelization relies mainly on partitioning (decomposing) the RDF data set on the level of statements (triples), see Figure 4a. The ontology data (also often referred as *tbox*) usually remains unpartitioned as its size is relatively small as compared with the actual data (*abox*), so that it is just replicated among all the compute nodes.

The Message-Passing Interface (MPI) is a process-based standard for parallel applications implementation. MPI processes are independent execution units that contain their own state information, use their own address spaces, and only interact with each other via interprocess communication mechanisms defined by MPI. Each MPI process can be executed on a dedicated compute node of the high performance architecture, i.e., without competing with the other processes in accessing the hardware, such as CPU and RAM, thus improving the application performance and achieving the algorithm speed-up. In case of the shared file system, such as Lustre [16], which is the most utilized file system standard of the modern HPC infrastructures, the MPI processes can effectively access the same file section in parallel without any considerable disk I/O bandwidth degradation. With regard to the data decomposition strategy presented in Figure 4a, each MPI process is responsible for processing the data partition assigned to it proportionally to the total number of the MPI processes (see Figure 4b). The position of any MPI process within the group of processes

involved in the execution is identified by an integer *R* (rank) between 0 and *N*-1, where *N* is a total number of the launched MPI processes. The rank *R* is a unique integer identifier assigned incrementally and sequentially by the MPI run-time environment to every process. Both the MPI process's rank and the total number of the MPI processes can be acquired from within the application by using MPI standard functions, such as presented in Listing 1.

```
import java.io.*;
import mpi.*;

class Hello {
  public static void main(String[] args) throws
       MPIException
  {
    int my_pe, npes; // rank and overall number of MPI
         processes
    int N;       // size of the RDF data set (number of
         triples)

    MPI.Init(args); // intialization of the MPI RTE

    my_pe = MPI.COMM_WORLD.Rank();
    npes  = MPI.COMM_WORLD.Size();

    System.out.println("Hello␣from␣MPI␣process" + my_pe +
         "␣out␣of␣" + npes);
    System.out.println("I'm␣processing␣the␣RDF␣triples␣
         from␣" + my_pe/npes + "␣to␣" + (my_pe+1)/npes);

    MPI.Finalize(); // finalization of the MPI RTE
  }
}
```

Listing 1. Acquiring rank and total number of processes in a simple MPI application.

The typical data processing workflow with MPI can be depicted as shown in Figure 5. The MPI jobs are executed by means of the *mpirun* command, which is an important part of any MPI implementation. *mpirun* controls several aspect of parallel program execution, in particular launches MPI processes under the job scheduling manager software like OpenPBS [17]. The number of MPI processes to be started is provided with the *-np* parameter to *mpirun*. Normally, the number of MPI processes corresponds to the number of the compute nodes, reserved for the execution of parallel job. Once the MPI process is started, it can request its rank as well as the total number of the MPI processes associated with the same job. Based on the rank and total processes number, each MPI process can calculate the corresponding subset of the input data and process it. The data partitioning problem remains beyond the scope of this work; particularly for RDF, there is a number of well-established approaches discussed in several previous publications, e.g., horizontal [18], vertical [19], and workload driven [20] partitioning.

Since a single MPI process owns its own memory space and thus can not access the data of the other processes directly, the MPI standard foresees special communication functions, which are necessary, e.g., for exchanging the data subdomain's boundary values or consolidating the final output from the partial results produced by each of the processes. The MPI processes communicate with each other

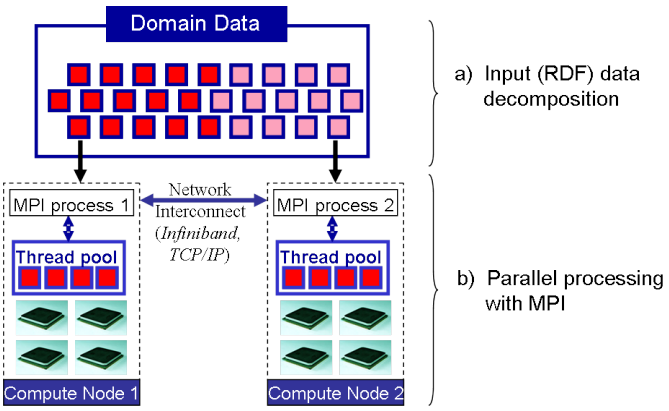


Figure 4. Data decomposition and parallel execution with MPI.

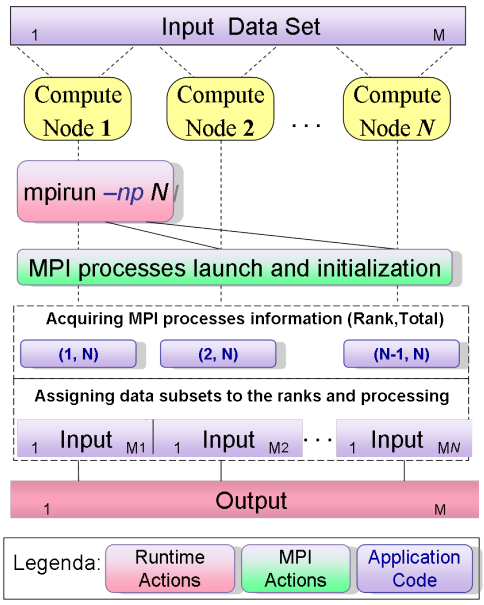


Figure 5. Typical MPI data-centric application's execution workflow.

by sending messages, which can be done either in "point-to-point"(between two processes) or collective way (involving a group of or all processes).

More details about the MPI communication can also be found in our previous publication [21].

IV. Open MPI Java Bindings

This section discusses implementation details of Java bindings for the Open MPI library.

A. MPI bindings for Java

Although the official MPI standard's bindings are limited to C and Fortran languages, there has been a number of standardization efforts made towards introducing the MPI bindings for Java. The most complete API set, however, has been proposed by mpiJava [22] developers.

There are only a few approaches to implement MPI bindings for Java. These approaches can be classified in two following categories:

- Pure Java implementations, e.g., based on RMI (Remote Method Invocation) [23], which allows Java objects residing in different virtual machines to communicate with each other, or lower-level Java sockets API.
- Wrapped implementations using the native methods implemented in C languages, which are presumably more efficient in terms of performance than the code managed by the Java run-time environment.

In practice, none of the above-mentioned approaches satisfies the contradictory requirements of the Web users on application portability and efficiency. Whereas the pure Java implementations, such as MPJ Express [24] or MPJ/Ibis [8], do not benefit from the high speed interconnects, e.g., InfiniBand [25], and thus introduce communication bottlenecks and do not demonstrate acceptable performance on the majority of today's production HPC systems [26], a wrapped implementation, such as mpiJava [27], requires a native C library, which can cause additional integration and interoperability issues with the underlying MPI implementation.

In looking for a trade-off between the performance and the usability, and also in view of the complexity of providing Java support for high speed cluster interconnects, the most promising solution seems to be to implement the Java bindings directly in a native MPI implementation in C.

B. Native C Implementation

Despite a great variety of the native MPI implementations, there are only a few of them that address the requirements of Java parallel applications on process control, resource management, latency awareness and management, and fault tolerance. Among the known sustainable open-source implementations, we identified Open MPI[28] and MPICH2[29] as the most suitable to our goals to implement the Java MPI bindings. Both Open MPI and MPICH2 are open-source, production quality, and widely portable implementations of the MPI standard (up to its latest 2.0 version). Although both libraries claim to provide a modular and easy-to-extend framework, the software stack of Open MPI seems to better suit the goal of introducing a new language's bindings, which our research aims to. The architecture of Open MPI [10] is highly flexible and defines a dedicated layer used to introduce bindings, which are currently provided for C, F77, F90 and some other languages (see also Figure 7). Extending the OMPI-Layer of Open MPI with the Java language support seems to be a very promising approach to the the discussed integration of Java bindings, taking benefits of all the layers composing Open MPI's architecture.

C. Design and Implementation in Open MPI

We have based our Java MPI bindings on the *mpiJava* code, originally developed in HPJava[30] project and currently maintained by the High Performance Computing Center Stuttgart[31]. mpiJava provides a set of Java Native Interface (JNI) wrappers to the native MPI v.1.1 communication methods, as shown in Figure 6. JNI enables the programs running inside a Java run-time environment to invoke native C code and thus use platform-specific features and libraries [32], e.g., the InfiniBand software stack. The application-level API is constituted by a set of Java classes, designed in conformance to the MPI v.1.1 and the specification in [22]. The Java methods internally invoke the MPI-C functions using the JNI stubs. The realization details for mpiJava can be obtained from [11][33].

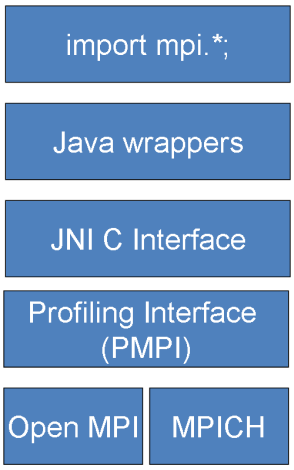


Figure 6. mpiJava architecture.

Open MPI is a high performance, production quality, MPI-2 standard compliant implementation. Open MPI consists of three combined abstraction layers that provide a full featured MPI implementation: (i) OPAL (Open Portable Access Layer) that abstracts from the peculiarities of a specific system away to provide a consistent interface adding portability; (ii) ORTE (Open Run-Time Environment) that provides a uniform parallel run-time interface regardless of system capabilities; and (iii) OMPI (Open MPI) that provides the application with the expected MPI standard interface. Figure 7 shows the enhanced Open MPI architecture, enabled with the Java bindings support.

The major integration tasks that we performed were as follows:

- extend the Open MPI architecture to support Java bindings,
- extend the previously available mpiJava bindings to MPI-2 (and possibly upcoming MPI-3) standard,
- improve the native Open MPI configuration, build, and execution system to seamlessly support the Java bindings,
- redesign the Java interfaces that use JNI in order to better conform to the native realization,
- optimize the JNI code to minimize its invocation over-

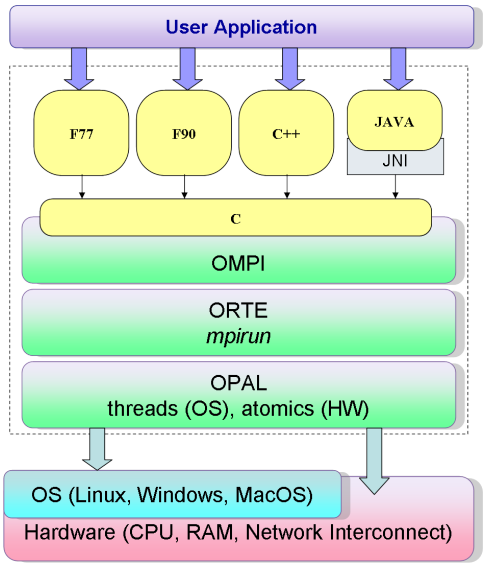


Figure 7. Open MPI architecture.

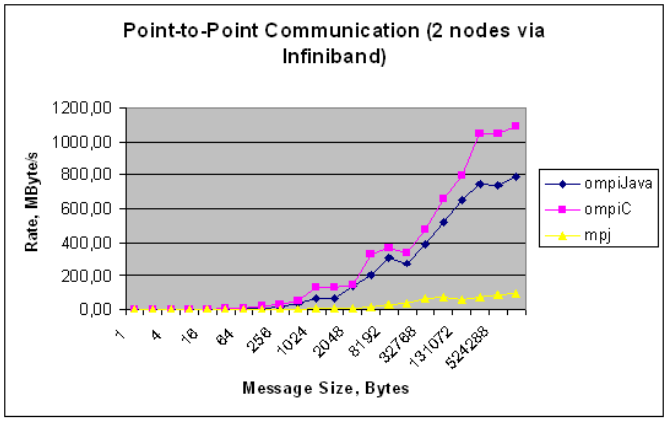


Figure 8. Message rate for the point-to-point communication.

head,

- and create test applications for performance benchmarking.

Both Java classes and JNI code for calling the native methods were integrated into Open MPI. However, the biggest integration effort was required at the OMPI (Java classes, JNI code) and the ORTE (run-time specific options) levels. The implementation of the Java class collection followed the same strategy as for the C++ class collection, for which the opaque C objects are encapsulated into suitable class hierarchies and most of the library functions are defined as class member methods. Along with the classes implementing the MPI functionality (MPI package), the collection includes the classes for error handling (Errhandler, MPIException), datatypes (Datatype), communicators (Comm), etc. More information about the implementation of both Java classes and JNI-C stubs can be found in previous publications [11][26].

D. Performance

In order to evaluate the performance of our implementation, we prepared a set of Java benchmarks based on those well-recognized in the MPI community, such as NetPIPE [34] or NAS [35]. Based on those benchmarks, we compared the performance of our implementation based on Open MPI and the other popular implementation (MPJ Express) that follows a "native Java" approach. Moreover, in order to evaluate the JNI overhead, we reproduced the benchmarks also in C and ran them with the native Open MPI. Therefore, the following three configurations were evaluated:

- **ompiC** - native C implementation of Open MPI (the actual trunk version), built with the GNU compiler (v.4.6.1),
- **ompiJava** - our implementation of Java bindings on top of *ompiC*, running with Java JDK (v.1.6.0), and
- **mpj** - the newest version of MPJ Express (v.0.38), a Java native implementation, running with the same JDK.

We examined two types of communication: point-to-point (between two nodes) and collective (between a group of nodes), varying the size of the transmitted messages. We did intentionally not rely on the previously reported benchmarks[36] in order to eliminate the measurement deviations that might be caused by running tests in a different hardware or software environment. Moreover, in order to ensure a fair comparison between all these three implementations, we ran each test on the absolutely same set of compute nodes.

The point-to-point benchmark implements a "ping-pong" based communication between two single nodes; each node exchanges the messages of growing sizes with the other node by means of blocking Send and Receive operations. As expected, our *ompiJava* implementation was not as efficient as the underlying *ompiC*, due to the JNI function calls overhead, but showed much better performance than the native Java based *mpj* (Figure 8). Regardless of the message size, *ompiJava* achieves around eight times higher throughput than *mpj* (see Figure 9).

The collective communication benchmark implements a single blocking message gather from all the involved nodes. Figure 10 shows the results collected for $P = 2^k$ (where k=2-7) nodes, with a varying size of the gathered messages. The maximal size of the aggregated data was 8 GByte on 128 nodes. Figure 11 demonstrates the comparison of collective gather performance for all tested implementations on the maximal number of the available compute nodes (128). Whereas the InfiniBand-aware *ompiJava* and *ompiC* scaled quite well, the native Java based *mpj* has shown very poor performance; for the worst case (on 128 nodes) a slow-down up to 30 times compared with *ompiJava* was observed.

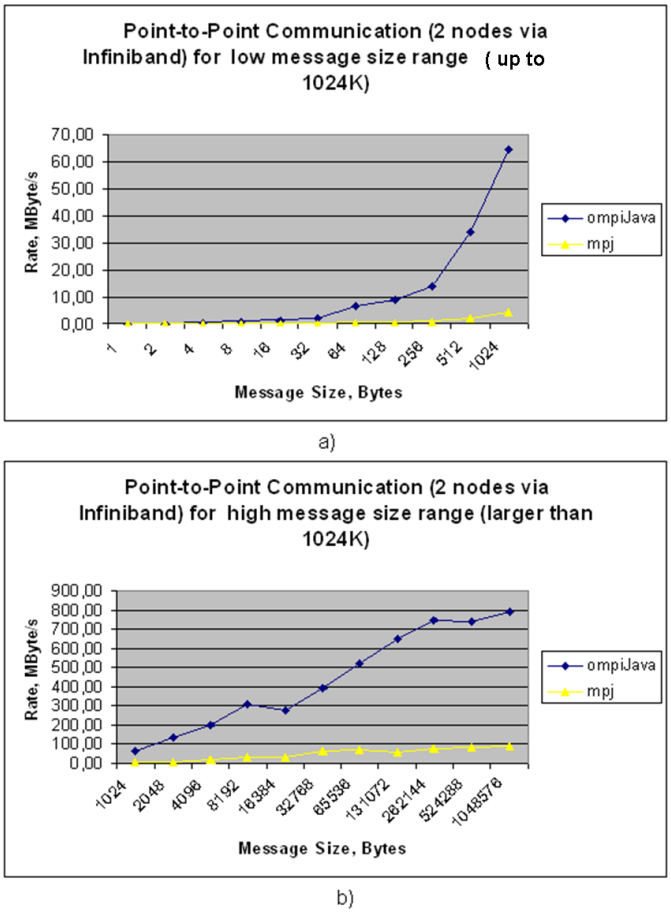


Figure 9. Comparison of the message rate for ompiJava and mpj for a) low and b) high message size range.

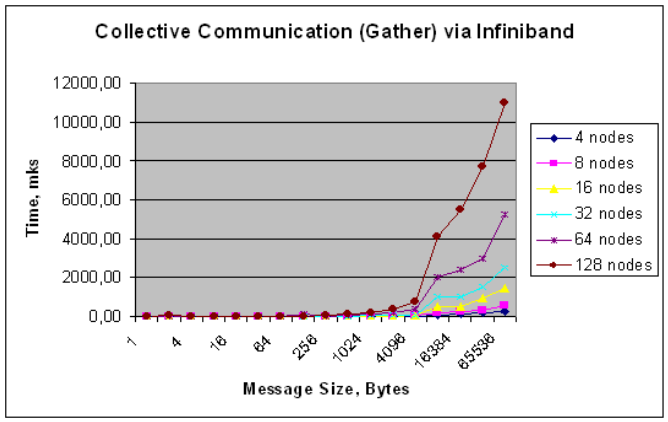


Figure 10. Collective gather communication performance of ompiJava.

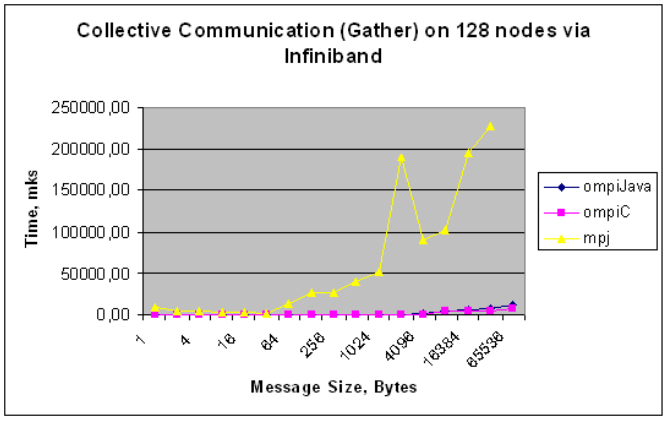


Figure 11. Collective gather communication performance on 128 nodes.

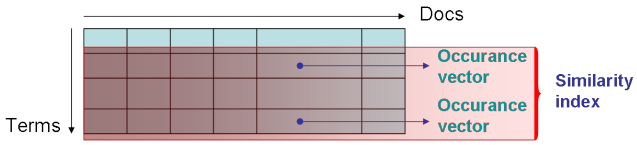


Figure 12. Similarity index computation in a document collection.

V. MPI Implementation of Random Indexing

Random indexing [37] is a word-based co-occurrence statistics technique used in resource discovery to improve the performance of text categorization. Random indexing offers new opportunities for a number of large-scale Web applications performing the search and reasoning on the Web scale [38]. We used Random Indexing to determine the similarity index (based on the words' co-occurance statistic) between the terms in a closed document collection, such as Wikipedia or Linked Life Data (see Figure 12).

The main challenges of the Random Indexing algorithms lay in the following:

- Huge and high-dimensional vector space. A typical random indexing search algorithm performs traversal over all the entries of the vector space. This means, that the size of the vector space to the large extent determines the search performance. The modern data stores, such as Linked Life Data or Open PHACTS consolidate many billions of statements and result in vector spaces of a very large dimensionality. Performing Random indexing over such large data sets is computationally very costly, with regard to both execution time and memory consumption. The latter poses a hard constraint to the use of random indexing packages on the serial mass computers. So far, only relatively small parts of the Semantic Web data have been indexed and analyzed.
- High call frequency. Both indexing and search over the vector space is highly dynamic, i.e., the entire indexing

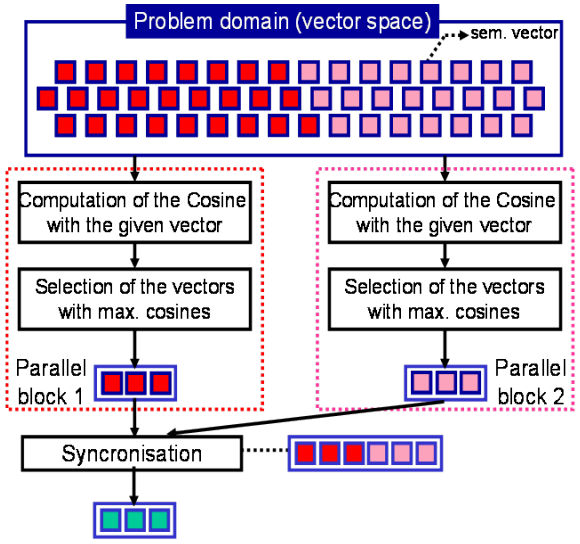


Figure 13. MPI-based parallel implementation of Airhead Search.

process repeats from scratch every time new data is encountered.

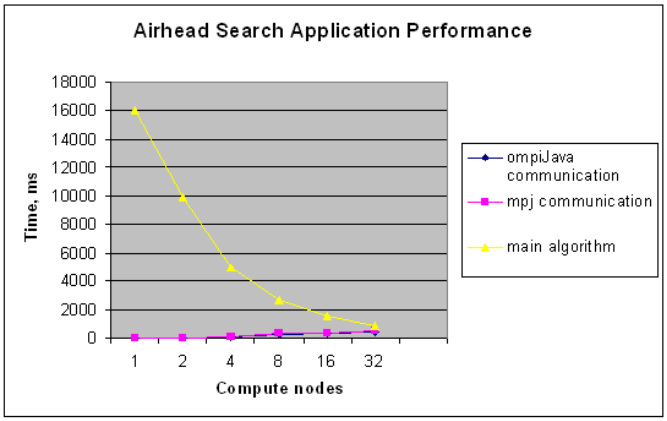
In our previous work [39], we have already reported on the efforts done on parallelizing the search operation of Airhead - an open source Java implementation of Random Indexing algorithm. Our MPI implementation of the Airhead search is based on a domain decomposition of the analyzed vector space and involves both point-to-point and collective gather and broadcast MPI communication (see the schema in Figure 13). In our current work, we evaluated the MPI version of Airhead with both *ompijava* and *mpj* implementations.

We performed the evaluation for the largest of the available data sets reported in [39] (namely, Wiki2), which comprises 1 Million of high density documents and occupies 16 GByte disk storage space. The overall execution time (wall clock) was measured. Figure 14a shows that both *ompijava* and *mpj* scale well until the problem size is large enough to saturate the capacities of a single node. Nevertheless, our implementation was around 10% more efficient over *mpj* (Figure 14b).

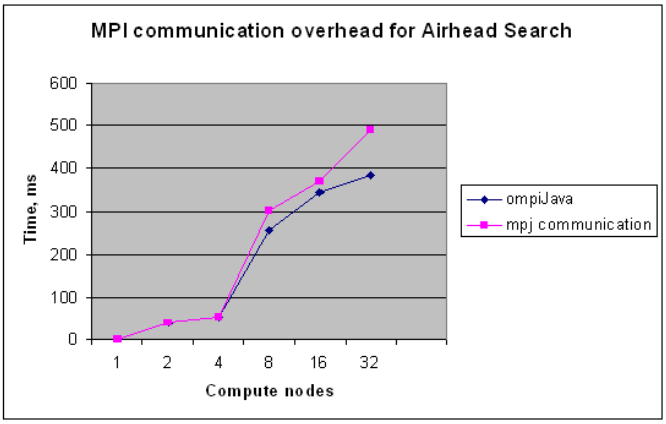
VI. Performance Analysis And Optimization Tools

Development of parallel communication patterns with MPI is quite a nontrivial task, in particular for large-scale use cases, which consist of hundreds and even thousands of parallel processes. The synchronization among the MPI processes of the parallel application can be a key performance concern. Among the typical problems the following appear most frequently:

- non-optimal balancing of the MPI processes load (i.e., wrong data decomposition),
- misconfiguration of the communication pattern preventing the applications scalability to the growing number



a)



b)

Figure 14. Airhead performance with ompiJava and mpj.

of compute nodes,

- incorrect usage of the MPI communication functions (e.g., when point-to-point communication are used instead of the collective ones, which lowers the performance and also prevents the scalability).

One of the advantages of the C-based Java binding implementation as compared with the "native-Java" approach is the possibility to use numerous performance optimization tools available for the traditional HPC applications. This is leveraged by the special profiling interface provided by the MPI standard - PMPI (see Figure 6). Using PMPI, performance analysis tools can inject the measurement code directly in the parallel application's object file and capture and aggregate statistics about the application execution at run-time. Among the parameters measured with PMPI are duration of a single MPI communication, total number of communications, processes that are involved in the communication, etc. The profiling code is dynamically linked with the MPI library and thus does not require any changes in either the application code or the MPI library. The captured events are stored in trace files using a special format, such as OTF - the Open Trace Format, which can then be

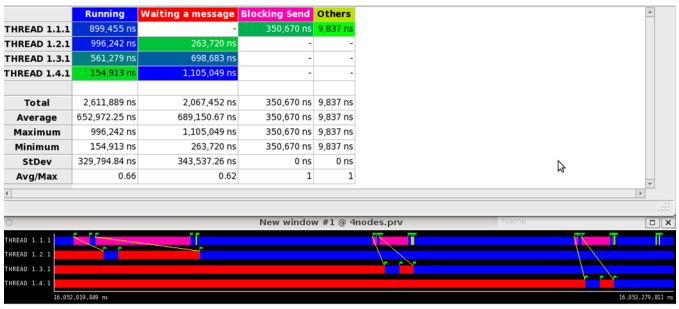


Figure 15. MPI Global Broadcast Communication visualization for four MPI processes with Paraver.

analyzed in order to retrieve and visualize the application's communication profile.

In our pilot investigations, we evaluated the ability of the *Extrae* [40] profiling library, developed by the Barcelona Supercomputing Center, to collect event traces of the MPI-parallelized Airhead Search application. For this purpose, we linked *Extrae* with our Java-enabled version of Open MPI and run the instrumented version of Airhead on the cluster. The traces collected as result of the execution were visualized with the Paraver [41] tool (see Figure 15), similar to any other MPI application in C or Fortran.

VII. Future Work

Our future work will concentrate on promoting both MPI standard and our ompiJava implementation to Semantic Web applications as well as improving the current realization of Java bindings in Open MPI.

With regard to promotion activities, we will be introducing our data-centric and MPI-based parallelization approach to further challenging data-intensive applications, such as Reasoning [42]. Regarding this application, there are highly successful MPI imlementations in C, e.g., the parallel RDFS graph closure materialization presented in [43], which are indicatively much more preferable over all the existing Java solutions in terms of performance. Our implementation will allow the developed MPI communication patterns to be integrated in existing Java-based codes, such as Jena [2] or Pellet [44], and thus drastically improve the competitiveness of the Semantic Web application based on such tools.

The development activities will mainly focus on extending the Java bindings to the full support of the MPI-3 specification. We will also aim at adding Java language-specific bindings into the MPI standard, as a reflection of the Semantic Web value in supercomputing.

The integration activities will concentrate on adapting the performance analysis tools to the specific of Java applications. Unfortunately, the existing performance analysis tools, such as Extrae discussed in the previous section, does not provide a deep insight in the intrinsic characteristics of the Java Virtual Machine, which however might be as important for the application performance optimization as the communication profile tailoring. For this purpose, the traditional performance analysis tools for the Java applications, such as ones provided by the Eclipse framework, must be extended with the communication profiling capabilities. Several EU-projects, such as JUNIPER, are already working in this direction.

VIII. Conclusion

High Performance Computing is a relatively new trend for the Semantic Web, which however has gained a tremendous popularity thanks to the recent advances in developing data-intensive applications.

The Message Passing Interface provides a very promising approach for developing parallel data-centric applications. Unlike its prominent alternatives, the MPI functionality is delivered on the library-level, and thus does not require any considerable development efforts to parallelize an existing serial application. Apart from a very flexible parallelization strategy, which foresees a number of parallelization options, either on the code, data, or both levels, but also delivers a very efficient communication mechanism, which takes full advantages of the modern supercomputing communication networks. Using MPI, the Semantic Web applications can enjoy the full backing of the high performance computing architectures. We would like to point out, that the current work is in no case an attempt to undermine the value of data-centric parallel implementations (like Hadoop), nor it is a replacement for any current data processing infrastructures. However many of the current parallel data processing systems can benefit from adopting MPI and ompiJava offers a set of good tools for this.

We introduced a new implementation of Java bindings for MPI that is integrated in one of the most popular open source MPI-2 libraries - Open MPI. The integration allowed us to deliver a unique software environment for flexible development and execution of parallel MPI applications, integrating the Open MPI framework's capabilities, such as portability and usability, with those of mpiJava, such as an extensive set of Java-based API for MPI communication. We evaluated our implementation for Random Indexing, which is one of the most challenging Semantic Web applications in terms of the computation demands currently. The evaluation has confirmed our initial considerations about the high efficiency of MPI for parallelizing Java applications. In the following, we are going to investigate further capabilities of MPI for improving the performance of data-centric applications, in particular by means of MPI-IO (MPI extension to support efficient file input-output). We will also concentrate on promoting the MPI-based parallelization strategy to the other challenging and performance-demanding applications, such as Reasoning. We believe that our implementation of Java bindings of MPI will attract Semantic Web development community to increase the scale of both its serial and parallel

applications. The successful pilot application implementations done based on MPI, such as materialization of the finite RDFS closure presented in [43], offer a very promising outlook regarding the future perspectives of MPI in the Semantic Web domain.

ACKNOWLEDGMENT

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A QoS-Aware BPEL Framework for Service Selection and Composition Using QoS Properties

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***Abstract*—The promise of service oriented computing, and the availability of web services in particular, promote delivery of services and creation of new services composed of existing services – service components are assembled to achieve integrated computational goals. Business organizations strive to utilize the services and to provide new service solutions and they will need appropriate tools to achieve these goals. As web and internet based services grow into clouds, inter-dependency of services and their complexity increases tremendously. The cloud ontology depicts service layers from a high-level, such as Application and Software, to a low-level, such as Infrastructure and Platform. Each component resides at one layer can be useful to others as a service. It hints the amount of complexity resulting from not only horizontal but also vertical integrations in building and deploying a composite service. Our framework tackles the complexity of the selection and composition issues with additional qualitative information to the service descriptions using Business Process Execution Language (BPEL). Engineers can use BPEL to explore design options, and have the QoS properties analyzed for the design. QoS properties of each service are annotated with our extension to Web Service Description Language (WSDL). In this paper, we describe our framework and illustrate its application to one QoS property, performance. We translate BPEL orchestration and choreography into appropriate queuing networks, and analyze the resulting model to obtain the performance properties of the composed service. Our framework is also designed to support utilizations of other QoS extensions of WSDL, adaptable business logic languages, and composition models for other QoS properties.**

***Keywords*—WSDL; WS-BPEL; Quality of Services; Non-functional Properties; Service Composition.**

I. INTRODUCTION

Service oriented architecture (SOA) is a flexible and scalable design methodology to seamlessly integrate and cooperate services in distributed software and systems. As more services are on the web and in the cloud, it becomes easier to create customized services dynamically by composing existing services and meet the service requirements. The framework we proposed serves the purposes [1]. Before invoking a service, a service requester has to query the functionality as well as the interaction protocols defined to access the service. Web Service Description Language (WSDL) [2] is a widely accepted standard from World Wide Web Consortium (W3C) for describing functionality of web services. The Universal Description, Discovery and Integration (UDDI) registry serves as a repository for the services with WSDL descriptions. Users can query the UDDI and find services meeting their needs since the functionality of the services can be obtained from their WSDL specifications [3].

Once the services are selected, interactions among the services are achieved using messaging protocol defined in WSDL. Even with ever increasing number of services, it may still not be possible to find the ”right” service, and in such cases, one has to either create a new service from scratch, or compose the service using existing services. Tools and frameworks are becoming available to aid in the dynamic composition of services [4], [5], [6], [7], [8]. Another issue that needs to be addressed is related to selecting the appropriate services that takes part in a composition, particularly when multiple services with the same functionality are available. In such cases, non-functional or Quality of Service (QoS) properties, such as performance, security, reliability become the delimiters [9], [10], [11], [12].

While standard WSDL describes the functionality of a service, it does not specify QoS or non-functional properties. In the previous work [1], we augmented the WSDL to permit specification of non-functional properties of a service. The additional information can help distinguish between services with the same functionality, and these properties can be used while composing new services to ascertain the QoS properties of the composed service.

Enterprise software systems or cloud computing often use business logic to refine their design and regulate the behavior of services according to business processes [13]. Business Process Execution Language (BPEL) has become the standard for describing the architecture of a service process [14]. It contains control constructs for the orchestration of component services in a workflow style. While tools and frameworks are available to use BPEL orchestrations in composing services, they are not suitable to evaluate the QoS properties of specific orchestrations [15], [16]. In this paper, we expand our framework to adapt the notion of BPEL to describe QoS-aware services for their selection and composition. We argue that based on our previous QoS-extension framework, BPEL is compatible for use of QoS extensions. The expansion is also backward compatible with the SOA in general and web services in particular. It is suitable for the incorporation of any tools that facilitate QoS extensions and models for analyzing QoS properties. We illustrate how to create queuing models

for various BPEL orchestration logic compositions. In the case study, we also demonstrate our framework for composing performance properties using stochastic models, such as the Layered Queueing Network (LQN) model.

The main contribution of our work is the framework that permits the description of QoS properties with services (using our QoS extensions to WSDL, or other suitable QoS extensions), reasonable composition processes of these services, and the generation of models for deriving QoS properties of composed services that use BPEL. While we focus on stochastic models, our framework can also be used to incorporate models for reliability, availability, as well as security, provided tools for deriving these properties for composed services from properties of component services are available.

The rest of the paper is organized as follows. Section II describes our QoS-extension framework and its suitability for use with BPEL. Section III gives details of BPEL service composition approaches. Section IV presents the rules for translating BPEL logic constructs into queuing network models for use by the Layered Queuing Network (LQN). Section V illustrates our framework with a case study. Section VI describes research that is closely related to ours. Finally, Section VII contains conclusions about our work and what we propose to do in the near future.

II. QoS-aware Framework in SOA

In this section, we present the QoS-aware framework in the SOA environment which is an extension to our previous work [1]. We first describe essential components of the framework, and its operational processes. Then, we consider the quality awareness extension to the business processes, specifically using WS-BPEL [17] to enable the performance evaluation result in service design, selection, and composition which include operational logic choices.

A. Framework Description

In our previous work, we extended WSDL to permit specification of non-functional property elements with services. Each web service can optionally describe QoS properties along with functional properties, in order to distinguish itself from other services providing similar functionality. QoS properties can include performance, reliability, security or other quality metrics. The framework is compatible with traditional SOA for either standard or quality-aware service publication, selection and interaction. The infrastructure of the framework augments the SOA with three elements:

- QoS-Aware WSDL Extension (QoS_WSDL): These are new WSDL elements for specifying QoS properties with services.
- Ontological QoS Modeling (QoS_Ontology): QoS properties and categories are classified by our ontology model allowing different classes of QoS properties and relationships among these categories.
- Testing and Composition QoS Modeling (QoS_TestCompose): QoS properties can be used for selecting services and evaluating QoS properties of composed services using component properties. The composition properties can be evaluated based on different ontological classes and relationships.

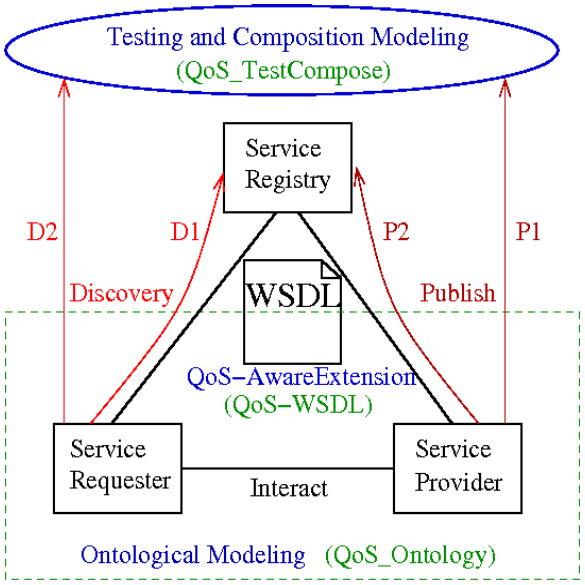

Figure. 1. QoS-Aware Service Oriented Architecture Modeling.

The QoS-aware framework for SOA is depicted in Figure 1. For a QoS-aware service to work, QoS_WSDL has to be prepared by instantiation of the QoS_Ontology model of the service. The value of the QoS properties can be obtained by using QoS-TestCompose as a testbed for analytical modeling or testing (P1). Once the Service Provider equips the service with the QoS extension, the provider can register the service specification on the Service Registry (P2). A Service Requester can query the Service Registry to discover qualified candidates by examining both functional and non-functional properties (D1). Functional properties are interpreted by reading WSDL, while non-functional properties are referenced by the QoS extensions. In case multiple services are selected with the same functional properties, the requester can use QoS properties to differentiate between the services. The selected services can be used to create new composed services and the QoS properties of the new services be obtained using the QoS-TestCompose Modeling(D2).

For those services that have not used our QoS extensions, our framework uses conventional selection and composition processes (P2 and D1).

B. QoS-Aware Framework with WS-BPEL Extension

Using our previous work, we now extended the QoS-Aware framework to use business processes. We discern service declaration types with atomic and process descriptions. An atomic service (AS) is the one whose provider offers functionality with design details but implementations hidden. Access to the service is achieved with required message exchange pattern (MEP) and binding of ports as shown in WSDL. In other words, an atomic service is opaque and represents the standard web services. We illustrated service selection and compositions

with respect to service performance in [1]. However, at that time, we did not use any specific logic for the composition.

A process service (PS) is a service that facilitates collaborations between services controlled by business logic. A PS may be composed by multiple AS and/or PS. PSes can be nested. At the lowest layer of the hierarchy, a PS should only consist of ASes. We will show that both AS and PS can be modeled and analyzed in our QoS-aware framework.

There are many well-known business process modeling languages available to formally describe the interactions among different service components with business logic [18]. These languages rely on well-defined workflow formats. In some cases they use meta-data that can be used for management purposes. In this paper, we use WS-BPEL or BPEL for short, to demonstrate the service selection and composition capabilities of our framework.

In the web service context, BPEL can be treated as a layer on top of WSDL [19]. BPEL provides the description of behavior and interactions of a process instance with its partners and resources through Web Service interfaces. Both the process and its partners are exposed as WSDL services [17]. Furthermore, BPEL follows WSDL model of separation between abstract information, such as message and port type, and concrete information, such as binding and endpoint. The two use cases for modeling BPEL processes are abstract and executable. Abstract processes describe the protocol that specifies the message exchange between parties without revealing their underlining implementations. While abstract processes may hide some of the required operational details, executable processes are fully specified and can be executed. Both abstract and executable processes share all the BPEL constructs, except that the former has additional opaque mechanisms for hiding operational details [17].

To include a PS in our framework, we assume that WSDL descriptions for all services are available. WSDL files describe how to use services, while BPEL describe collaborations among the services or tasks. In accordance to our previous design of the framework, only concrete WSDL is relied upon in our QoS-aware framework. Quality of Services with concrete bindings provides more specific range of values, derived from actual tests or analyses. The service that is extended for use in our framework can be viewed as an AS with a concrete WSDL. Or an abstract AS can be included in our framework, provided the QoS properties are derived through a concrete binding (as shown by process P1 in Figure 1).

Now we consider if the assumptions can be applied to the cases of acquiring a PS in the framework. For an executable PS, it is natural to assume that the services involved in the PS have concrete WSDLs, since an executable process is assumed to be concrete. For an abstract PS to be included in the framework, it must first be transformed into an executable PS. The transformation is called Executable Completion [17] in the web services context of WS-BPEL. The main algorithm of the transformation and related issues concerning QoS properties will be addressed in later sections.

With the adaptation of PS into the framework, we now consider the process of publishing and discovery operations for processes. Once again, an executable PS can be observed as services with concrete WSDL in the framework. To publish a PS service, it applies the same process P1 and P2, shown in Figure 1; for service registration of ASes, additional service meta data is added to the QoS_Ontology compartment for describing management related information. Since the framework differentiates a PS from an AS, the ontology model notes the service identification and service type classification when a service is instantiated. The additional information includes identification of a PS, the business process structure, and its sub-components. Note that the additional information of a PS is stored in the framework and is independent of the data minted in a Service Register of the SOA triangle. To discover a PS service, it makes no difference as to discovering any AS with QoS annotations in its registered WSDL (D1). Re-discovery of a PS service is required to first discover its sub-services as ASes, and submit the business process to QoS_TestCompose for updating QoS values (D2).

Although only concrete AS and executable PS are allowed in the framework, abstract processes can still be included. An abstract process can be viewed as embedding multiple use cases. The use cases are differentiated by their usage profiles. From the abstract processes, one can analyze the profiles to obtain specific values for QoS properties of the processes. To this end, we suggest that records of abstract processes be kept so as to facilitate QoS-aware compositions using different business process operations. We will discuss how PSes can be used in our framework in Section III.

III. Service Compositions with WS-BPEL in the QoS-Aware Framework

SOA enables a flexible and adaptable web service discovery and service composition. To allow for selection and composition based on QoS properties within our framework, we need to devise processes to guide QoS-aware business process selection and compositions. Since WS-BPEL is an established standard to describe business processes in the web services context, we will use BPEL to describe business processes in our framework.

Orchestration and choreography are two aspects of creating businesses from composite web services [19]. Orchestration refers to an executable process that interacts with internal and external web services. Since the executable process may include business logic and task execution order, it represents the control flow among the participating services. On the other hand, choreography refers to the interactions (or data flow) among participants who cooperate to achieve the objectives of the composed services. Choreography coordinates message exchanges occurring among services. For our purpose, we adapted BPEL4Chor [20], an extension of BPEL to address service composition, as the choreography framework. Engineers can use the language and available tools to readily model service interactions. We will show how this BPEL choreography can be used within our QoS-aware service composition framework.

The following subsections include discussions of the applicability of quality awareness to both orchestration and choreography compositions, and their operational processes.

Note that the focus of the service composition here concerns non-functional properties while assuming the functional semantics in the selection and composition has already been completed. We use the term service candidates to refer to the services already selected for composition based on functional requirements.

Our framework is designed to permit the use of many different approaches for specifying QoS properties, provided appropriate tools for selecting services meeting specific non-functional properties are also available.

A. Business Process Service Orchestration

A service orchestration is to organize the sub-services of a PS, and the message exchange with other services to achieve its service purposes. The PSes considered here are executable with their sub-services are also executable. Since the PS and its component services are all executable, they are eligible to apply the QoS extension when registering the service in the framework. Service composition from the perspective of orchestration involves sub-services selection. The PS selection for orchestration comes down to two scenarios: a fixed process organization, and process candidates of the same functionality with alternative design.

A PS may consist of m sub-services whose organization is based on the business process logic and how the tasks are ordered. Candidates for the m component sub-services are selected based on both functional and non-functional (QoS) properties. Since candidate services are assumed to use QoS extended WSDL, QoS references can be obtained for services and appropriate service components can be selected based on QoS properties.

In the case of multiple candidates of the same services with alternative business processes, they can be further classified as fixed or non-fixed sub-services. If the sub-services are fixed, the whole PS can be treated as AS. Then, the service selection only involves comparing the QoS values of the targeted non-functional attributes.

If the sub-services can be changed dynamically, each of the process candidates may be evaluated using multiple use cases. Each use case that belongs to a process candidate must be re-discovered for its QoS values. The result of QoS criteria for each candidate can be obtained, which can be used to match the requirements in order to make the decision.

B. Business Process Service Choreography

As stated perviously, choreography describes the interaction protocols (or data flows) among component services of a business process. While orchestration utilizes executable processes for modeling, choreography uses abstract process to describe the collaboration among service partners.

Since our QoS-aware framework requires concrete services with binding so that non-functional properties can be measured, the abstract nature of choreography in describing service interactions is not a direct fit for our framework. Thus, we need to extend the abstract interactions with appropriate concrete annotations of QoS attributes. Since our framework adapts BPEL as the descriptive language for business processes, we adapt BPEL4Chor [20] to model service choreography. We further annotate the interactions to make the choreography QoS-aware.

BPEL4Chor consists of three artifact types:

- Participant behavior description (PBD): It defines control flow dependencies between activities. It uses the Abstract Process Profile to describe requirements on the behavior of a participant. The profile inherits from Abstract Process Profile for Observable Behavior specified in BPEL, with the addition of identifying activities with unique identifiers. The PBD is essentially an abstract process with the additional attributes kept in the profile.
- Participant topology: It defines the collaboration structure of participant types, participants, and message links. The topology describes the communication structure of the service interactions among participants.
- Participant grounding: It defines the actual configuration of the choreography, and shows the connections to the concrete WSDL of the service participants. For each message link defined in the participant topology, a port type and its operation is specified. After the grounding, every PBD of the service can be transformed to an executable BPEL process based on their profiles.

An initial high level mapping from the modules of BPEL4Chor to our framework is straightforward. Although our framework requires concrete service data, abstract process is included in the framework. And, it is feasible to use abstract processes during the composition process before the new grounding of composition is admitted in the framework. The processes of adapting the composition to our QoS framework are presented below. We will refer to the processes shown in Figure 1 in our discussions below.

- From BPEL4Chor to QoS-Aware Extension
  The main product of a service choreography is an executable process. The new service can be included in the QoS-extension framework by first submitting to the QoS_TestComposite for QoS evaluation (D2). Corresponding process data is established with additional specific records for a choreography including PBD for all the participants and the composition topology. Recording a PBD is compatible with storing an abstract process, which is supported in the QoS-Aware extension.
- From QoS-Aware Extension to BPEL4Chor
  The main activity of BPEL4Chor is to identify a set of service participants to create a new service. The process involves selecting the service participants, extracting the PDB, and applying BPEL4Chor processes to compose the new service. The participants are restricted to only PSes since we have to identify the names of the operations. The QoS-aware framework facilitates the selection process by providing QoS values during discovery (D1). The selection process is similar to the selection process of a PS as introduced in Section III-A. Once we select the participants for composition, we will need the PDB for each participant. Since each participant selected is executable PS, there always exits one and

only one abstract PS in the framework that belongs to the PS. Transforming a PS to a PDB is straightforward with adding the unique name to the message exchange operations. With the named message links, practitioners then put together the required participant topology with the design. The grounding information for each linked operation is already available with an executable PS. Then BPEL4Chor composition process is complete, and the new composite service is created. To accommodate the created PS in the framework, the same processes mentioned in Section II-B is followed.

IV. From WS-BPEL to LQN

In this section, we explain the QoS_TestCompose module in our framework to illustrate how QoS properties of services that are composed using BPEL are calculated. Modeling non-functional properties for services and their composition is not always straightforward, since combining QoS properties of different services are based on underlying mathematical models. For example, given a process with the service components executed in sequential order, one may assume that the response time of the combined process is the sum of the response times of the component services. However, this will not be accurate because combining performance properties rely on stochastic processes. In other words, for obtaining performance attributes of a composed process we must use stochastic models. In our case, we use the layered queueing network (LQN) for modeling performance. However, other stochastic models and tools can be used to compute QoS properties of processes using BPEL.

The following subsections give a brief introduction to the essential elements of BPEL and LQN. Then we derive the transformation rules for mapping from BPEL compositions to models in LQN, and discuss how LQN can be used to compute performance attributes.

A. WS-BPEL constructs

WS-BPEL [17] is a standard language intended to describe business processes for web services. The idea is to represent collaborations among services or tasks described in the WSDL language. As a descriptive language using XML format to describe workflow of business process, BPEL consists of two types of activities: Basic and Structured.

Basic activities are atomic activities mainly describing service interactions. They include <receive> and <reply> , which represent waiting for a message, and response to a message respectively; <invoke> enables a web service operations offered by a service partner. The invocation enables either a one-way or request-response message exchanges. Other basic activities include <assign> to update a value of a variable, <exit> to end the process, <wait> to delay the execution, and <empty> to express no-op operation. Still others include <scope> , <throw> ,<compensate> , and <validate> that handle from the execution scopes to fault handling operations. New activity creation is also possible through <extensionActivity>.

Structured activities control the process order of activities. They can be nested in other structured activities as well. The constructs include <sequence> and <flow> to express sequential and parallel order of the enclosed tasks. The control flow constructs include <if> that sets a boolean condition for activities, <while> and <repeatUntil> that iterate through their enclosed processes until the condition becomes false; <forEach> controls the number of times the set of enclosed tasks can repeat, either running in sequential or parallel, while <pick> chooses among tasks to be executed depending on the occurrence of the event.

B. Layered Queueing Networks

Layered queueing network [21] is an extended queueing model with the layered structure representing servers at higher levels making requests to servers at lower levels. Each task in the model involves sharing and consuming processing resources. An entry of a task can be modeled as the service operation stub receiving requests and responding with a reply to higher level systems. The entry can be further refined with activities representing the workflow of its sub-components which are organized with precedence operators, such as fork and join. For each task and activities, there are resource requirements specified, as service demand in time. The interactions between different servers and their tasks can be modeled with phases representing message receipt and response in different time slots. The nature of the communication can be defined as synchronous and asynchronous, which model blocking and non-blocking interactions respectively.

As modelers put together the service architecture and information needed for the system integration, a queueing network is created. The system modeling can be subjected to either open or close networks during performance analysis. LQN comes with an analytic solver (lqns) and a simulator (lqsim) to generate the performance indexes such as response time, utilization, and throughput.

LQN models can also be expressed in XML format. A further analysis to explore the design space with different combination of system configuration is also possible with its LQX tool. LQX is a general purpose programming language used for the control of input parameters to the LQN solver system. The language allows a user to put together a wide range of different set of input parameters, and solve the model accordingly.

C. Transition Rules from BPEL to LQN

A structure of business process in BPEL largely consists of activities and their corresponding fault handlers, in addition to variables, correlation sets, and partner links. Since performance evaluation of the business processes is the focus here, the derivation of the transformation rules only focuse on the process activities. For the performance analysis purpose, the activities in the event and fault handlers can follow the same set of rules, and integrated with the activities in the main processes.

The main process activities usually begins with a list of sequential activities. The behavior of the activities, both basic and structured, are described by the control constructs. The main task of the transformation is to maintain the same

TABLE I. MAPPING BPEL BASIC ACTIVITY TO LQN ELEMENTS.

BPEL Basic Activity	LQN	Description
<receive>	Pre-precedence (or a join-list)	Getting a message from a service partner.
<reply>	Request (send-no-reply) : direct reply Request (forwarded) : indirect reply	Sending a message to a service partner.
<invoke>	Request (send-no-reply) : one-way Request (rendezvous) :request-response	Invocation of a service offered by a service partner. It can be one-way or request-response interactions.
<wait>	Activity with a think time	A delay for a timer.
<empty>	Activity with zero service time	A no-op holder which does nothing.
<exit>	N/A	Immediate termination
<assign>	N/A	Assign a value to a variable.
<validate>	N/A	Validate the value of variable defined in WSDL.
<throw>	N/A	Generate a fault from business process. Fault handler needs to be specifically modeled.
<rethrow>	N/A	Regenerate a fault from fault handler. Fault handler needs to be specifically modeled.
<compensate>	N/A	Compensate actions can not be completed. Fault handler needs to be specifically modeled.
<compensateScope>	N/A	Compensate actions can not be completed in a specified scope. Fault handler needs to be specifically modeled.

TABLE II. MAPPING BPEL STRUCTURED ACTIVITY TO LQN ELEMENTS.

BPEL Structure Activity	LQN	Description
<sequence>	Precedence: Sequence	A list of service activities executed in the specific order.
<flow>	Precedence: And-Fork & And-Join	A bag of service activities executed in concurrent and finished in synchronization.
<if>	N/A [Use Or-Fork & Or-Join to emulate the condition with a probability 1 or 0.]	Take different actions depends on the Boolean condition.
<pick>	N/A [Use Or-Fork & Or-Join to emulate the condition with a probability p.]	Activity is chosen depending on the kind of message or timeout events.
<while>	N/A [Precedence: Loop to emulate the number of iteration.]	Iteration on the Boolean condition evaluated to true.
<repeatUntil>	N/A [Precedence: Loop to emulate the number of iteration.]	Iteration will stop on the Boolean condition evaluated to true.
<forEach>	N/A [Precedence:Loop to emulate the number of iteration]	Repeat activities multiple times, activities in each iteration can be modeled with <sequence>or <flow>

activity orders as in BPEL when creating the LQN model. For basic activities, the order of the behavior relates to mainly communication protocols. For structured activities, the order can be focused on the mapping of business logic.

The order of the control flow in the transformation is realized using precedence of activity connections in LQN tasks. The precedence can be sub-classed into Join and Fork for modeling synchronization and concurrency of activities. To connect one activity to another, the source activity connects to a pre-precedence (or Join). A pre-precedence in turn connects to a post-precedence (or Fork), and then to the destination activity. More details on precedence types can be found in the LQN User manual [21].

Service requests in LQN can be of three types: rendezvous, send-no-reply, and forwarded. Rendezvous is a blocking synchronous request, while the send-no-reply is an asynchronous request. Forwarded requests are redirected to a subsequent server, which may forward the requests again, or reply to the original client. In the translation, we consider the message exchange pattern to match either blocking or non-blocking, and either one-way or two-way for service invocation.

The summary of mapping of basic constructs are listed in Table I, while the mapping of structured constructs are listed in Table II. For each mapping entry, a brief description is included. For those elements that have no direct LQN semantic counterparts, we use (N/A) with explanation. Since the focus of the transformation is on performance analysis, the corresponding performance models for fault handling activities should be obtained by following the error handling mechanisms designated in the processes. The handling processes can then be subjected to the transformation rules to obtain appropriate performance models. The part of fault handling of the transformation and its performance evaluation is not included in this paper.

D. Data Dependency in Transformation

There is no direct equivalent LQN transformation for the BPEL conditional construct such as if-else. However, an Or-Fork representing a branching point with a given probability p to a selected process path can emulate the semantics of if construct. The probability is set to 1.0 for the if-clause, if the condition should be evaluated to true. On the other hand, the else-clause will be taken with the probability of the if-clause set to zero, if the condition should be evaluated to false. The transformation from <if> in BPEL to LQN can thus be expressed using the semantic of Or-Fork and Or-Join with appropriate probability p. The probability depends on the variables involved in the condition. The frequency of which path is taken depends on the statistical or empirical evaluations. Each sample represents a specific service system configuration that is invoked in a specific use case.

The conditional variables can be related to either service workload or the frequency of the variable assignments. For example, in a sorting algorithm, workload as the size of input list can impact the service time. The business process may consider splitting the input into smaller sizes, and merging the result later. The condition may also depend on a multivariate function when multiple outcomes are possible. Data profiling and other empirical evaluations can be used to assign probability values with each outcome [22]. Similar approach can be applied to <pick> where the Boolean condition becomes the frequency of the message variable. The sum of the probabilities of each case in the Or-Fork is to be 1.

For the loop control statements, such as <while> and <repeatUntil> , the Boolean condition should be analyzed using the number of times the iteration will be executed. The counterpart in the LQN is a loop (for a service) which is executed desired number of times. <forEach> is similar to these iterative controls with the addition of specifying the execution type, in sequence or parallel, of activities in the loop clause.

V. Case Studies

A. Facial Detection and Recognition Example

A building security monitoring system, which uses facial detection and recognition technique, is used as the example to demonstrate how to use our framework. The purpose of the system is to detect intruders, and raise an alarm when intruders are detected, as well as recognizing the intruders using facial recognition software to compare with existing database of stored images.

A general computation of facial detection and recognition is split into multiple tasks – signal processing, image analysis of machine learning algorithms and processes. In our example, the service is divided into three modules: Facial Detection (FD), Image Converter (IC), and Facial Recognition (FR).

- FD receives video frame input and detects if there are faces appearing in the image. If no face is detected, no action will be taken. However, if faces are detected, alarm messages will be sent and image frame will be the output for further processing.
- IC receives image frames with faces detected, and prepare the normalized file formats for each face. The output consists of the images that can be compared against images stored in the databases.
- FR receives the normalized face images as input, and sets the connections to databases containing images of faces for identification. Once there is a match, a report is sent to human operators with information about the persons identified.

The three modules will be considered as web services, and our goal is to create a new web service that will combine these component services, using sequential composition in the order of FD, IC, and FR. The process sequence of the three services in BPEL is shown in Listing 1, Listing 2, and Listing 3 respectively.

Each BPEL is transformed into a LQN model for analysis. To submit the service into the framework, the LQN model is

Listing 1. Facial Detection BPEL (FD).

```
<sequence>
  <opaqueActivity name="DetectFacialProcess" />
  <if>
    <condition opaque="yes" />
      <flow>
        <invoke wsu:id="SubmitICReq"/>
        <opaqueActivity name="SubmitAlarm"/>
      </flow>
  <else>
      <opaqueActivity name="SubmitNoResult" />
  </else>
  </if>
</sequence>
```

Listing 2. Image Converter BPEL (IC).

```
<sequence>
  <receive wsu:id="ReceiveICReq" createInstance="yes
      " />
  <if>
    <opaqueActivity name="SplitImageFrame"/>
    <forEach name="splitFile" wsu:id="
        NormalizeFrameSize" parallel="yes">
      <startCounterValue>1</startCounterValue>
      <finalCounterValue>2</finalCounterValue>
      <scope>
        <opaqueActivity name="NormalizeMultipleImage
            "/>
      </scope>
    </forEach>
  <else>
    <opaqueActivity name="NormalizeNormalImage"/>
  </else>
  </if>
  <invoke wsd:id="SubmitFRReq"/>
</sequence>
```

Listing 3. Facial Recognition BPEL (FR).

```
<sequence>
  <receive wsu:id="ReceiveFRReq" createInstance="yes
      "/>
  <forEach wsu:id="queryDatabase" parallel="yes"
      opaque="yes">
    <startCounterValue>1</startCounterValue>
    <finalCounterValue>3</finalCounterValue>
    <scope>
      <opaqueActivity wsu:id="
          FacialRecognitionProcess" />
    </scope>
  </forEach>
</sequence>
```

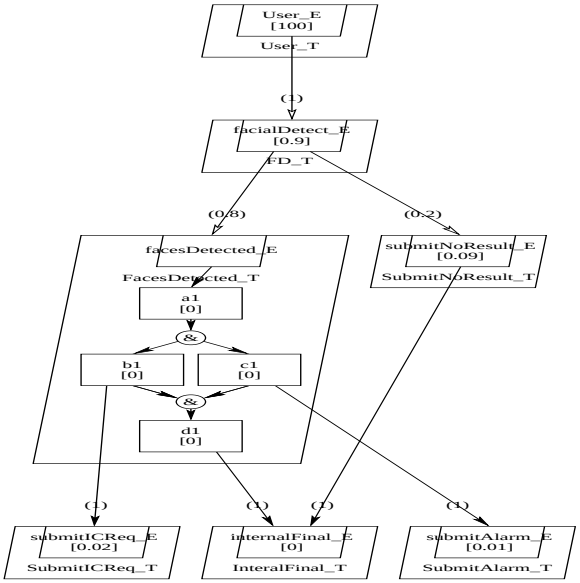

Figure. 2. Facial Detection LQN Model.

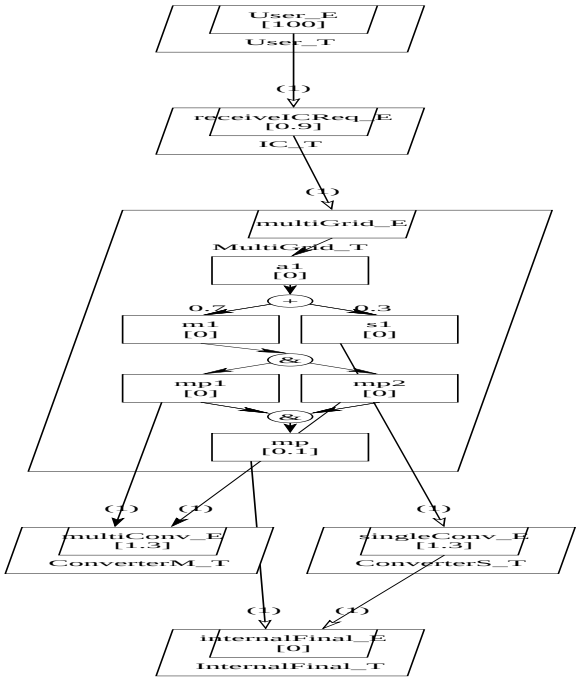

Figure. 3. Image Converter LQN Model.

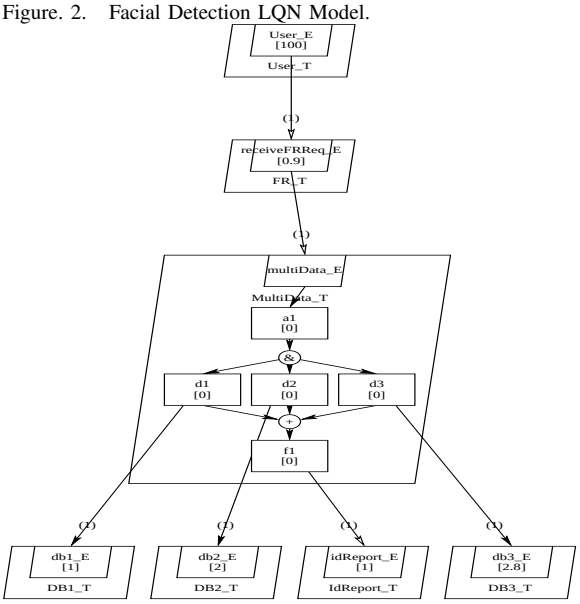

Figure. 4. Facial Recognition LQN Model.

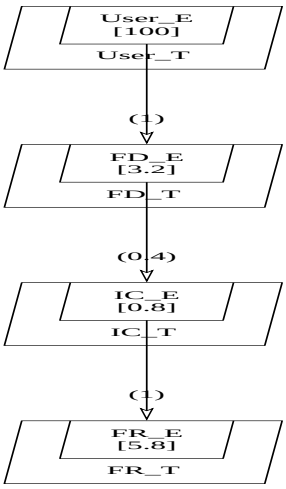

Figure. 5. FD IC FR Sequential Composition LQN Model.

analyzed with the result of the performance indexes obtained from QoS values of individual services. The transformation of the LQN models are shown in Figure 2, Figure 3, and Figure 4 respectively.

The entire composition for the building security application can be sought in different ways depending on the approaches the engineers use. We demonstrate two example scenarios to show how the framework facilitates compositions. In a simplified scenario, all services can be considered as atomic services, while in a more flexible scenario, the composition utilizes the workflow processes to leverage the service choices in order to gain a better performance.

To compose the the system in the simplest case, service discovery process (D1, shown in Figure 1) is applied. For FD, IC, and FR, QoS values such as service execution time are obtained from their QoS extended WSDL files. A simple version of the sequential BPEL expression is created in Listing 4.

The transformation steps along with the quality attributes obtained from the WSDL extension of each services, together create the LQN model of the composition. The LQN model

Listing 4. Atomic Composition of FD, IC, and FR.

```
<sequence>
  <opaqueActivity name="FD_Process" />
  <opaqueActivity name="IC_Process" />
  <opaqueActivity name="FR_Process" />
</sequence>
```

Listing 5. Choreography Topology for Process Service Composition of FD

```
<?xml version="1.0" encoding="UTF-8"?>
<topology name="
     example_facialDetectRecognizetopology"
     targetNamespace="http://agentmode.com/
     choreography/facial/topology"
   xmlns:fd="http://agentmode.com/choreography/facial
       /detecter"
   xmlns:ic="http://agentmode.com/choreography/facial
       /converter"
   xmlns:fr="http://agentmode.com/choreography/facial
       /recognizer"
   xmlns:xsi="http://www.w3.org/2001/XMLSchema-
       instance">

  <participantTypes>
    <participantType name="FD"
        participantBehaviorDescription="fd:detecter"
         />
    <participantType name="IC"
        participantBehaviorDescription="ic:converter
        " />
    <participantType name="FR"
        participantBehaviorDescription="
        fr:recognizer" />
  </participantTypes>

  <participants>
    <participant name="detecter" type="FD" selects="
        converter" />
    <participant name="converter" type="IC" selects=
        "recognizer" />
    <participant name="recognizer" type="FR" />
  </participants>

  <messageLinks>
    <messageLink name="icRequest" sender="detecter"
        sendActivity="SubmitICReq" receiver="
        converter" receiveActivity="ReceiveICReq"
        messageName="icRequest" />
    <messageLink name="frRequest" sender="converter"
         sendActivity="SubmitFRReq" receiver="
        recognizer" receiveActivity="ReceiveFRReq"
        messageName="frRequest" />
  </messageLinks>
</topology>
```

is depicted in Figure 5. The new composition along with the performance indexes resulting from analyzing LQN models can be published using service publish process (P2, shown in Figure 1).

A more flexible way to consider the composition is to observe the web services components as processes. We first retrieve web services along with their processes. Applying BPEL4Chor processes, a topology file is created to build the service interactions. A snapshot of the topology configuration is shown in Listing 5. The result of the composition along with the derived BPEL and corresponding LQN model is shown in Figure 6.

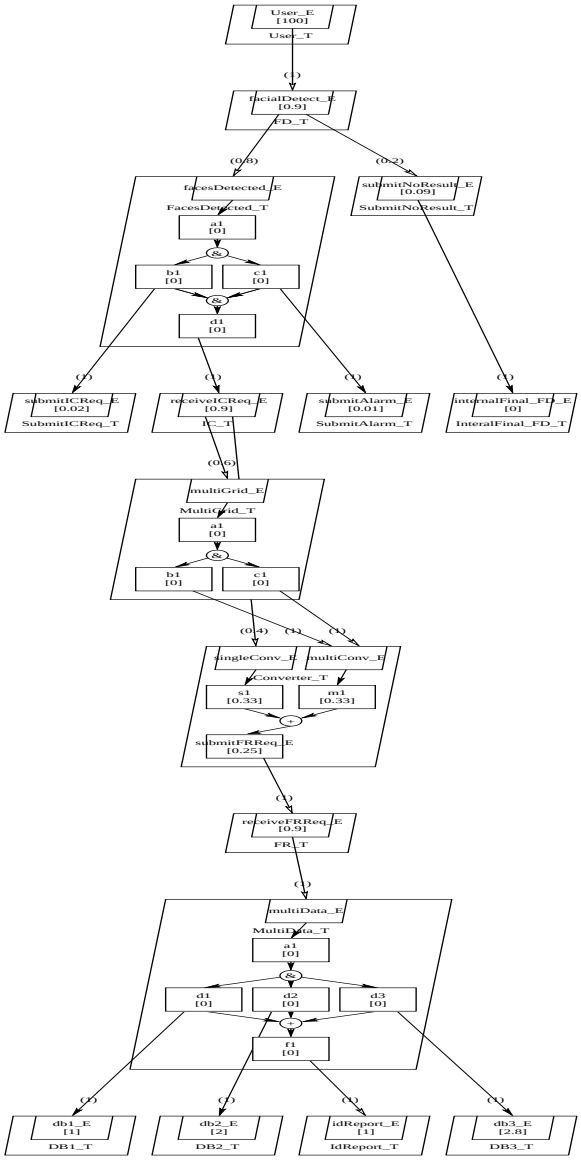

Figure. 6. FD IC FR Choreography Model.

B. Data Dependency Considerations

In the Image Converter (IC) BPEL process, the if-clause distinguishes between single and multiple faces that need to converted, since converting multiple faces increases workload on the processing systems. If the image contains multiple faces, it may be desirable to use multiple processes executing concurrently to improve the speed of IC process. Here we model two identical servers executing the same job by splitting the conversion tasks into two assuming two faces are detected. Each server, which either processes the single task or two tasks, has the same execution performance and same capacity. The service time depends on the probabilities associated with detecting one or two faces. In this example, we vary the if-clause probability from 0.01 to 0.99, and estimate the effective

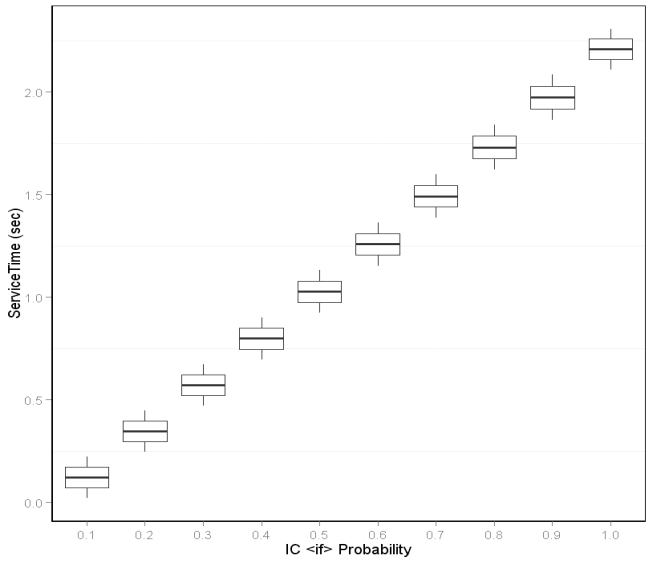

Figure. 7. IC Service Execution Time vs if-clause Probability.

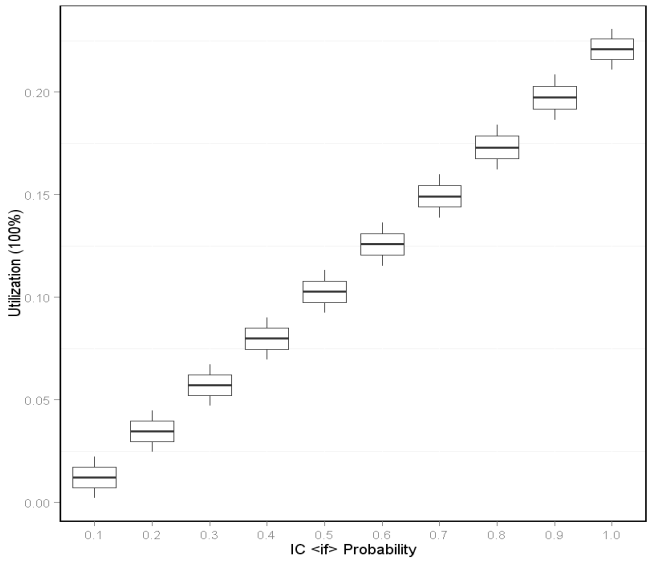

Figure. 8. IC Utilization vs if-clause Probability.

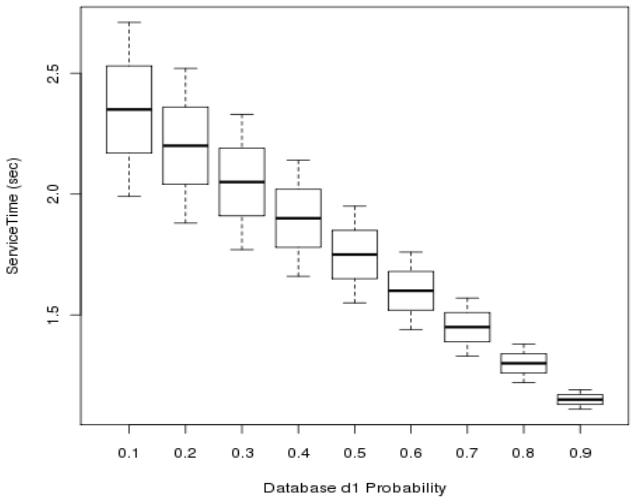

Figure. 9. FR Service Execution Time vs Database Probability.

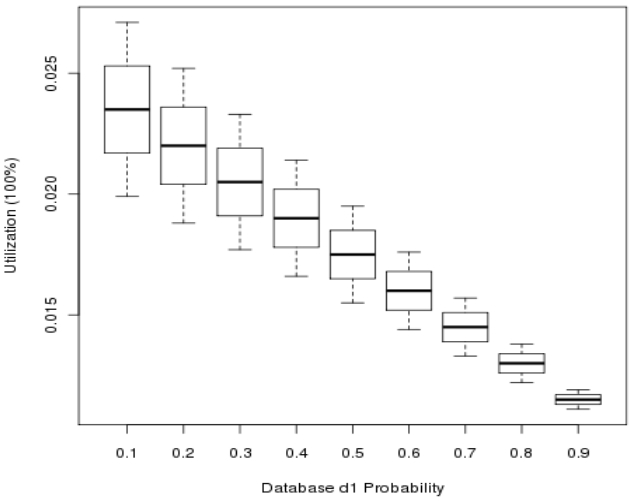

Figure. 10. FR Utilization vs Database Probability.

performance. Figure 7 shows the execution time ranges while the probability with the if-clause is changed. Figure 8 shows the utilization of the image conversion servers.

Similar method is also be used with Facial Recognition (FR) BPEL process, using either a single or multiple tasks to compare the faces with those in the database. To further speedup the process, the database may be organized into frequently accessed faces and less frequently accessed faces. In this example, we separated the facial detabases into three separate databases, d1, d2, and d3. Rather than concurrently querying all three databases, modelers can select just one representative database based on the likelihood of finding a match. Figure 9 shows the execution time of the FR service while adjusting the probability of success with d1. Figure 10 shows the utilization versus the probabilities.

C. Performance Space Considerations

Various design topologies that yield different service performances can also be considered. In this example, system structure and server capacity are explored. Consider the IC example for multiple image conversion. Instead of running two converters concurrently, suppose we want to explore the alternatives that execute them sequentially as a two-step

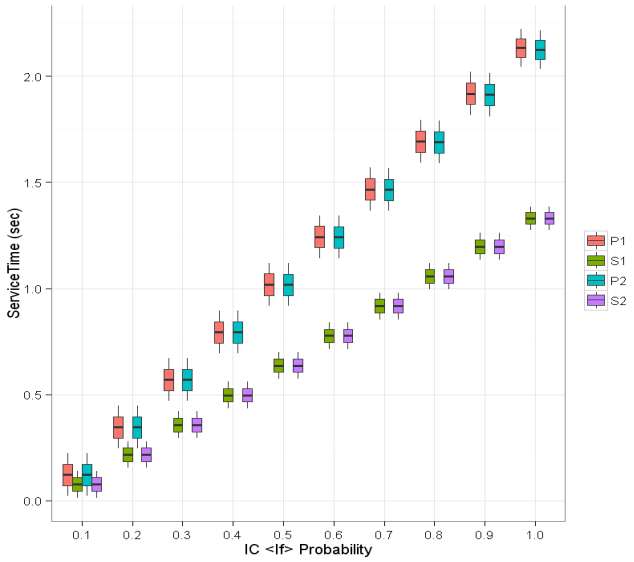

Figure. 11. IC Service Execution Time vs if-clause Probability on Service Design Alternatives.

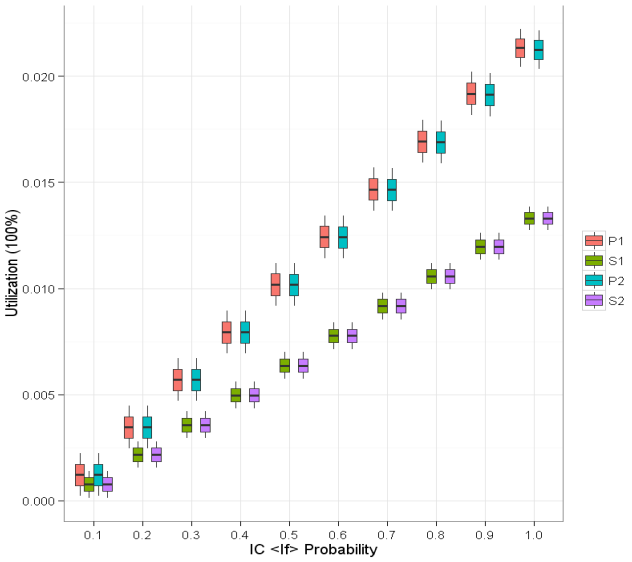

Figure. 12. IC Utilization vs if-clause Probability on Service Design Alternatives.

pipeline, where the execution time of each step is only one forth compared to the parallel ones. There are also options that the server can be equipped with single or multiple processors (e.g., multicore systems) to speed up the service. Together these options can be analyzed by the LQN. Figure 11 shows the service times of the converter compared to the previously shown split workflow; we use S to represent the sequential flow and P to represent parallel workflow and the suffix indicates the number of processors.

VI. Related Works

The promise of service oriented computing, and the availability of web services in particular, promote delivery of services and creation of new services composed of existing services [23] – service components are assembled to achieve integrated computational goals. Business organizations strive to utilize the services and provide new service solutions and they will need appropriate tools to achieve these goals [24]. As webs and internet based services grow into clouds, inter-dependency of services and their complexity increases tremendously. The cloud ontology suggested in [25] depicts service layers from a high-level, such as Application and Software, to a low-level, such as Infrastructure and Platform. Each component resides at one layer can be useful to others as a service. It hints the amount of complexity resulting from not only horizontal but also vertical integrations in building and deploying a composite service. Our framework tackles the complexity of the selection and composition issues with additional qualitative information to the service descriptions in BPEL. Engineers can use BPEL to explore design options, and have the QoS properties analyzed for the design. QoS properties of each service are annotated with our WSDL extension for future references.

There have been several works on QoS-awareness for BPEL services. In [26], a service broker offers composite service with multiple QoS classes to the users. The selection scheme optimizes aggregated QoS of incoming request flows using linear programming. In [27], business workflow is parsed into a tree structure, where heuristic algorithms are applied for selecting service candidates based on QoS properties. In [28], QoS is acquired by constructing activity graph and reasoning the dependencies among them for the QoS parameters, including response time and cost. A declarative approach is proposed in [29] by creating the policy-based language QoSL4BP to specify QoS constraints and logic over scopes of the orchestration. QoS planning, monitoring, and adaptation of the BPEL can be expressed to model the service behavior. An extension to BPEL for specifying QoS and non-functional requirements is proposed in [30]. The extension point is at the service invocation of a partner web service. Our framework is able to provide compatible SOA infrastructure to test on different approaches surveyed above and others, however, the foundation to address QoS properties for BPEL relies on the WSDL extension at the service level [1]. The benefit is that modeling business services to annotate QoS properties is compatible with standard WS-BPEL without the need to introduce other artifacts.

Performance evaluation on BPEL often involves analytical model construction by transforming the business logic into appropriate model logic. In [31] and [32], BPEL processes are translated into stochastic petri nets by a set of rules to model waiting queues and their performance distributions. In [33], a formalism for the SYNTHESys framework [34] is generated by the translation from BPEL to PerfBPEL models. The PerfBPEL serves as the performance annotation to the BPEL workflow, and a Markov chain for the model can be generated. Then multi-formalism modeling technique enables

the use of other tools for analysis. In [35], BPEL is annotated with a performance metadata for operations and resources. A queueing model can be derived from these annotations to generate the bounds of throughput and response times. While the translation is similar to ours, our framework uses an ontology for QoS data management, and use LQN to keep the original mapping of service architecture. In [36], support from abstract to executable processes for service orchestration is proposed according to three levels: needed functionality, expected QoS, and composition flow. Process realization, discovery, classification, and selection steps lead to the composition. The expected QoS is reasoned by a classification method to select services for composition. While our framework can also rank services using ontology models and plug in different selection filters, the QoS prediction for service composition is based on the result of modeling analysis.

A feature-completed Petri net semantic counterpart for BPEL has been established in [16]. As mapping from BPEL is easily obtained, Petri net can be subjected to formal model checking [37] and workflow performance analysis [38].

VII. Conclusion

In this paper, we described our framework for web service QoS-aware selection and composition of web services using BPEL. With the foundation of WSDL extension to annotate non-functional properties, web services can be selected based on both functional and non-functional (QoS) properties. We described the process for publishing and discovering services which meet requirements in the standard service oriented architecture. We show that services in BPEL description can be seamlessly accommodated in the framework. By adapting BPEL and BPEL4Chor for service composition, we reason about the feasibility of service orchestration and choreography in our framework. To illustrate the applicability of our framework to derive QoS properties of composed services, we use performance properties such as throughput, response times and utilization. To this end, we described transformation rules for converting BPEL into appropriate queuing networks which can be used by the LQN (Layered Queuing Network) tool that can compute throughput, utilization, and response times. We used a case study to demonstrate this process. Although we focused on performance in the paper, our framework can also be used to compute other QoS properties such as reliability, security, availability, with appropriate rules for converting BPEL logic into corresponding models and tools for obtaining QoS properties from these models.

VIII. Acknowledgements

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Supporting Test Code Generation with an Easy to Understand Business Rule Language

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***Abstract*—The paper addresses two fundamental problems in requirements engineering. First, the conflict between understandability for non-programmers and a semantically well-founded representation of business rules. Second, the verification of productive code against business rules in requirements documents. As a solution, a language to specify business rules that are close to natural language and at the same time formal enough to be processed by computers is introduced. A case study with 30 test persons indicates that the proposed language caters to a better understandability for domain experts. For more domain specific expressiveness, the language framework permits the definition of basic language statements. The language also defines business rules as atomic formulas, that are frequently used in practice. This kind of constraints is also called common constraints. Each atomic formula has a precise semantics by means of predicate or Interval Temporal Logic. The customization feature is demonstrated by an example from the logistics domain. Behavioral business rule statements are specified for this domain and automatically translated to an executable representation of Interval Temporal Logic. Subsequently, the verification of requirements by automated test generation is shown. Thus, our framework contributes to an integrated software development process by providing the mechanisms for a human and machine readable specification of business rules and for a direct reuse of such formalized business rules for test cases.**

Keywords*—*Requirements engineering; business rules; common constraints; natural language; testing; logic.

I. INTRODUCTION

In software development, different stakeholders with different knowledge and intention cooperate, typically domain experts and developers. Requirements engineers are acting as negotiators between these two worlds and prepare requirement specifications in a way that can be understood by both sides. Unstructured natural language in requirements documents does not ensure identical interpretations by different stakeholders, especially by domain experts and developers. In order to overcome the problem of divergence between specification and implementation we proposed *AtomsPro Rule Integration Language* (APRIL) [1] [2], a business rule language that is both, understandable enough to domain experts and translatable to executable representations. To raise the expressiveness of APRIL we have also defined a framework to add new language constructs.

By the introduction of APRIL, we propose a means to develop a formalized version of business rules specifications by precise semantics that support human- as well as machine-readability. The APRIL statements representing business rules are easy to design and can be customized by the construction of tailored statements, a feature, which we introduce via a novel combination of pattern building mechanisms. In this paper, we show how to utilize the framework for extending APRIL's expressiveness using atomic formulas that constitute the link between statements that are like natural language and formal frameworks. Moreover, we also present some common constraints that are incorporated as atomic formulas.

Formal specifications enhance the established software development process. As a general advantage, such specifications allow consistency checking of business rules, e.g., reveal conflicts or proof properties. The aspect we want to focus on in this work is based on the fact that in the established software development process, code and corresponding tests are developed based on the natural language specification. In order to reduce complexity of the development process, we support automated creation of tests based on formal APRIL statements representing business rules. With our method, human understandable formal specifications can be used to directly generate formal logical conditions and behavior specifications for testing. This approach shifts the creation of the test code from the developer to the requirements engineer, which helps to improve test-driven development projects [3] [4].

The paper is structured as follows: Section II gives an impression of the context and the facets of the work presented. Section III presents the framework for our language to describe business rules close to natural language. After laying down the fundamentals, we demonstrate in Section VII the transformation of example statements in our language into computer processable test code. In Section IV, we present the utilization of the extension mechanism to incorporate a set of frequently used constraints, known as common constraints, into APRIL. Section VII-B deals with usability aspect of APRIL, explored in a case study. After the discussion of related work (Section VIII), a conclusion will be drawn and future work will be presented (Section IX).

II. OVERVIEW

The APRIL framework can be embedded into standard software development processes. As an example, the seamless integration into the V-Model is shown in Figure 1. Aspects that will be detailed in this paper are highlighted in dark grey.

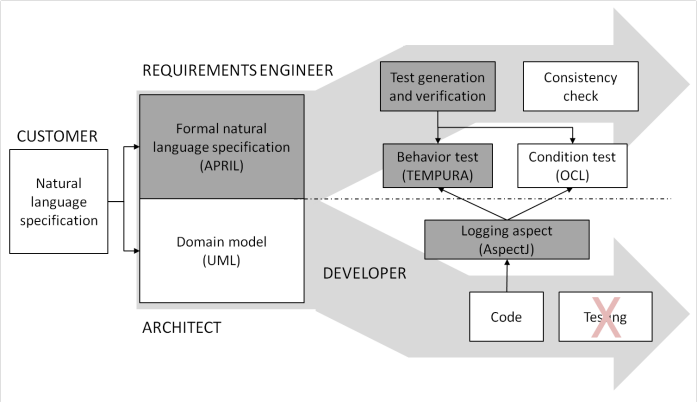

Fig. 1. Overview of the software development process using APRIL.

Next to the clear definition of business rules, our framework aims at supporting the generation of computer executable test code from formal specifications that are close to natural language and thus enable the verification of the productive code against the original user specification. In Section III, a detailed explanation of the substantial concepts of the APRIL language is given, exemplifying the formalization of business rules as APRIL statements in Section III-A. Section VII-B presents the results of a case study that shows that ARPIL is understandable even to untrained test persons. The specification of complex real-world business rules using mix-fix notation and decomposition into reusable sub-statements (APRIL-Definitions) is presented in Section III-B. Section III-C deals with support for customizing parts of the language using so-called atomic formulas. These are verbalized versions of operations on sets, predicate-logic formulas and special common constraints and provide a precise semantics for APRIL Definitions. In Section IV we present common constraints that are incorporated into APRIL using the extension mechanism to add atomic formulas. In practice, these frequently used constraints can make up a significant part of the overall constraints defined on a software system.

Tests based on APRIL statements can be generated to check conditions using invariants, pre- and post-conditions in the Object Constraint Language (OCL) [5] notation. Checking process behavior is done by the use of a subset of Interval Temporal Logic (ITL) called Tempura [6]. The rationale for applying our testing-framework is laid down in Section VII-A. Section VII-B presents the testing-framework by example, taking into account the significant concepts for defining a custom atomic formula for modeling a simple example-process and the relation to the semantic frameworks presented in Section VI. This section will also include a presentation of the automated test generation for behavior testing using Tempura. Due to space limitations, the detailed presentation of generating OCL-statements is omitted and can be reviewed in [2]. Some translation examples are shown alongside the introduction of the APRIL language.

After the discussion of related work (Section VIII), a conclusion will be drawn and future work will be sketched (Section IX).

III. The APRIL framework - Specifying business rules in formal natural language

Business rules are restrictions of certain object constellations and behaviors based on domain models [7]. Typically in software development, requirements engineers produce business rules in natural language and hand them to developers along with the respective domain models to enable the development of a software-system compliant to these input artifacts. Mostly, those natural language business rules are informal and suffer from ambiguity and imprecision. Therefore, we introduced APRIL, which is a language to specify business rules, close to natural language and such is easy to use. On the other hand, APRIL has a formal semantics, which is based on OCL and in consequence, an unambiguous description of business rules is possible.

A. Business Rules in APRIL

In general, the different types of business rules in the industrial practice are: Integrity Rules, Derivation Rules and Rules to describe behavior [8]. Despite the fact that there are fundamental intentional differences, these rule types have one aspect in common: The description of the semantics of parts of the real world into formal representations by means of logic. In APRIL, we use UML-class models [9] to formally represent business domain models. The reason is that the UML-class model is widely used for representing conceptual schemas and is easily understood by people. APRIL requires UML-class models as the domain of discourse to specify business rules as constraints, which are of the following types: **invariant, pre-, post-condition and behavioral rules**. Invariants describe allowed system states that must not be violated during any point in time. This is unlike the pre- and post-conditions, which have a restricted scope right before and after a transition. The fourth rule type describes behavior explicitly. Behavioral rules can describe operations lasting over multiple state transitions [7], which is not possible with a single pair of pre- and post-condition.

In Figure 2, a simple domain model of an order system, with the basic concepts Order, Customer Shipment, Vehicle and Product is shown as UML-class model. As an example of

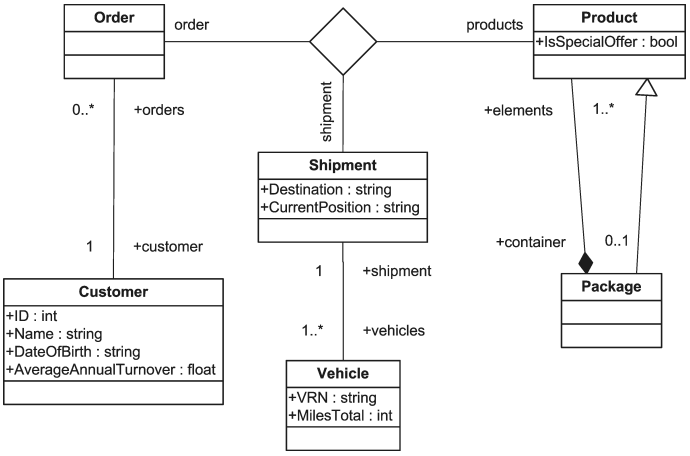

Fig. 2. UML-model of the example domain model.

APRIL usage on the class model, the corresponding statement for the invariant rule1 can be seen in Listing I.

```
1  Invariant rule1 concerns Customer:
2      A premium customer who buys a special offer must pay
3      0 EURO for the shipment of that order.
```

Listing I. TOP-LEVEL RULE, COMPOSED OF SEVERAL APRIL DEFINITIONS.

The header (line 1) of a rule contains its name *(rule1)* and the token after the keyword **concerns**, which represents the context set (represented by the class name *Customer*) of the business rule to which the formula after the colon applies. With respect to UML-models, the context in invariant rules is represented by a class name and by a qualified method name in the case of pre- and post-conditions respectively. The rule body (lines 2-3) contains the actual business rule. In order to use a natural language sentence in the needed formal way, a couple of definitions have to be installed, which are explained in Section III-B continuing this example. Moreover, a detailed specification of APRIL including default logic- and set- operators, is given in [2].

The mathematical representation of the rule can be expressed as predicate logic formula as follows.

$$\forall c \in \{\text{Customer}_{allInstances}\}\ (\text{isPremium}(c)) \implies$$
$$\exists p \in \{c.\text{orders.product}\}\ \text{isSpecialOffer}(p) \implies$$
$$\forall o \in \{c.\text{orders}\}\ \{\text{isSpecialOffer}(o.\text{product}) \wedge$$
$$\text{isFreeOfCharge}(o.\text{shipment})\})$$

B. APRIL-Definitions

APRIL Definitions are special mix-fix operators, which allow the intuitive construction of patterns that decompose large business rules into smaller, comprehensible and reusable sub-statements. Mix-fix is a particularly useful technique to form natural language statements [10]. Mix-fix operators allow to compose an operator's constants and placeholders in arbitrary order. The design of the APRIL-Definition's headers is based on sequences of static name parts and placeholders. Both static name parts and placeholders can be arbitrarily composed to express a business statement reflected as a natural language sentence pattern. This makes them particularly easy to construct for humans [11]. The below given example D.1, shows a definition signature between the *Definition* and the *yielding* keyword. Here placeholders, wrapped by the outmost brackets, and keywords are mixed together to constitute a pattern. Sentences based on the pattern come close to a natural language sentence, when the placeholders get filled out with the correct concepts of the domain model.

Despite the convenience that mix-fix operators provide to humans, it is quite challenging to implement the parser logic [12], especially for nested definition calls. The problem is that the parser has to recognize a *definition call* embedded inside an ID-token sequence in what is in the grammar specification another *definition call* (see highlighted EBNF-grammar rules in Listing II). As a consequence, a conventional context free grammar provides only insufficient means to specify sub ID-token streams with a different semantics to their embedding ID-token streams. To overcome this, we use the ANTLR v3 [13] parser-/compiler-generator framework. The framework allows to specify semantic annotations [14], which is actually user defined code (e.g., in Java), that gets inserted into the proper positions of the grammar to guide parser decisions, based on the semantics of tokens. Consider Listing II, where the Boolean return-values of the semantic annotations indicated by α_0 and α_1 influence the generated parsers resolution algorithm. The semantic annotations indicated by the symbols α_n represent Java code that gets integrated into the parser. The implemented logic performs the link between syntax and semantics. For instance, when a token with the value *Customer* gets recognized, the semantic annotation allows to conclude on further decision steps for the parser. Or also trigger some type-checking mechanism. However, for parsing mix-fix operators, we limit the nesting depth to three, which was shown to be sufficient in our preliminary case study.

```
definition::= 'Definition' nameSignature 'yielding'
              typeDef 'is defined as' ruleBody '.'
nameSignature::= (ID | parameterDef)+
parameterDef::= '(' name=ID 'as' type=ID ')';
typeDef::= ID | ID '(' typeDef ')';
ruleBody::= statement+ ;
statement::= ... | referenceOrDefinitionCall | ...;
referenceOrDefinitionCall::= {α0}modelReference
                           |{α1} definitionCall | ...;
definitionCall::= ID (ID | referenceOrDefinitionCall)* ;
```

Listing II. GRAMMAR SNIPPET FOR APRIL DEFINITIONS

Given the example from Section III-A, the APRIL-Definitions (D.1)-(D.3) decompose the business rule statement from Listing I into reusable and easy to define sub-statements with a signature in mix-fix notation.

(D.1) ***Definition*** *All (customers* ***as*** *Collection(Customer)) who buy (products* ***as*** *Collection(Product)) must pay (price* ***as*** *Number) EURO for the shipment* ***yielding*** *Boolean*
is defined as
every *customer* ***satisfies that every*** *"ordered product"* ***satisfies that*** *shipment.fee = prize*
with
"ordered products" (orderer as Customer) ***is defined as***
each *product* ***where*** *product.order.customer = orderer.*

(D.2) ***Definition*** *premium customer* ***yielding*** *Collection(Customer)*
is defined as
each *customer* ***in all instances of*** *Customer* ***where*** *customer.AverageAnnualTurnover > 20,000 .*

(D.3) ***Definition*** *special offer* ***yielding*** *Collection(Product)*
is defined as
each *product* ***in all instances of*** *Product* ***where*** *product.IsSpecialOffer.*

In (D.1), the orders of specific customers are mapped to a shipment prize. On the other hand, (D.2) is a set-comprehension on the set of all customers defining, what a premium customer is. Furthermore, (D.3) defines attributes that characterize special offers.

In order to provide a precise semantics, APRIL **atomic formulas** are used. They are verbalized versions of operations on sets, predicate-logic formulas and special common constraints sketched by Halpin [10]. For example, the *every-satisfies-that*-statement of Definition (D.1) is an atomic formula in APRIL that constitutes a universal quantification that is by default incorporated into the language. Some more operators are

described in [2]. Default atomic formulas are for maintaining sufficient expressive power and straight-forward translation into executable representations.

Moreover, we have defined some syntactical rules for the default atomic formulas to make their syntax a bit more appealing. For example the auto-mapping of plural to singular symbols. Like in D.1, in which the symbol "ordered products" represents a collection of objects of type Product and the symbol "ordered product", which is used as iterator symbol for the univesal quantification. One auto-mapping rule says that if any iterator symbol postfixed with an "s" equals a symbol that is in the scope of the same function or definition the short form, omitting the "in Collection(<Type>)" declarator can be used. This only applies if the types can be resolved and the symbol is unique in the entire scope stack.

In order to resolve symbols from their usage to their definition, APRIL uses different scope levels, e.g., like global and local variables known from the most programming languages. The precendences for resolving symbols are as follows:

- Atomic formulas (with iterator(s))
- Local variable / local method symbols
- Definition signatures (symbolic name with types of parameters)
- Class names and role names from the UML model used in the rule header after the *concerns* keyword

If we consider the example from Listing D.1 the body of the definition contains two nested universal quantification opertors $\forall_1.customer(i_1|P(i_1))$ with $P(i_1) := \forall_2.f_{LM}(i_1)(i_2|P(i_2)))$ and $f_{LM}(i_1) :=$ "ordered product"(i_1) with i_n are iterator variables, bound to the respective universal quantification operator. Note that we have marked the universal quantifiers with indexes, which makes it easier to refer to them later. The following annotated excerpt of D.1 illustrates the earlier definition:

every$_{\forall_1}$ customer **satisfies that** (
every$_{\forall_2}$ "ordered product" **satisfies that** (shipment.fee = prize)$_{P_2}$)$_{P_1}$

In this case the iterators i_1 and i_2 are related by $i_2 \in Ret_1 := f_{LM}(i_1)$, whereas $f_{LM}(i_1)$ is actually defined in the local members (LM) section of definition D.1 after the *with* keyword. Ret_1 is the return value yielded by f_{LM}. That is the local method f_{LM} with the symbolic name "*ordered products*", which takes a single parameter of type *Customer*. The method itself is implicitly typed as collection by the set comprehension function used in the proposition $P_{f_{LM}}$ of its body, which is:

"ordered products" (orderer as Customer) **is defined as**
(**each** product **where** product.order.customer = orderer)$_{P_{f_{LM}}}$.

The inference mechanism of the typing of f_{LM} works as described earlier by simply adding a "s"-postfix of the iterator so the short form of the operator "***each*** *product* ***where*** ..." can be resolved to the conventional form "***each*** *product* ***in*** *products* ***where*** ...". The symbol *products* can be resolved within the scope of D.1 as this is one of the parameters of type "Collection(Product)". Thus, the set comprehension also yields the same type. If we memorize $\forall_1$ that uses the symbol "*ordered product*" as iterator symbol and we also apply the "s"-postfix mechanism then "ordered products" is resolvable as local method. As $\forall_2$ is nested in $\forall_1$ that uses an iterator variable (i_1) represented by symbol *customer* of type Customer, the call to f_{LM} does not necessitate to explicitly state the parameter, which would be the iterator of the surrounding operator i_1 of $\forall_1$. This abbreviation mechanism is similar to that, e.g., used in λ-expressions in C# 4.0. Resuming the body statement of $\forall_2$, the scope stack now adds the symbol "ordered product", which is actually i_2, at its lowest level. Thus, both the immediate short navigation *shipment.fee* and the conventional navigation "*ordered product*"*.shipment.fee* are both valid in this context. We chose the short form for our example. The ability to unambiguously resolve the types of the used symbols is obligatory to detect trivial typing faults during design time of a business rule. Moreover, it is helpful in the translation process into the target language as it gives at least some evidence that the business rule is formally correct.

APRIL uses OCL as target language for translating invariants and pre-and post conditions. Behavioral rules are translated into Tempura, which is briefly explained later.In order to extend APRIL's expressiveness over general purpose operators provided by OCL, we allow the customization of atomic formulas that can be tailored to a certain domain. This delegates the design of the atomic formulas as natural language statements to the human user, who is still the best choice for this creative task.

C. Extending APRIL with Custom Atomic Formulas

Like definitions, customizable atomic formulas are defined using textual business patterns *(bp)*. Here, a requirements engineer can, e.g., reuse his already existing, informal textual business patterns [11], which, unlike the more abstract Definitions, express a very basic business rule- or business process pattern that regulates the business concepts and facts under consideration. For example, if a requirements engineer wants to verbalize business process statements which specify that in a warehouse all elements in a goods-stock move to a dedicated truck-loading bay and have to pass a certain gate on their way, she would have to specify parts of the grammar. Generally, a context free grammar consists of a start symbol, production rules, terminals and non-terminals [15]. Therefore, a state of practice language implementation mechanism described by Parr [14] is used. First, a formal production rule of the new atomic formula must be specified. Formal production rules are used to generate text recognition algorithms of a parser that processes statements of a language to generate a parse tree. Second, a parse tree rewrite rule has to be specified along with the production rule. Parse tree rewrite rules are instructions for the parser on how to construct the *abstract syntax tree* (AST) from the parse tree.

The AST is a condensed version of the parse tree that can be influenced by semantic considerations to form a concise and expressive logical representation of the parsed statements. For APRIL the AST provides the necessary flexibility to incorporate user defined language parts and also makes it particularly easy to extract the necessary parameters for the compiler. For clarification, Listing III sketches the definition of a user defined atomic formula. It formalizes the example operator that reflects the scenario mentioned above. In line 1,

the production rule with the name of the non-terminal (atomic formula) *moveTo* is introduced. The definition of the new atomic formula's regular syntax is defined in the lines 2-7. Here, the non-terminal *referenceOrDefinitionCall* is similar to that in Listing II. This non-terminal is a predefined APRIL concept and can either refer to an element of the related domain model (e.g., to class names Store, Bay, Gate) or to values in the scope stack of the parent rule or definition, in which the formula is used. The references to the parse tree nodes of type *referenceOrDefinitionCall* in the lines 3, 5 and 7 are stored one by one in the local variables source, target and routeNode. Line 9 concludes the specification of the grammar rule with the parse tree rewrite rule. It is delimited from the syntax rule by the "→" sign. It tells the parser to construct a tree with the MOVETO-terminal as root node having three leaves: source, target and routeNode.

```
1  moveTo :
2  'all elements in'
3  source=referenceOrDefinitionCall
4  'move to'
5  target=referenceOrDefinitionCall
6  'over'
7  routeNode=referenceOrDefinitionCall
8
9  → ^(MOVETO $source $target $routeNode);
```

Listing III. GRAMMAR RULE AND PARSE TREE REWRITE RULE FOR THE OPERATOR **MOVETO** IN ANTLR 3.0.

The grammar rule and the parse tree rewrite rule in Listing III get injected into dedicated areas of the APRIL core grammar. Parameterization of the APRIL-compiler is straight forward, which is depicted in Figure 3. In the second pass, a so called tree parser interprets the AST (of the rewrite rule MOVETO) and decides, which target language template to apply to the AST of the atomic formula. It then passes the values of the leaf-nodes (here the values of the variables $source, $target and $routeNode) to the parameters of the respective template. The instantiated template is the actual translation of the atomic formula into the target language, representing the semantics of the respective operator. Please see Listing V as an example instantiation.

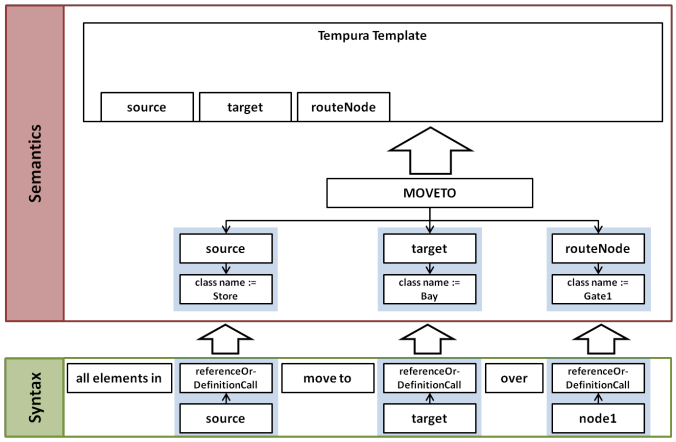

Fig. 3. Translation example of the atomic operator **moveTo**.

IV. FREQUENTLY USED BUSINESS RULES AS ATOMIC FORMULAS

A central aspect that increases the expressiveness of APRIL is the utilization of language constructs that allow to shortly specify business rules. These abbreviations are frequently used in practice and would be partly complicated to formulate in the underlying target languages. Such constraints are also often referred to as common constraints. Costal et.al. [16] show that these types of business rules can cover a significant amount of the overall constraints occurring in real life systems. In order to give the presented common constraints a structure, we have grouped them together based on the taxonomy presented in Figure 4, which was inspired by Halpin et al. [10] and Miliauskaite et al. [17] [18] and will be explained in the following subchapters.

A. Constraints on Values

Restricting values of variables can be done in several ways. For example assigning an integer data type to a variable restricts its values to a given range of natural numbers. Another way is to use relational operators with, e.g., constants to explicitly constrain variables. Therefore, the conventional and well known binary relational operators (e.g.,{<,>,=,<>,<=,>=}) are used. Although APRIL's is meant to be close to natural language, we use the mathematical representation for the afore mentioned operators as atomic formulas as we think this is well known enough to anyone. Moreover, if this might be too disconcerting for a user to use in a language like APRIL, it is possible to redefine that particular part of the grammar to give these operators a natural language syntax (e.g., "A>B" may become "A greater than B"). Here is an example:

Invariant Values **concerns** Vehicle:
MilesTotal<100000 .

B. Identifier

According to Miliauskaite et al. [18], a useful and strongly demanded constraint is the identifier or primary identifier known to ERM [19], ORM [20], xUML [21] and relational database management systems (RDBMS). UML's class attributes are predestined for holding a primary identification rule stated in APRIL or OCL, as UML class diagrams by default lack such means. This can be shown with the help

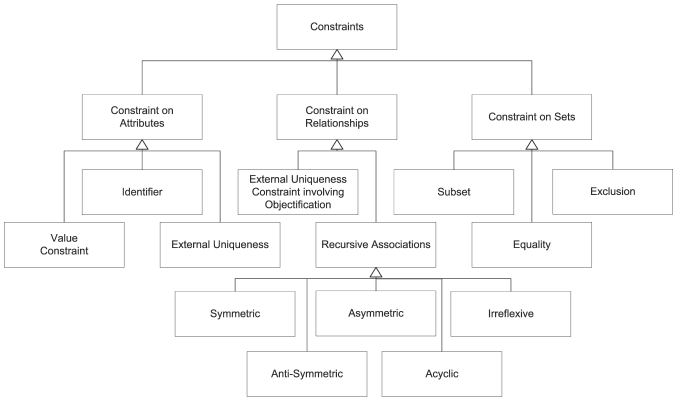

Fig. 4. Taxonomy of some important common constraints.

of the model in Figure 2. A common scenario is that an object is identified by an attribute that carries a unique value over all objects of the entire population. This can be formalized as follows:

APRIL:

Invariant id **concerns** Customer:
each ID is unique .

OCL:

context id **inv** Customer:
Customer.allInstances→isUnique(ID)

A more general version of the primary identifier constraint is the internal uniqueness constraint also called composed identifier. It says that value combinations of two or more attributes of an object are unique [10] [17]. The APRIL and OCL versions look like:

APRIL:

Invariant composedId **concerns** Customer:
each Name, DateOfBirth combination is unique .

OCL:

context Customer **inv** composedId:
Customer.allInstances→forAll(c1,c2 | c1 <> c2 implies
not((c1.Name = c2.Name and c1.DateOfBirth = c2.DateOfBirth)))

Towards a reasoning of common constraints we can say that if a class has a tuple of attributes $\{a_1,...,a_i\}$ out of which at least one has to obey a primary identifier constraint it is redundant to additionally specify that the combination of $\{a_1,...,a_i,...,a_n\}$ has to obey a composed identifier constraint.

C. External Uniqueness

A uniqueness constraint is denoted as external if the identification scheme is bound to another attribute of an associated class. For example an object *a* may be related to an object *b* only once. This does not restrict the overall occurrence of object *b* throughout the entire model as it might be that *a* is also related to an object *c*.

In the example below, the constraint only holds if different instances of `Vehicle` with potentially equivalent values in `VRN` (vehicle registration number) are not linked to the same instance of `Shipment`. The combination of `Shipment` and the attribute `VRN` of the class `Vehicle` is inherently done by the navigation path from `Shipment` to `Vehicle` by stating its concrete role name, `vehicles`. This collects all instances of `Vehicle` that are linked with the current instance of `Shipment`.

APRIL:

Invariant externalUniqueness **concerns** Shipment:
VRN is unique in vehicles.

OCL:

context Shipment **inv** externalUniqueness:
vehicles→isUnique(VRN)

D. External Uniqueness Involving Objectification

This type of constraints deals with associations that are regarded as objects. Hence, objectification [29], known as reification in UML, aims to combine multiple classes or attributes to a single one in order to apply constraints on the combination. In UML, this is typically done using association classes which objectify the association between two classes [8]. Hence, an object of an association class identifies a unique n-tuple of linked objects. In an attempt to generalize several UML concepts, Gogolla et al. [23] uncover how to transform association classes and association-qualifiers into n-ary associations (with n>=2 at this point). As they show in [24], there are several problems with the use and constraining of n-ary associations and thus, the n-ary association has to be transformed into a proper set of binary associations. For our example in Figure 2 it would mean that the association diamond in the middle of the three associated classes (Order, Shipment, Product) is transformed into an additional synthetic class, e.g., called ASSOC being associated to each of the afore mentioned classes with a binary association. In order to handle objectification in business rule statements between two or more Classes $\{c_1,...,c_N\}$ the APRIL *"each c_1,...,c_N combination"* expression is used. It returns a set of synthetic association objects instanciated from class ASSOC each of which is associated to one object of the corresponding type of c_1,...,c_N. The first example shows how to constrain tuples of classes. We omit the prose explanation for the APRIL constraint here because we consider it to be self explanatory.

APRIL:

Invariant externalUniqueness **concerns** Product:
each Product, Order, Shipment **combination** is unique .

OCL:

context Product
inv externalUniqueness:
Product.allInstances→forAll(c |
Order.allInstances→forAll (b |
Shipment.allInstances→forAll (a |
ASSOC.allInstances→select(assoc | assoc.product = c and
assoc.order = b and assoc.shipment = a)→size()<=1)))

E. Recursive Associations

A UML class can be associated with itself (see class Product in Figure 2). This allows recursions between objects. Rules on such models are called ring constraints [10]. Common ring constrains follow typical association properties. Here are some examples:

- *Irreflexive* constraints do not allow objects to refer to theirselves which is formally stated below. Note that the OCL keyword `self` corresponds to the lower-cased class name in the APRIL rule body.

APRIL:

Invariant irreflexive **concerns** Package:
package **is not in** elements .

OCL:

context Package **inv**:
elements→excludes(**self**)

- A *transitive* constraint says that if a first object bears the relationship to a second and the second to a third one then the first also bears a relationship to the third. This can be formally stated as follows.
- An *intransitive* constraint is the negation of the coresponding *transitive* constraint.
- *Symmetric* means that if the first bears the relationship to the second, then the second bears the relationship to the first. However, a ring constraint defined in a UML class diagram is by default symmetric so there is no need to state that an association is symmetric if it is meant to be optional. If not the following example shows how it can be stated.
- *Asymmetric* means that if the first bears the relationship to the second, then the second cannot bear the relationship to the first.
- *Anti-Symmetric* means that if the objects are different, then if the first bears the relationship to the second, then the second cannot bear that relationship to the first.
- *Acyclic* means that a chain of one ore more instances, which are linked to objects of the same type cannot form a recursive loop (cycle).

As acyclic constraints are common practice in business rule modelling [10] we can define a new atomic formula. That is the "*deep collection of*"-operator. The notation of the operator is exemplified in the listing below. The semantics of the operator is as follows:

Let A be a set of objects of type τ and $\{a_0 \dots a_n\} \cup \emptyset$ be elements of A. Let $R_n(a_n, A_n := \{a_{n+1,j} \dots a_{n+1,k}\} \backslash \emptyset)$ be the representation of a set of relations between an element a_n and a non-empty set $A_n \subset A$.

Then $A_{deep} := \bigcup A_m(R_m)$; with $0 \leq m \leq n$. After all $(a_0, A_{deep}) \models$ *"deep collection of"*(a_0).

APRIL:

Invariant acyclic **concerns** Package:
package **is not in deep collection of** elements.

OCL:

context Package **def** :
successors(): Collection(Product) =
self.elements→
union(self.elements.successors())
context Package **inv** acyclic:
self.successors()→excludes(self)

In the OCL example, the first constraint defines a synthetic operation named `successor()` that is recursively called within an OCL union operation which is called on the set of `elements` of the current object. The intent is to unite all the `Package` objects linked with the current objects `elements` that also play this role in the linked subordinated objects. This construct is inherently typed as collection type `Collection`.

F. Sets

The upper part of the Table I shows the verbalization of common constraints on sets according to Costal et al. [16] and Miliauskaite et al. [18]. Note that lower case latters denote elements of sets and upper case letters denote sets.

The lower, folded part of the table handles a specialization of the natural-join operator, indicated by $\bowtie'$. In APRIL it is used to "navigate" through UML class models, gathering (sets-of) objects along association graphs, which then can be utilized to formulate constraints. Hence, this is one of the most important constructs in APRIL and deserves special mention. The semantics is equivalent to OCL's [5] *collect*-operation.

mathematical	APRIL	OCL
$a \in A$ $B \in A$	*a is in A* *B is in A*	$A \rightarrow$ *includes* (a) $A \rightarrow$ *includesAll* (B)
$A = B$	$A = B$	$A = B$
$A \cap B = \emptyset$ $a \notin A$	*A is not in B* *a is not in A*	$B \rightarrow$ *excludesAll*(A) $A \rightarrow$ *excludes*(a)
$A \bowtie' B$	$A.B$	$A.B$ $A \rightarrow$collect(B)

TABLE I. SOME COMMON CONSTRAINTS ON SETS.

More conventional and common constraints in APRIL can be found in [2].

V. CASE STUDY ON THE ACCEPTANCE OF APRIL

The goal of the case study was to discover, if the APRIL syntax is understandable to untrained users with a basic understanding of logic. For this, a representative group of thirty computer science students in their first and second year could be motivated to participate. The major part was completely inexperienced in the field of UML-modeling and has never heard of OCL before. We considered OCL version 2.0 as the benchmark language. That was because OCL 2.0 -as a part of the UML specification- is an established and well defined language that is close to our purpose: defining business rules on UML-class models. Two days before the case study, an information sheet was handed to the test persons, that explained the very basics of the APRIL and OCL syntax. This included predicate logic operators (e.g., universal and existential quantifier), operators on sets (e.g., for union, exclusion and intersection of sets) and the very important *join* operator. Moreover, necessary concepts of UML-class models were explained, necessary to comprehend the APRIL and OCL materials. This comprised the use of the most important class models concepts, e.g., classes, associations, roles and multiplicities. Directly before launching the case study session, a brief introduction into the domain of discourse was given, on which the APRIL and OCL constraints were written against. The case study sheet consisted of four sections. The first section dealt with questions on an example UML-class model and intended to show how mature the skills of the experimentees in UML modeling were

and also if the essentials of the related UML-model were comprehended that were necessary to understand the tasks given in the succeeding parts. The second and third section demanded to try to interpret and write down the meaning of a given sequence of 18 APRIL and 18 OCL constraints in own words. The 36 constraints were based on an example UML-class model that consisted of 5 classes. Each APRIL and OCL constraint had its semantic counterpart in the opposite language. The complexity of the constraints was increasing continually, whereas the simplest constraint was like the listing for the value constraint in Section IV-A. The APRIL constraint with the highest complexity was comparable to that in Listing I including all related Definitions from D.1 to D.3 and Listing IV as its OCL representation, respectively. In the last and shortest section, the test persons had to formulate OCL and APRIL constraints, based on business rules, given in real natural language. The conduction of the case study was organized as follows. The group of test persons was divided into two equally sized subgroups each starting either with the third part (OCL) or the second part (APRIL). This was to counterbalance potential learning effects. Remember, each constraint had its semantic counterpart in the opposite language and that is why learning effects could not be precluded. The results were as follows with respect to the average ratio of correct answers or correctly interpreted APRIL or OCL business rules:

- UML-part: 74% with an average spread of 10%.
- Simple expressions: OCL: 38%, APRIL: 69%
- Complex expressions: OCL: 36%, APRIL: 57%
- Writing expressions: OCL: 12%, APRIL: 27%

Textual feedback of the test persons:

- About 50 per cent of the test persons spent less than 20 minutes in their preparation phase. About 30 per cent were unprepared. Persons of the remaining 20 per cent invested one to two hours to prepare for the survey.
- About 90 per cent of the test persons subjectively estimated that APRIL is more understandable than OCL. Whereas, 2 students found both languages equally understandable and one student with a significant background in other formal languages found, that OCL is more understandable.

The resulting percentage of APRIL, reflecting the correctly interpreted constraints, allows to conclude that it is possible for untrained test persons to understand APRIL statements. A surprisingly high number of test persons was able to write rules. This discipline has been considered to pose a bigger problem, regarding the low preparation effort of 20 minutes for the major part of the testees. Students who invested more time for preparation gained better results in both interpreting and writing APRIL rules. For OCL we were not able to observe a similarly strong coherence between preparation time and improved results. The unexpectedly very good understandability of UML-class models, even without any preparation, might be a good indication that the combination of a graphical notation to represent concept models and a textual notation for constraints is suitable to specify understandable business rules.

VI. APRIL'S TARGET LANGUAGES

APRIL makes use of the logical frameworks OCL and Tempura to underpin its language constituents with a well defined semantics. Both languages are briefly introduced in the subsequent sections.

1) OCL: As part of the UML, OCL 2.3.1 is the target language for APRIL-invariants, pre- and post- conditions. For the sake of brevity, we give a rudimentary introduction to OCL because it is well known. The interested reader should consult the literature on OCL. The specification of OCL 2.3.1 can be found on [5].

OCL restricts UML-class models using predicate logic and operations on sets. Arithmetic-, Boolean- and relational operators are used in the conventional way. Existential and universal quantifiers allow to quantify on propositions holding on an object population derived from a class model. In order to give an idea of the OCL syntax, we provide in Listing IV a translation into OCL of the example mentioned earlier in Listing I and the definitions from (D.1)-(D.3). Here, we used OCL's decomposition mechanisms to cater to an improved readability.

```
context Customer inv rule1:
Customer::
All_customers_who_buy_products_must_pay_price_for_shipment(
  Customer::premium_customers(),
  Product::special_offers(),
  0)

context Customer def:
All_customers_who_buy_products_must_pay_price_for_shipment(
    customers : Collection(Customer),
    products : Collection(Product),
    price : Real) : Boolean =
      customers→forAll(customer |
        products→select(product |
          product.order.customer = product)→forAll(orderedProduct |
            orderedProduct.shipment.price = price))

context Customer def:
premium_customers() : Collection(Customer) =
  self.AverageAnnualTurnover > 20,000 EURO)

context Product def:
special_offer(): Collection(Product) =
    self.IsSpecialOffer = true
```

Listing IV. POSSIBLE OCL-TRANSLATION OF LISTING I

2) Tempura: Tempura is an executable subset of Interval Temporal Logic (ITL) [6]. ITL enhances predicate calculus with a notation of discrete time, expressed by separated states, and associated operators. A key feature of ITL and Tempura is that the states of a predicate are grouped together as nonempty sequences of states called intervals σ_{plus}. For example the shortest interval of states σ on a predicate can be represented by $< s >$ where s is a state. Please note that here the length σ := $|\sigma|$ = 0, which is generally the number of states in σ minus 1. The semantics of ITL keeps the interpretations of function and predicate symbols independent of intervals. Thus, well known operators like {+, -, *, and, or, not,...} are interpreted in the usual way. The characteristic operator for ITL is the operator *chop (;)*, which says that a prefix subinterval is *followed by* a suffix subinterval. Both subintervals share one state "between" them. Conventional temporal logic operators such as *next* (○) and *always* (□) examine an interval's suffix

subintervals whereas chop splits the interval into two parts and tests both. Furthermore, Moszkowski [6] shows how to derive operators such as always and sometimes from chop. In ITL, the formula $w := w_1; w_2$ is true if $\Im_{\langle \sigma_0..\sigma_i \rangle} [\![w_1]\!]$ and $\Im_{\langle \sigma_i..\sigma_{|\sigma|} \rangle} [\![w_2]\!]$ are true in the respective sub-formulas. Note that w_1 and w_2 share the same subinterval σ_i. We adopt some examples from [6], which are as follows:

σ	P	R
s	1	2
t	2	1
u	3	1

The lenght of interval σ is expressed by $|\sigma|$ and is defined as the number of the states in σ minus one. Thus, in our example, $|\sigma| = 2$.

The following formulas on the predicates P and R are true on the interval $< stu >$:

- $P = 1$. The initial value of P is 1.
- $\bigcirc(P) = 2$ and $\bigcirc(\bigcirc(P)) = 3$. The next value of P is 2 and the next next value of P is 3.
- $P = 1$ and P gets $P + 1$. The initial value of P is 1 and P gets increased by 1 in each subsequent state.
- $R = 2$ and $\bigcirc(\Box(R)) = 1$ The initial value of R is 2 and R is always 1 beginning from the next state.
- $P \leftarrow 1$; $P \leftarrow P + 1$; $P \leftarrow P + 1$. The formula $e_2 \leftarrow e_1$ is true on an interval if $\sigma_0(e_1)$ equals $\sigma_{|\sigma|}(e_2)$. Thus, $\leftarrow$ is called temporal assignment.

We adopt Tempura because it is able to model operations lasting over multiple state transitions, which would not be possible with a single pair of OCL pre- and post-conditions. Moreover, the reader will recognize similarities with the rationale of the test-definitions given in Section VII-A.

VII. GENERATING TEST CODE FROM APRIL STATEMENTS

This section clarifies the connection between APRIL and its target languages utilizing the *moveTo*-operator example introduced earlier. Section VII-A describes the basic rationale that influence the test framework presented in Section VII-B. The test framework is applied to an application, which helps to track movements of goods in a logistics centre. For testing the correct routing, we use the example operator *moveTo* described in Section III-C.

A. Testing

For generating proper test-code based on APRIL statements, the classification of different test types into black- and white-box testing has to be clarified. Our definition of the test types is as follows: Each function f_i in the set of functions F ::= $\{f_0, \ldots, f_n\}$ of a component under test (CUT) triggers a state transition and obeys a predefined signature. This signature requires a tuple of input values (f_{IN}) and yields a tuple of output values (f_{OUT}). A signature of a function is an interface describing a contract [22] with IN- and OUT-data, which is specified in UML-class models. We assume that a composite function g_{ik} is a conglomerate of some functions f_i to f_k, for some natural numbers $0 <= i < k <= n$. Then, any OUT-signature of a proceeding function f_j must correspond to the IN-signature of the succeeding function f_{j+1}, for some natural numbers $k < j <= i$. This convention of the inner structure can be formalized by $OUT(f_j) == IN(f_{j+1})$, which we want to abbreviate with D_j. It represents an element of a function sequence. Moreover, the following holds $IN(g_{ik}) == IN(f_i)$ and $OUT(g_{ik}) == OUT(f_k)$.

A white-box test necessitates the knowledge of the entire sequence of $D_{D_0,\ldots,D_n}$ as the internal structure of g (g_{ik}), which is normally the case as the user knows the source code. If $D(g)$ is unknown, tests are limited to reason on the data given by $IN(g)$ and $OUT(g)$, they are called black-box tests. In APRIL, black-box tests are issued to the invariants, pre- and post-conditions.

For the specification of behavioral models, we extend our recent definition of white-box tests beyond reasoning on D. We use Interval Temporal Logic (ITL) [6] for modeling behavior in white-box-tests. Therefore, we introduce behavioral constraints in APRIL, which we regard as orthogonal to the invariants as well as pre- and post-conditions. Assume D represents a state σ_1 that maps a set of values to their corresponding variables at one certain point in time. Then let σ be an ordered set of states σ_0 to σ_n, each of which describes a different D at different subsequent, discrete points in time. In our understanding, the knowledge of σ is sufficient for applying white-box-tests, which we want to utilize in our framework.

B. Test Framework and Case Study

In this section, we build a representative example around the behavioral all-elements-move-to-operator introduced in Section III-C. The definitions of the previous section are used in our test framework, which deals with logistic processes to handle the material flow in a warehouse. It consists of a simple 3-tier architecture with RFID-readers and light sensors at the field-level and an ERP-system at the top level. Between these two levels, we use an RFID-middleware -Rifidi [23]- for information exchange and filtering.

The connection between a specification in Tempura and a function in the productive code is the test data. Therefore, the user has to provide initial test data $IN(f_0)$, constituting an important part of a test-case. The productive code affects the data $OUT(f_i)$ in the memory for each invocation of f_i, which marks a new interval at the same time. Thus, each time a function under test f_i gets invoked a snapshot of the input data (f_{IN}) prior to the invocation and output data (f_{OUT}) when f_i is left gets generated. The test data for the Tempura-statements is provided by recorded history-data that is stored in a properly formatted log-file containing a condensed version of the data-snapshots. The retrieval of the test data from the running system is achieved via AspectJ [24]. Therefore, AspectJ pointcut statements are generated based on the reference-nodes (see Listing III) to class-attributes found in the AST of an APRIL statement. The use of AspectJ permits us to leave the original code of the productive system untouched.

The use case for the earlier mentioned example with the behavioral operator *moveTo* formalized in Listing III is as follows: Imagine a warehouse that has a high-bay storage

and a loading bay for lorries. Both, storage and lorry-bay are connected with a conveyor belt. Each of the three components is equipped with one RFID-reader that can detect tagged-goods in its near field to allow tracking whether the correct thing takes the right path in the right direction. For a customer order, all goods in store contained in the order must go from the store to the lorry-bay via the conveyor belt. For simplicity we assume that each good will be detected by exactly one of the three RFID-readers at a time. This simplification is an abstraction of the real world, which does not influence considerations regarding the presented methodology.

OUTPUT	σ_I	STORE	GATE1	BAY
	I=1	"a","b"		
	I=2	"b"	"a"	
	I=3	"b"		"a"
	I=4		"b"	"a"
	I=5			"a","b"

TABLE II. REPRESENTATION OF LOG-FILE RECORDED FOR EXAMPLE-OPERATOR

The described scenario can be reflected by a log file as depicted in Table II, if the actual memories of the readers holding the IDs of the tags can be accessed in the productive application via the following reference-IDs: STORE for the RFID-reader observing the near-field of the storage, GATE1 for the conveyor and BAY for the lorry-bay. The data in the log file is formatted as array with the symbolic name OUTPUT.

```
define store_moves_to_Bay_over_Gate1 () = {
  len(|OUTPUT|-1) and
  I = 0 and
  I gets I+1 and
  moveAtoB(OUTPUT[I][Store], OUTPUT[I][Gate1]) and
  moveAtoB(OUTPUT[I][Gate1], OUTPUT[I][Bay]) and
  OUTPUT[|OUTPUT|-1] [Bay] ← OUTPUT[0] [Store]
}.

define moveAtoB (A,B) = {
  if (|A| > 0) then {
    first(A) gets last(B) and skip
  }
}.
```

Listing V. TEMPLATE FOR THE ALL-ELEMENTS-MOVE-TO OPERATOR.

With regard to the model, the Tempura statements in Listing V hold. They are actually an instantiation of a template that is used by the APRIL-compiler for translating the move-to-operator if used in an APRIL statement like in Listing VI.

```
all elements in Store move to Bay over Gate1.
```

Listing VI. USAGE OF THE ALL-ELEMENTS-MOVE-TO OPERATOR.

The formatting of the statements is according to String-Template described by Parr [25] and contains generic parts that get filled according to the parameters of the operator in Listing VI.

VIII. RELATED WORK

SBVR-Structured-English (SE) and similarly RuleSpeak [26] are so-called controlled languages to express business rules in a restricted version of natural language. Both are based on SBVR, which defines semantic parts, e.g., terms and facts to determine business concepts and their relations. The syntactic representation of these parts is achieved by text formatting and coloring, which could be used to aid parsing SE-statements. From our viewpoint, mixing technical information with the textual representation is problematic because formalized and natural language semantics have to be maintained in one and the same statement. However, natural language does not utilize text formatting information for transporting semantics.

Nevertheless, SE is used for model representation, which Kleiner et al. [27] utilize as a starting point for translating schema descriptions (in SE) into UML-class models, which is helpful for software development. Unfortunately, they leave the treatment of business rules for further work. Regarding the customizability aspect of business statements, the approach of Sosunovas et al. [28] presents another way, utilizing regular patterns. They pursue a three-step approach to constructing business rule templates that are first defined on an abstract level and then tailored to fit a specific domain with every further refinement step. Therewith, they provide precise meta-model-based semantics to the template elements but -as they admit- not to the business rule resulting from using the template.

In the field of semantic web, several controlled natural language (CNL) approaches have been elaborated. Hart et al. [29] propose a CNL called Rabbit to specify ontologies. The language provides means to specify concepts and relations in a dictionary like manner. Axioms describe the kind of relations between concepts and also allow to specify cardinalities on relations and constraints based on propositional logic. Moreover, Rabbit allows to reference other ontologies to make use of already existing concepts and axioms.

A pragmatic approach to define natural language constructs in CNL is presented by Spreeuwenberg et al. [30] and van Grondelle et al. [31]. They use patterns with a regular syntax consisting of constants and placeholders that can be replaced by instances of meta model concepts. Each pattern is related to a graph in the meta model to represent its semantics exclusively based on that meta model. However, from our viewpoint the interesting thing is that they emphasis the particular simplicity of the construction of patterns even for untrained persons. That is also what we found out with our APRIL definitions.

Another interesting approach in generating tests from requirements specifications is introduced by Nebut et al. [32]. They utilize UML use-case models combined with contracts represented by pre- and post- conditions to specify sequences of state transitions. Based on these contracts, they simulate the modeled behavior by intentionally "instantiating" the use case model. This approach could be a worthy extension to ours, which uses historical data that could also be generated by simulation. Moreover, Nebut et al. show how to generate test-cases from sequence diagrams and test objectives, that cater to a defined test coverage.

IX. CONCLUSION AND FUTURE WORK

With APRIL we want to provide a customizable and semantically well-founded notation that is close to natural language and suitable for humans as well as for computers. A core feature of APRIL is the ability to define abstract mix-fix operators that are particularly useful to define natural language expressions as reusable patterns. We consider this pattern building technique as sufficiently intuitive even for untrained

persons, which we could show in a case study with 30 test persons. The semantic underpinning of the mix-fix operators is achieved by customizable atomic formulas. Te ease the use of APRIL, we have encorporated additional atomic formulas that are based on frequently used constraints in practice, so called common constraints. The syntax of atomic formulas can be tailor-made for any domain. This is exemplified by a new atomic formula taken from the logistics domain to model behavior. We extend APRIL's grammar and present a mapping to the interpretation function based on Interval Temporal Logic. With the use of the new atomic formula and the transformation into the instantiated Tempura statement, executable test code can be generated. This way, our framework contributes to an integrated software development process by providing unambiguous and understandable business rules that can be used for specification purposes and for automatically generating tests.

From the current viewpoint, some issues are still open. Further evaluation is needed to determine wether the specification of the grammar rules and their corresponding rewrite rules are suitable to a typical requirements engineer. The use of OCL and especially Tempura, for creating the templates requires a considerable amount of skills. Moreover, using APRIL requirements requires a basic understanding of logic and set-theory. It has to be discovered if the aforementioned challenges are manageable by the typical requirements engineer in reasonable amout of training-time. Hence, future work will target on refining the presented approach with a focus on methodologies to improve APRIL's usability.

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Design and Classification of Mutation Operators for Abstract State Machines

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***Abstract*—Mutation testing is a well established fault-based technique for assessing and improving the quality of test suites. Mutation testing can be applied at different levels of abstraction, e.g., the unit level, the integration level, and the specification level. Designing mutation operators is the most critical activity towards conducting effective mutation testing and analysis. Mutation operators are well defined for a number of programming (e.g., C, Java, etc.) and specification (e.g., FSM, Petri Nets, etc.) languages. In this paper, we design and classify mutation operators for the Abstract State Machines (ASM) formalism. The designed operators are defined based on the types of faults that may occur in ASM specifications and can be classified into three categories: (1) Domain operators, (2) function update operators, and (3) transition rules operators. Furthermore, a prototype mutation tool for the *CoreASM* language, has been built to automatically generate mutants and check their validity. We illustrate our approach using a simple *CoreASM* implementation of the *Fibonacci* series. Finally, an empirical comparison of the designed operators is presented and discussed.**

Keywords*—*Mutation testing; specification; mutation operator; Abstract State Machines (ASM); domain operators; function update operators; transition rules operators; CoreASM.

I. INTRODUCTION

In this article, we describe an extension of our work on designing Abstract State Machines mutation operators published in [1].

Fault based testing strategies aim at finding prescribed faults in a program [2]. Mutation testing [3] is a well established fault-based testing technique for assessing and improving the quality of test suites. Mutation testing uses mutation operators to introduce small modifications, or mutations, into the software artifact (i.e., source code or specification) under test. Mutation operators are classified by the language constructs they are created to alter. Given the fact that a program/specification being mutated is syntactically correct, a mutation operator must produce a mutant that is also syntactically correct. The objective is then to select test cases that are capable to distinguish the behavior of the mutants from the behavior of the original artifact. Such test cases are said to *kill* the mutants. However, it may also be that the mutant keeps the program's semantics unchanged-and thus cannot be detected by any test case. Such mutants are called *equivalent* mutants. The detection of equivalent mutants is, in general, one of biggest obstacles for practical usage of mutation testing. The effort needed to check if mutants are equivalent or not, can be very high even for small programs [4].

Since the number of possible faults for a given program or specification can be large, mutation-based testing strategies are based on the following two principles: (1) the Competent Programmer Hypothesis [3], which states that competent programmers tend to write programs that are *close* to being correct. In other words, a program written by a competent programmer may be incorrect but it is generally likely close to being correct (containing relatively simple faults) (2) the Coupling Effect [3], which states that a test data set that catches all simple faults in a program is so sensitive that it will also catch more complex faults. Analogously to the Competent Programmer Hypothesis [3], Ammann and Black [5] have proposed the *Competent Specifier Hypothesis* stating that analysts write specifications which are likely to be close to what is desired.

In a recent survey on the development of mutation testing, Jia and Harman [4] have stated that more than 50% of the mutation related publications have been applied to Java [6], [7], Fortran [8], [9] and C [10]. Although mutation testing has mostly been applied at the source code level, it has also been applied at the specification and design level [11], [4]. Formal specification languages to which mutation testing has been applied include Finite State Machines [12], [13], [14], Statecharts [15], Petri Nets [16], and Estelle [17].

Fabbri et al. [12] have applied specification mutation to validate specifications based on Finite State Machines (FSM). They have proposed 9 mutation operators, representing faults related to the states (e.g., wrong-starting-state, state-extra, etc.), transitions (e.g., event-missing, event-exchanged, etc.) and outputs (e.g., output-missing, output-exchanged, etc.) of an FSM. In a related work, Fabbri et al. [15] have defined mutation operators for Statecharts, an extension of FSM formalism, while Batth et al. [18] have applied mutation testing to Extended Finite State Machines (EFSM) formalism. Hierons and Merayo [14] have investigated the application of mutation testing to Probabilistic (PFSMs) or stochastic time (PSFSMs) Finite State Machines. The authors have defined new mutation operators representing FSM faults related to altering probabilities (PFSMs) or changing its associated random variables (PSFSMs) (i.e., the time consumed between the input being applied and the output being received).

The widespread interest in model-based testing techniques provides the major motivation of this research. We, in particular, focus on investigating the applicability of fault-based

testing (vs. scenario-based testing) to Abstract State Machines (ASM) [19] specifications. In this paper, we extend our previous work [1] on designing ASM-based mutation operators by:

- Extending the set of operators, introduced in [1], by adding the *Call Rule Operators*, the *Pick Rule Operators*, and the *Extend Rule Operators*.
- Refining the classification of the proposed ASM-based mutation operators. The resulting ASM-based operators can be classified using three categories: (1) ASM domain operators, (2) ASM function update operators, and (3) ASM transition rules operators.
- Presenting *CoreASM* [20], an ASM-based language, illustrative examples of the proposed mutation operators.
- Presenting an enhanced version of our *CoreASM* [20] mutation prototype tool, for automatic generation, validation, and execution of *CoreASM* mutants.
- Analyzing the generated mutants using an illustrative example of a *CoreASM* specification of *Fibonacci series*.
- Presenting an empirical comparison of the proposed *CoreASM* mutation operators using three *CoreASM* specifications: *Dining Philosophers*, *Vending Machine*, and *Rail Road Crossing*.

The remainder of this paper is organized as follows. The next section provides an overview of the Abstract State Machines (ASM) [19] formalism and the *CoreASM* language. In Section III, we define and classify a collection of mutation operators for *CoreASM* language. An analysis of the generated mutants is presented in Section IV. Section V describes the *CoreASM* Mutation toolkit. To demonstrate the applicability of the proposed approach, Section VI describes the application of *CoreASM* mutation operators to Fibonacci specification. An empirical comparison of *CoreASM*-based mutation operators is presented in Section VII. Finally, conclusions are drawn in Section VIII.

II. Abstract State Machines

Abstract State Machines (ASMs), originally known as *Evolving Algebras*, were first introduced by Yuri Gurevich [21], [19] in an attempt to improve on Turing's thesis [22] so that:

> "*Every algorithm is an ASM as far as the behavior is concerned. In particular the given algorithm can be step-for-step simulated by an appropriate ASM [23]." (The ASM Thesis)*

This means that an activity that is conceptually done in one step can be executed in the model in one step. This is in contrast to Turing machines, where simple operations might need any finite number of steps.

Abstract State Machines have been used to capture sequential, parallel and distributed algorithms. ASMs combine two fundamental concepts of transition systems: (1) transitions to model the dynamic aspects of a system, and (2) abstract states to model the static aspects at any desired level of abstraction. Börger and Stärk [24] further developed ASMs into a system engineering method that guides the development of software from requirements capture to implementation.

Widely recognized applications of ASMs include semantic foundations of a wide variety of programming languages like C++ [25], C# [26], and Java [27], logic programming languages such as Prolog [28] and its variants, hardware languages such as VHDL [29], system design languages like the ITU-T standard for SDL [30], [31], Web service description languages [32], design of distributed systems [33], [34], etc.

A. ASM Program

Abstract State Machines (ASM) [19] define a state-based computational model, where computations (runs) are finite or infinite sequences of states $\{S_i\}$ obtained from a given initial state S_0 by repeatedly executing transitions δ_i:

$$S_0 \xrightarrow{\delta_1} S_1 \xrightarrow{\delta_2} S_2 \qquad \cdots \qquad \xrightarrow{\delta_n} S_n$$

An ASM $\mathcal{A}$ is defined over a fixed vocabulary $\mathcal{V}$, a finite collection of function names and relation names. Each function name f has an arity (number of arguments that the function takes). Function names can be static (i.e., fixed interpretation in each computation state of $\mathcal{A}$) or dynamic (i.e., can be altered by transitions fired in a computation step). Dynamic functions can be further classified into:

- Input functions that $\mathcal{A}$ can only read, which means that these functions are determined entirely by the environment of $\mathcal{A}$. They are also called monitored.
- Controlled functions of $\mathcal{A}$ are those which are updated by some of the rules of $\mathcal{A}$ and are never changed by the environment.
- Output functions of $\mathcal{A}$ are functions which $\mathcal{A}$ can only update but not read, whereas the environment can read them (without updating them).
- Shared functions are functions which can be read and updated by both $\mathcal{A}$ and the environment.

Static nullary (i.e., 0-ary) function names are called constants while Dynamic nullary functions are called variables.

Given a vocabulary $\mathcal{V}$, an ASM $\mathcal{A}$ is defined by its program $\mathcal{P}$ and a set of distinguished initial states S_0. The program $\mathcal{P}$ consists of transition rules and specifies possible state transitions of $\mathcal{A}$ in terms of finite sets of local function *updates* on a given global state. Such transitions are atomic actions. A transition rule that describes the modification of the functions from one state to the next has the following form:

if *Condition* **then** <*Updates*> **endif**

where *Updates* is a set of function updates (containing only variable free terms) of the form:

$$f(t_1,t_2,\ldots,t_n) := t$$

where t_1, t_2, ..., t_n, and t are first order terms.

The set of function updates are simultaneously executed when *Condition* (called also *guard*) is true. In a given state, first all parameters t_i, t are evaluated to their values, v_i, v, then the value of $f(v_1,\ldots,v_n)$ is updated to v. Such pairs of a function name f, which is fixed by the signature, and an optional argument $(v_1,\ldots,v_n)$, which is formed by a list of dynamic parameters value v_i, are called *locations*.

Example 1: The following rule yields the update-set $\{(x, 2), (y(0), 1)\}$, if the current state of the ASM is $\{(x, 1), (y(0), 2)\}$:

$$\textbf{if} \quad (x = 1) \quad \textbf{then} \quad \begin{array}{l} x := y(0) \\ y(0) := x \end{array}$$

In every state, all the rules which are applicable are simultaneously applied. A set of ASM updates is called *consistent* if it contains no pair of updates with the same location updated with two different values, i.e., no two elements *(loc,v)* and *(loc,v')* with $v \neq v'$. In the case of inconsistency, the computation does not yield a next state.

Example 2: The following update set {(x, 1), (y, 2), (x, 2), (y, 2)}, is inconsistent due to the conflicting updates for x (i.e., x is updated with different values 1 and 2). It is worth noting that even though y is updated twice, it does not lead to an inconsistent update since it has been updated with the same value 2.

$$\begin{array}{l} x := 1 \\ y := 2 \\ x := 2 \\ y := 2 \end{array}$$

For a detailed description and a rigorous mathematical definition of the semantic foundations of Abstract State Machines, the reader is invited to consult [19], [24], [35], [36].

B. CoreASM Language

The *CoreASM* project [37] focuses on the design of a lean executable ASM language, in combination with a supporting tool environment for high-level design, experimental validation and, where appropriate, formal verification of abstract system models [20]. The *CoreASM* engine, implemented in *Java*, consists of a parser, an interpreter, a scheduler, and an abstract storage. The interpreter, the scheduler, and the abstract storage work together to simulate an ASM run. For a detailed description of *CoreASM* architecture, reader is invited to consult [20].

CoreASM is designed with extensibility in mind, supporting the extension of both the specification language and the execution engine's behavior through plug-ins (e.g., *Standard*, *KernelExtensions*, *Abstraction*, *TurboASM*, etc.).

Figure 1 shows a typical structure of a *CoreASM* specification. Every specification starts with the keyword **CoreASM** followed by the name of the specification. Plugins that are required are then listed with the keyword **use** followed by the name of the plugin (e.g., **use** Standard). The Header block is where various definitions take place (e.g., Declaration of an enumeration type). The **init** rule (the rule that creates the initial state) is defined by the keyword **init** followed by a rule name. This would be the rule that initializes the state of the ASM machine. The body of the init rule must be declared in the rule declaration block along with other user defined rules.

To run a *CoreASM* specification, two user interfaces are available:

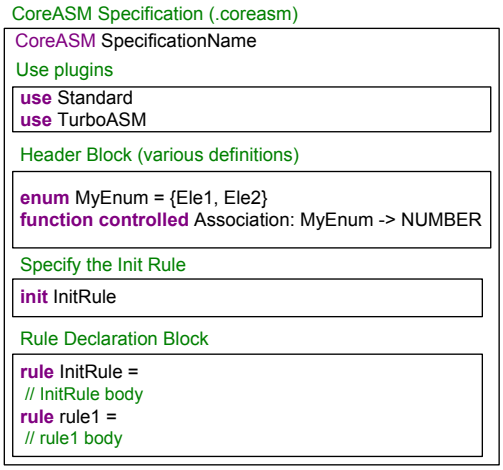

Fig. 1. Typical Structure of a CoreASM Specification

- A comprehensive command-line user interface called *Carma*, which accepts the name of the specification file and optional termination conditions (e.g., --steps 10 and/or --empty-updates) as arguments. For example, the following command runs *Spec.coreasm* using *Carma* and stops after 10 steps, or after a step that generates empty updates.

  carma --steps 10 --empty-updates Spec.coreasm

- A graphical interactive development environment in the *Eclipse* platform, known as the *CoreASM Eclipse Plugin*.

In what follows, we define and classify mutation operators for Abstract State Machines.

III. Abstract State Machines Mutation Operators

In order to formulate mutation operators for ASM formalism, we use the following guiding principles, introduced in [38]:

- Mutation categories should model potential faults.
- Only simple, first order mutants (i.e., a single change to an artifact) should be generated.
- Only syntactically correct mutants should be generated.

A. Categories of ASM Mutation Operators

There exist several aspects of an ASM specification that can be subject to faults. These aspects can be classified into three main categories of mutation operators, each category contains many mutation operators, one per a fault class:

1) ASM domain mutation operators.
2) ASM function update mutation operators.
3) ASM transition rules mutation operators.

Although the proposed categorization yields few generic categories that can be applied to any ASM-based language, the operators themselves are dependent on the syntax of the ASM-based language. Indeed, given that a specification being mutated is syntactically correct, a mutation operator must produce a mutant that is also syntactically correct. To do so,

it is required that a valid syntactic construct be mapped to another syntactic construct in the same language. In addition, peculiarities of language syntax have an effect on the kind of mistakes that a modeler could make. For instance, aspects such as procedural (e.g., *CoreASM* [20] language) versus object oriented (e.g., *AsmL* [39] language) are captured in the language syntax. In this paper, we target the *CoreASM* [20] language.

B. ASM Domain Mutation Operators

A domain (called also *universe* or *background*) consists of a set of declarations that establish the ASM vocabulary. Each declaration establishes the meaning of an identifier within its scope. For example, the following *CoreASM* [20] code defines a new enumeration background *PRODUCT* having three elements (Soda, Candy, and Chips) and three functions *selectedProduct*, *price*, and *packaging*:

enum PRODUCT = {Soda, Candy, Chips}
function selectedProduct: → PRODUCT
function price: PRODUCT → NUMBER
function packaging: PRODUCT*PRODUCT → NUMBER

ASM domains/universes can be mutated by adding or removing elements:

- Extend Domain Operator (EDO): the domain is extended with a new element.
- Reduce Domain Operator (RDO): the domain is reduced by removing one element.
- Empty Domain Operator (EYDO): the domain is emptied.

These mutation operators can be applied to enumeration (See Table I), universes, collections, the set background, the list background, and the map background.

TABLE I. EXAMPLES OF ASM DOMAIN MUTATION OPERATORS FOR *CoreASM*

Domain Mutation Operator	CoreASM Mutant S'
Extend Domain Operator (EDO)	enum PRODUCT = {Soda, Candy, Chips, Sandwich}
Reduce Domain Operator (RDO)	enum PRODUCT = {Soda, Candy}
Empty Domain Operator (EYDO)	enum PRODUCT = {}

C. ASM Function Update Mutation Operators

A function update has the following form:

$$f(t_1, t_2, \ldots, t_n) := \text{value}$$

Depending on the type of operands, the traditional operators [8], [40] such as Absolute Value Insertion (ABS), Arithmetic Operator Replacement (AOR), Logical Operator Replacement (LOR), Statement Deletion (SDL), Scalar Variable Replacement (SVR), and Unary Operator Insertion (UOI) can be applied. In addition to these traditional mutation operators, we define *Function Parameter Replacement (FPR)* operator, where parameters of a function are replaced by other parameters of a compatible type. Two Types are compatible if values of one type can appear wherever values of the other type are expected, and vice versa.

- *Function Parameter Replacement (FPR)*: parameters of a function are replaced by other parameters of the same type.
- *Function Parameter Permutation (FPP)*: parameters of a function of same type are permuted.

Table II illustrates some examples of the proposed function update mutation operators.

TABLE II. EXAMPLES OF FUNCTION UPDATE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
ABS	x := a + b	x := a + abs(b)
AOR	x := a + b	x := a - b
LOR	y := m and n	y := m or n
SDL	x := a + b	skip
SVR	x := a * b	a := a * b
UOI	x := 3 * a	x := 3 * -a
FPR	price(Soda):=70	price(Candy):=70
FPP	packaging(Soda, Candy):=1	packaging(Candy, Soda):=1

D. ASM Transition Rules Mutation Operators

The transition relation is specified by guarded function updates, called *rules*, describing the modification of the functions from one state to the next. An ASM state transition is performed by firing a set of rules in one step.

1) Conditional Rule Mutation Operators: The general schema of an ASM transition system appears as a set of guarded rules:

$$\textbf{if } \mathit{Cond} \textbf{ then } Rule_{then} \textbf{ else } Rule_{else} \textbf{ endif}$$

where *Cond*, the guard, is a term representing a boolean condition. $Rule_{then}$ and $Rule_{else}$ are transition rules.

Many types of faults may occur on the guards of conditional rules [41]. Some of these faults include Literal Negation fault (LNF), Expression Negation fault (ENF), Missing Literal fault (MLF), Associative Shift fault (ASF), Operator Reference fault (ORF), Relational Operator fault (ROF), Stuck at 0(true)/1(false) fault (STF). Table III illustrates the mutation operators addressing the above fault classes. Furthermore, we define three additional conditional rule mutation operators:

- *Then Rule Replacement Operator (TRRO)*: replaces the rule $Rule_{then}$ by another existing rule.
- *Else Rule Replacement Operator (ERRO)*: replaces the rule $Rule_{else}$ by another existing rule.
- *Then Else Rule Permutation Operator (TERPEO)*: permutes the $Rule_{then}$ and the $Rule_{else}$ rules. It is worth noting that operators *TERPEO* and *ENO* would produce syntactically different but semantically equivalent mutants.

2) Sequence Rule Mutation Operators: The sequence rule aims at executing rules/function updates in sequence. *TurboASM* plugin offers two forms of sequential rules:

$$\textbf{seq } Rule_1 \textbf{ next } Rule_2 \quad (1)$$

TABLE III. EXAMPLES OF CONDITIONAL RULE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
LNO (Literal Negation)	**if** (a **and** b)	**if** (**not** a **and** b)
ENO (Expression Negation)	**if** (a **and** b)	**if not** (a **and** b)
MLO (Missing Literal)	**if** (a **and** b)	**if** (b)
ASO (Associative Shift)	**if** (a **and** (b **or** a))	**if** ((a **and** b) **or** a)
ORO (Operator Reference)	**if** (a **and** b)	**if** (a **or** b)
ROO (Relational Operator)	**if** (x >= c)	**if** (x <= c)
STO (Stuck at 0/1)	**if** (a **and** b)	**if** (*true*)
TRRO (Then Rule Replacement)	**if** a **then** *R1* **else** *R2*	**if** a **then** *R3* **else** *R2*
ERRO (Else Rule Replacement)	**if** a **then** *R1* **else** *R2*	**if** a **then** *R1* **else** *R3*
TERPEO (Then Else Rule Permutation)	**if** a **then** *R1* **else** *R2*	**if** a **then** *R2* **else** *R1*

Evaluates $Rule_1$, applies the generated updates in a virtual state, and evaluates $Rule_2$ in that state. The resulting update set is a sequential composition of the updates generated by $Rule_1$ and $Rule_2$.

$$\textbf{seqblock}\ Rule_1\ \ldots Rule_n\ \textbf{endseqblock} \quad (2)$$

Similar to the **seq** rule (above), this rule form executes the listed rules in sequence. The resulting update set is a sequential composition of the updates generated by $Rule_1 \ldots Rule_n$.

We define the following mutation operators for the sequence rule:

- *Add Rule Operator (ARO)*: adds a new rule to the sequence of rules.
- *Delete Rule Operator (DRO)*: deletes a rule from the sequence of rules.
- *Replace Rule Operator (RRO)*: replaces one of the rules in the sequence by another rule.
- *Permute Rule Operator (PRO)*: changes the order of the sequence rules by permuting two rules.

Table IV illustrates examples of the sequence rule mutation operators.

TABLE IV. EXAMPLES OF THE SEQUENCE RULE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
ARO	**seqblock** *R1 R2* **endseqblock**	**seqblock** *R1 R2 R3* **endseqblock**
DRO	**seqblock** *R1 R2 R3* **endseqblock**	**seqblock** *R1 R3* **endseqblock**
RRO	**seqblock** *R1 R2* **endseqblock**	**seqblock** *R1 R3* **endseqblock**
PRO	**seqblock** *R1 R2* **endseqblock**	**seqblock** *R2 R1* **endseqblock**

3) Block Rule Mutation Operators: If a set of ASM transition rules have to be executed simultaneously, a block rule (included in the BlockRule plugin) is used:

$$\textbf{par}\ Rule_1\ \ldots\ Rule_n\ \textbf{endpar}$$

The update generated by this rule is the union of all the updates generated by $Rule_1 \ldots Rule_n$. The sequence rule operators (i.e., ARO, DRO, and RRO defined in Section III-D2) can be applied to the block rule. Table V illustrates the sequence-block exchange mutation operator.

Applying PRO to a block rule, will produce an equivalent specification (i.e., **par** *R1 R2* **endpar** is equivalent to **par** *R2 R1* **endpar**). Section IV-B discusses equivalent mutants.

TABLE V. EXAMPLES OF THE BLOCK RULE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
ARO	**par** *R1 R2* **endpar**	**par** *R1 R2 R3* **endpar**
DRO	**par** *R1 R2 R3* **endpar**	**par** *R1 R3* **endpar**
RRO	**par** *R1 R2* **endpar**	**par** *R1 R3* **endpar**

4) Sequence-Block Exchange Operator: In addition to the sequence and block mutation operators, we define the *Sequence-Block Exchange Operator (SBEO)* to exchange a sequence rule with a block rule and vice versa. Table VI illustrates the sequence-block exchange mutation operator.

TABLE VI. EXAMPLES OF THE SEQUENCE-BLOCK RULE MUTATION OPERATOR

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
SBEO	**seqblock** *R1 R2* **endseqblock**	**par** *R1 R2* **endpar**
SBEO	**par** *R1 R2* **endpar**	**seqblock** *R1 R2* **endseqblock**

5) Choose Rule Mutation Operators: The choose rule consists on selecting elements (non deterministically) from specified domains that satisfy guards φ, then evaluates $Rule_{do}$. If no such elements exist, then evaluates $Rule_{ifnone}$.

$$\textbf{choose}\ x_1\ \textbf{in}\ D_1, \ldots, x_n\ \textbf{in}\ D_n\ \textbf{with}\ \varphi\ (x_1, \ldots, x_n)\ \textbf{do}\ Rule_{do}\ \textbf{ifnone}\ Rule_{ifnone}$$

The **with** and **ifnone** blocks are optional. The guard φ may be a simple boolean expression of predicate logic expressions.

To cover the *choose* rule, we define the following mutation operators:

- *Choose Domain Replacement Operator (CDRO)*: replaces a variable domain with another compatible domain.
- *Choose Guard Modification Operator (CGMO)*: alters the guard φ using the operators described in Table III. In this paper, we consider simple boolean expressions as guards. Predicate logic expressions such as *exists* are left for future work.
- *Choose DoRule Replacement Operator (CDoRO)*: replaces the rule $Rule_{do}$ by another rule.
- *Choose IfNoneRule Replacement Operator (CIRO)*: replaces the rule $Rule_{ifnone}$ by another rule.
- *Choose Rule Exchange Operator (CREO)*: replaces the $Rule_{do}$ rule by $Rule_{ifnone}$ rule.

Table VII illustrates the choose rule mutation operators.

TABLE VII. EXAMPLE OF THE CHOOSE RULE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
CDRO	**choose** x **in** Set1 **with** (x >= 0)	**choose** x **in** Set2 **with** (x >= 0)
CGMO	**choose** x **in** Set1 **with** (x >= 0)	**choose** x **in** Set1 **with** (x <= 0)
CDoRO	**choose** x **in** Set1 **do** R1	**choose** x **in** Set1 **do** R2
CIRO	**choose** x **in** Set1 **do** R1 **ifnone** R2	**choose** x **in** Set1 **do** R1 **ifnone** R3
CREO	**choose** x **in** Set1 **do** R1 **ifnone** R2	**choose** x **in** Set1 **do** R2 **ifnone** R1

6) Forall Rule Mutation Operators: The synchronous parallelism is expressed by a *forall* rule, which has the following form:

forall x_1 in D_1, ..., x_n in D_n **with** φ **do** $Rule_{do}$

where x_1, ..., x_n are variables, D_1, ..., D_n are the domains where x_i take their value, φ is a boolean condition, $Rule_{do}$ is a transition rule containing occurences of the variables x_i bound by the quantifier.

We define the following mutation operators for the *forall* rule that are quite similar to the ones of the *choose* rule :

- *Forall Domain Replacement Operator (FDRO)*: replaces a variable domain with another compatible domain.
- *Forall Guard Modification Operator (FGMO)*: alters the guard φ using the set of operators introduced in Table III.
- *Forall DoRule Replacement Operator (FDoRO)*: replaces the rule $Rule_{do}$ by any other rule.

TABLE VIII. EXAMPLES OF THE FORALL RULE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
FDRO	**forall** x **in** Set1 **with** (x = 0) **do** R1	**forall** x **in** Set2 **with** (x >= 0) **do** R1
FGMO	**forall** x **in** Set1 **with** (x = 0) **do** R1	**forall** x **in** Set1 **with** (x <= 0) **do** R1
FDoRO	**forall** x **in** Set1 **do** R1	**forall** x **in** Set1 **do** R2

7) Choose-Forall Exchange Operator: In addition to the proposed *forall* and *choose* rule mutation operators illustrated in Tables VIII and VII, we define the *Choose-Forall Exchange Operator (CFEO)* to exchange a *choose* rule with a *forall* rule and vice versa (See Table IX).

TABLE IX. EXAMPLES OF THE CHOOSE-FORALL EXCHANGE OPERATOR FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
CFEO	**forall** x **in** Set1 **do** R1	**choose** x **in** Set1 **do** R1
CFEO	**choose** x **in** Set1 **do** R1	**forall** x **in** Set1 **do** R1

8) Let Rule Mutation Operators: The *let* rule, included in the *LetRule* plugin, assigns a value of a term *t* to the variable *x* and then execute the rule *Rule* which contains occurrences of the variable *x*. The syntax of a *Let* rule is:

let (x = t) **in** $Rule$

We define the following *Let* rule mutation operators (see Table X):

- *Let Variable Assignment Operator (LVAO)*: assigns a different value to *x*, other than *t*, of a compatible type.
- *Let Rule Replacement Operator (LRRO)*: replaces the rule *Rule* by another rule that has occurrences of *x*.
- *Let Rule Variable Replacement (LRVR)*: replaces the variable *x* by another variable of same type.

TABLE X. EXAMPLES OF THE LET RULE OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
LVAO	**let** x = 1 **in** R1	**let** x = 2 **in** R1
LRRO	**let** x = 1 **in** R1	**let** x = 1 **in** R2
LRVR	**let** x = 1 **in** R1	**let** y = 1 **in** R1

9) Call Rule Mutation Operators: The call rule executes the previously defined transition rule R with the given parameters. Parameters are passed in a call-by-name fashion; i.e., they are passed unevaluated. The syntax of a *Call* rule is:

R(a_1, ..., a_n)

We define the following *Call* rule mutation operators (see Table XI):

- *Call Rule Parameter Replacement (CRPR)*: replaces the actual rule parameter by another parameter of the same type.
- *Call Rule Parameter Exchange (CRPE)*: permutes actual parameters if they are of the same type.

TABLE XI. EXAMPLE OF CALL RULE MUTATION OPERATOR

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
CRPR	rule Add(a, b)= return a+b rule Main = addition := Add(x,y)	rule Add(a, b)= return a+b rule Main = addition := Add (x,**z**)
CRPE	rule Add(a, b)= return a+b rule Main = addition := Add(x,y)	rule Add(a, b)= return a+b rule Main = addition := Add (**y**,**x**)

10)Pick Rule Mutation Operators: The pick rule, part of the *ChooseRule* plugin, provides another way of pick non-deterministically a value that satisfies a given condition from an enumerable. Its syntax is as follows:

pick *x* **in** *D* **with** *guard*

To cover the *pick* rule, we define the following mutation operators:

- *Pick Domain Replacement Operator (PDRO)*: replaces the domain D with another compatible domain.
- *Pick Guard Modification Operator (PGMO)*: alters the guard φ using the operators described in Table III.

Table XII illustrates the pick rule mutation operators.

11)Extend Rule Mutation Operators: The extend rule, part of *ExtendRule* plugin, is used to construct new elements and add them to a specific domain. The resulting update set is the updates generated by $Rule$.

TABLE XII. EXAMPLE OF THE PICK RULE MUTATION OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
PDRO	**pick** x **in** D1 **with** (x >= 0)	**pick** x **in** D2 **with** (x >= 0)
PGMO	**pick** x **in** D1 **with** (x >= 0)	**pick** x **in** D1 **with** (x <= 0)

extend *D* **with** *id* **do** *Rule*

We define the following *Extend* rule mutation operators (see Table XIII):

- *Extend Domain Replacement Operator (EDRO)*: replaces the domain by another compatible domain.
- *Extend Rule Replacement Operator (ERRO)*: replaces the rule $Rule$ by another one.
- *Extend Id Replacement Operator (EIRO)*: extends the domain with another element of a compatible type (e.g., extend the domain D1 with id2 instead of id1). All occurrences of the *id* are replaced in *Rule*.

TABLE XIII. EXAMPLES OF THE EXTEND RULE OPERATORS FOR *CoreASM*

Mutation Operator	CoreASM Spec S	CoreASM Mutant S'
EDRO	**extend** D1 **with** id1 **do** R1	**extend** D2 **with** id1 **do** R1
ERRO	**extend** D1 **with** id1 **do** R1	**extend** D1 **with** id1 **do** R2
EIRO	**extend** D1 **with** id1 **do** R1	**extend** D1 **with** id2 **do** R1

Other CoreASM-specific rules and constructs such as *Case* rule, add/remove *List* constructs, enqueue/dequeue *Queue* constructs, etc. are not covered in this paper.

E. CoreASM*: What is not Mutated*

Some mutation operators may have a possible infinite domain on which they operate. For instance, given the fact that the set of types might be infinite, it is difficult to determine how the declaration of a variable of one specific type may be mutated. This is applicable to libraries, functions names, etc. For the *CoreASM* language, the following entities are not mutated:

- Variable declarations.
- Format of strings in I/O functions.
- The *init* rule declaration (i.e., *init* InitRule)
- Plugin names introduced using the **use** keyword.
- Rule declarations
- Rule names indicating a call to a rule. Note that the actual parameters in a *Call* rule are mutated (e.g., *CRPR* and *CRPE* operators) but the rule names are not.

IV. ANALYSIS OF THE GENERATED MUTANTS

A. Inconsistent Updates

Applying *SBEO* operator may result into mutants that are syntactically correct but containing inconsistent updates. Therefore, the computation does not yield a next state. Table XIV shows a simple *CoreASM* sequence rule and its corresponding mutant after applying *SBEO* operator. The execution of the produced mutant may lead to an inconsistent update of variable a (i.e., in case variable a is updated twice simultaneously with different values (a+1 $\neq$ b)).

TABLE XIV. APPLYING SBEO OPERATOR THAT LEADS TO AN INCONSISTENT UPDATE

CoreASM Spec S	CoreASM Mutant S'
rule Main =	rule Main =
seqblock	**par**
$a := a + 1$	$a := a + 1$
$a := b$	$a := b$
endseqblock	**endpar**

B. Equivalent Mutants

In many cases, applying *CoreASM* mutation operator produces a specification that is equivalent to the original specification. For instance, the application of the *PRO* (Permute Rule Operator) to a block rule (e.g., **par** R1 R2 **endpar**), would produce a mutant (e.g., **par** R2 R1 **endpar**) that is equivalent to the original specification.

Similarly, applying *SBEO* operator may produce a mutant that is equivalent to the original specification. This might be the case when the rules enclosed within the parallel/sequence blocks are independent (i.e., with different functions updates). Table XV shows a specifications *S* and its mutant *S*'. Rules "a:=a+1" and "b:=b+1" are independent (i.e., Variables a and b are updated independently). Hence, no test cases would kill mutant *S*'. However, the original specification S produces 2 states (i.e., one a:= a + 1 and one for b := b +1) whereas its mutant S' produces only one single state (i.e., a:= a +1 and b := b + 1 are executed in one single step).

TABLE XV. APPLYING SBEO OPERATOR PRODUCES A MUTANT THAT IS EQUIVALENT TO THE ORIGINAL SPEC

CoreASM Spec S	CoreASM Mutant S'
rule Main =	rule Main =
seqblock	**par**
$a := a + 1$	$a := a + 1$
$b := b + 1$	$b := b + 1$
endseqblock	**endpar**

In general, like traditional programming languages, detecting *CoreASM* equivalent mutants is an undecidable problem [40].

V. COREASM MUTATION TOOLKIT

Figures 2, 3, and 4 illustrate the Microsoft .NET C#-based, *CoreASM Mutation Toolkit* GUI. The GUI is composed of four tab pages: (1) Mutants Generator tab (Figure 2), (2) Mutants Viewer tab (Figure 3), (3) Test Execution tab (Figure 4), and (4) Help tab. The user starts with loading a *CoreASM* specification, then he/she selects one or multiple operators from the three operator categories. The produced mutants are created and stored in separate files in a separate directory.

In Section III, we have stated that only syntactically correct mutants are generated, as a result of applying the mutation

operators. This guiding principle is further enforced by checking the validity of the produced mutants using the *Carma* command line. The invalid mutants, if any, are then discarded. The error output for syntactically invalid mutants is stored in a log file.

The generated mutants can be viewed using the second tab page (see Figure 3). Statistics about the type and the number of produced valid mutants are listed in the log section.

The test execution GUI (Figure 4) allows for the execution of test cases against the generated mutants. The test case definition include a sequence of inputs that the specification requires the user to enter, a sequence of expected outputs (one per line), and a sequence of strings from which the output will be extracted (one per line).

VI. Illustrative Example: Fibonacci Series

In this section, we apply mutation testing to a *CoreASM* specification that produces *Fibonacci* numbers. The *Fibonacci* numbers or Fibonacci series are the numbers in the following integer sequence:

$$0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, \ldots$$

By definition, the first two numbers in the Fibonacci sequence are 0 and 1, and each subsequent number is the sum of the previous two. In mathematical terms, the sequence F_n of Fibonacci numbers is defined by the recurrence relation:

$$F_n = F_{n-1} + F_{n-2}$$

Figure 5 describes the *CoreASM* recursive implementation for producing *Fibonacci* numbers. The user is asked to enter a number from the standard input (the entered string is converted into a *Number* and stored in variable *n*), then the function *fibo_r* is invoked and the output is printed on the standard output using the *print* directive.

```
CoreASM Fibonacci
use Standard
init InitRule
rule InitRule =
  seqblock
      n := toNumber(input("Enter n now \n:"))
      print "Fibonacci(" + n + ") using pure recursion: " + fibo_r(n)
      program(self) := undef
  endseqblock
derived fibo_r(x) =
      local r in return r in
      if x < 0 then r := 0
      else if x < 2 then r := x
      else r := fibo_r(x-2) + fibo_r(x-1)
```

Fig. 5. *CoreASM* Fibonacci Recursive Specification

The input domain for the Fibonacci example can be partitioned into three blocks: (1) negative numbers, (2) zero, and (3) positive numbers. The refinement of the resulting three blocks lead to the creation of three test cases: (TC1) input:-1, expected output:0, (TC2) input:0, expected output:0, and

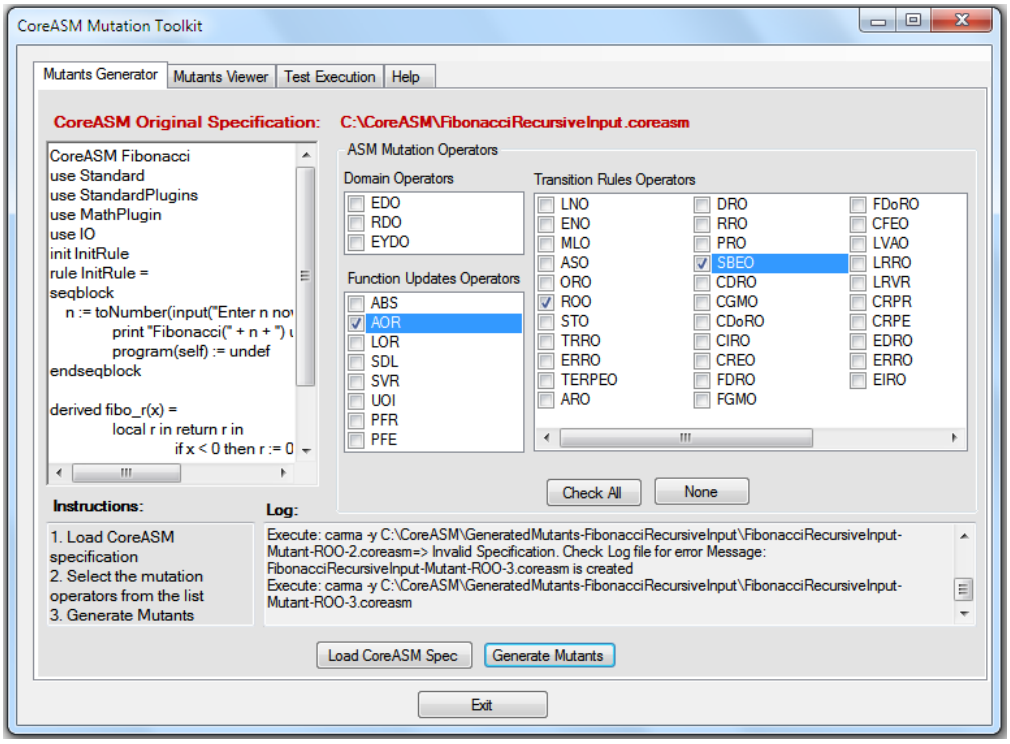

Fig. 2. CoreASM Mutation Toolkit: Mutants Generation GUI

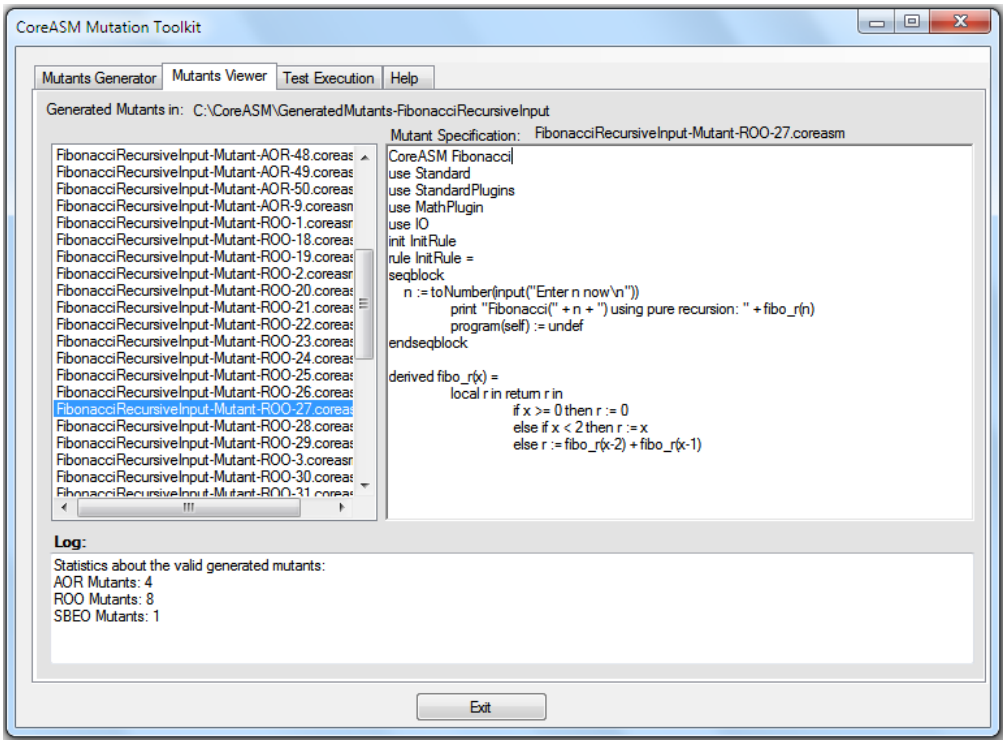

Fig. 3. *CoreASM* Mutation Toolkit: Mutants Viewer GUI

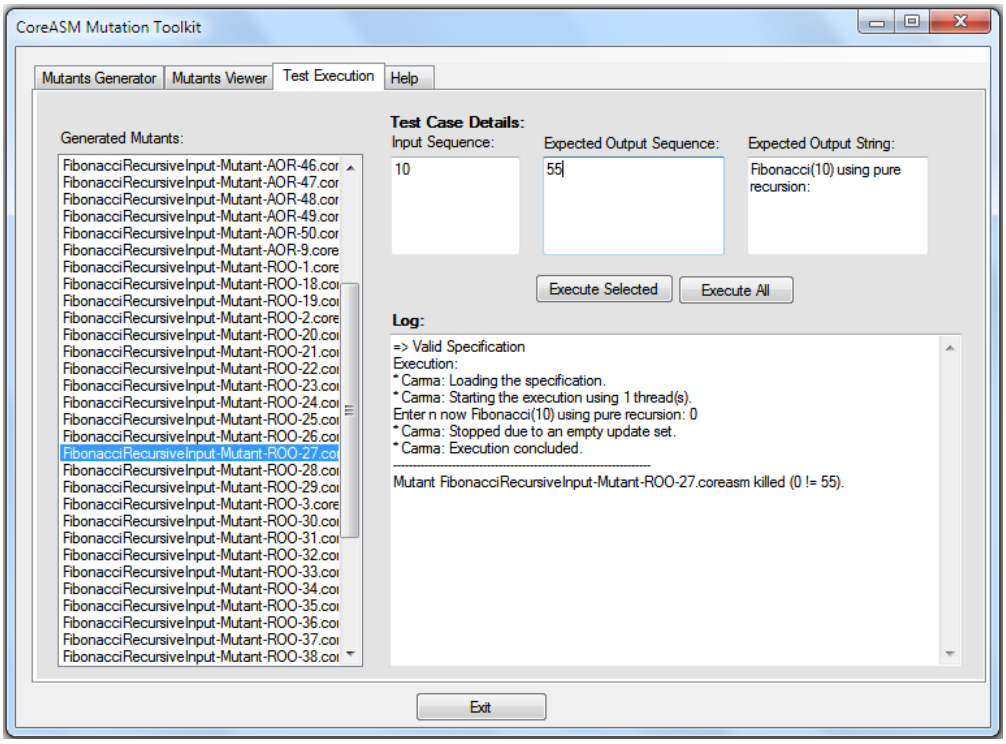

Fig. 4. *CoreASM* Mutation Toolkit: Mutants Executor GUI

(TC3) input:10, expected output:55.

Table XVI shows the distribution breakdown into separate operators of the 48 generated mutants (i.e, valid mutants only). The execution of a test case leads to one the following two outputs:

- A numeric output value. For example, the execution of the TC3 against mutant *FibonacciRecursiveInput-Mutant-ROO-27.coreasm* (Figure 4) produces an output equal to 0, which is different from the expected output 55. Hence the test case has killed the mutant. This mutant is said to be of type error revealing.
- A *null* output in case the execution is not conclusive. For example, the execution of TC3 against mutant *FibonacciRecursiveInput-Mutant-AOR-9.coreasm* which replaces *fibo_r(x-2)* with *fibo_r(x+2)* leads to a *null* output. Again, the test case has killed the mutant.

Fourty seven mutants have been killed by the proposed test suite. Mutant *FibonacciRecursiveInput-Mutant-ROO-1.coreasm* that replaces $x<0$ by $x<=0$) remains alive. This mutant is equivalent to the original specification and cannot be killed by any test case.

TABLE XVI. GENERATED MUTANTS STATISTICS FOR THE FIBONACCI EXAMPLE (FIGURE 5)

Mutation Operator	Number of Valid Mutants	Number of Killed Mutants
ABS	6	6
AOR	4	4
SDL	3	3
SVR	3	3
UOI	6	6
STO	4	4
ENO	2	2
ROO	8	7
TRRO	2	2
ERRO	2	2
TERPEO	1	1
CRPR	6	6
SBEO	1	1
Total	48	47

The test set effectiveness (TC_{eff}) (also called *adequacy score*) is computed by the following equation:

$$TC_{eff} = \frac{M_k}{M_t - M_e} \quad (3)$$

where M_k is the number of killed mutants, M_t is the total number of generated mutants, and M_e is the number of equivalent mutants.

A test set effectiveness score of 100% is acquired for the three proposed test cases.

VII. EMPIRICAL COMPARISON OF MUTATION OPERATORS

To empirically compare the proposed mutation operators, we ran experiments on three *CoreASM* specifications:

- Dining Philosophers [42] (98 LOC).
- Vending Machine [43] (208 LOC).
- Rail Road Crossing [44] (107 LOC).

Tables 6(a), 6(b), and 6(c) illustrate the number of resulting mutants for each mutation operators for each specification. We made the following observations:

- The number of mutants produced by domain operators is low (2, 3, and 4 respectively). Indeed, we were able to apply *EDO* only. Applying *RDO* and *EYDO* have produced syntactically incorrect mutants for the three specifications.
- The number of mutants produced by transition rules operators (e.g., *ROO*, *STO*, etc.) is the highest amongst the three categories. This is expected because the general schema of an ASM transition system appears as a set of guarded rules.
- The number of rules, the number of used variables, the number of conditions, the number of rule calls, etc. are important factors impacting the number of produced *CoreASM* mutants.
- ROO (relational operator) is the operator that have produced the largest number of mutants for the vending machine and the rail road crossing examples.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we have extended our previous work [1] on designing mutation operators for the Abstract State Machines (ASM) formalism. The developed operators are classified into three categories: (1) Domain operators, (2) function update operators, and (3) transition rules operators. Furthermore, a prototype mutation tool for the *CoreASM* language, has been built to automatically generate mutants and check their validity. We have illustrated our approach using a simple *CoreASM* implementation of the *Fibonacci* series. An initial empirical comparison of the number of generated mutants is presented and discussed.

As a future work, we are planning to enhance our empirical study by considering parameters such as the number of variables, the number of rules, etc, and by assessing the effectiveness of the defined mutation operators.

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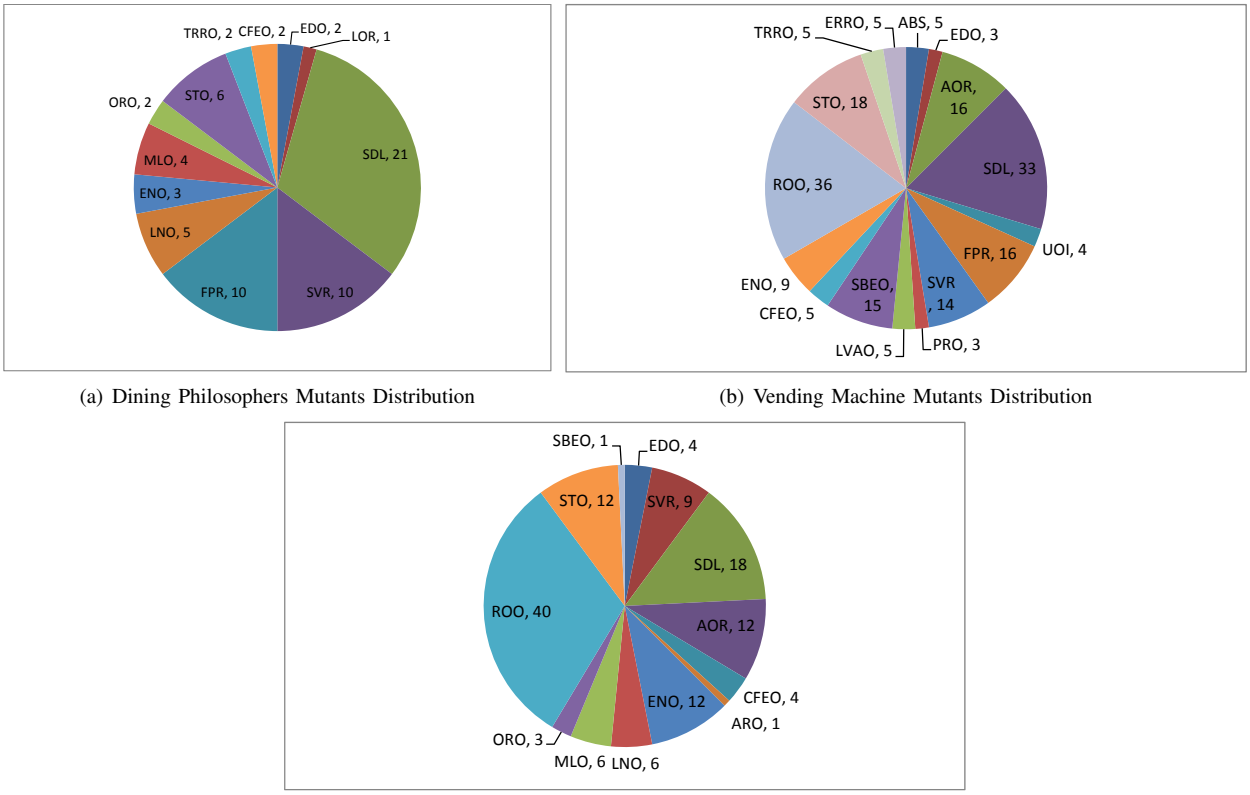

(a) Dining Philosophers Mutants Distribution

(b) Vending Machine Mutants Distribution

(c) Rail Road Crossing Mutants Distribution

Fig. 6. Number of Generated Mutants for Dining Philosophers, Vending Machine, and Rail Road Crossing *CoreASM* Specifications

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Transformational Implementation of Business Processes in SOA

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Abstract—**The paper develops a method for transformational implementation and optimization of business processes in a service oriented architecture. The method promotes separation of concerns and allows making business decisions by business people and technical decisions by technical people. To achieve this goal, a description of a business process designed by business people is automatically translated into a program in Business Process Execution Language, which is then subject to a series of transformations developed by technical people. Each transformation changes the process structure in order to improve the quality characteristics. Two approaches to the verification of the process correctness are discussed. The first one applies a correct-by-construction approach to transformations. The other one relies on automatic verification of the transformed process behavior against the behavior of the original reference process. The verification mechanism is based on a mapping from Business Process Execution Language to Language of Temporal Ordering Specification, followed by a comparison of the trace set that is generated using a program dependence graph of the reference process and the trace set of the transformed one. When the design goals have been reached, the transformed BPEL process can be executed on a target SOA environment using a BPEL engine.**

Keywords-business process; service oriented architecture; BPEL; LOTOS; transformational implementation.

I. INTRODUCTION

This paper is an extension of the ICSEA paper [1] on transformational implementation of business processes in a service oriented architecture. A business process is a set of logically related activities performed to achieve a defined business outcome [2]. The structure of a business process and the ordering of activities reflect business decisions made by business people and, when defined, can be visualized using an appropriate notation, e.g., Business Process Model and Notation [3] or the notation of ARIS [4]. The implementation of a business process on a computer system is expected to exhibit the defined behavior at a satisfactory level of quality. Reaching the required level of quality may need decisions, made by technical people and aimed at restructuring of the initial process in order to benefit from the characteristics offered by an execution environment. The structure of the implementation can be described using another notation, e.g., Business Process Execution Language [5] or UML activity diagrams [6].

This paper describes a transformational method for the implementation and optimization of business processes in a service oriented architecture (SOA). The method begins with an initial definition of a business process, written by business people using Business Process Modeling Notation (BPMN). The business process is automatically translated into a program in Business Process Executable Language (BPEL), called a reference process. The program is subject to a series of transformations, each of which preserves the behavior of the reference process, but changes the order of activities, as means to improve the quality of the process implementation, e.g., by benefiting from the parallel structure of services. Transformations applied to the reference process are selected manually by human designers (technical people) and performed automatically, by a software tool. When the design goals have been reached, the iteration stops and the result is a transformed BPEL process, which can be executed on a target SOA environment.

Such an approach promotes separation of concerns and allows making business decisions by business people and technical decisions by technical people.

A critical part of the method is providing assurance on the correctness of the transformational implementation of a business process. Two approaches to the verification of the process correctness are discussed in this paper. The first one applies a correct-by-construction approach that consists in defining a set of safe transformations, which do not change the process behavior. If all transformations are safe, then the transformed program will also be correct, i.e., semantically equivalent to the original reference process.

The other approach relies on automatic verification of the transformed process behavior against the behavior of the original reference process. The verification mechanism is based on a mapping from BPEL to Language of Temporal Ordering Specification (LOTOS), followed by a comparison of the trace set that is generated using a program dependence graph of the reference process and the trace set of the transformed one.

The rest of this paper is organized as follows. Related work is briefly surveyed in Section II. The semantics of a BPEL process and its behavior are defined in Section III. A set of safe transformations are introduced in Section IV. An illustrative case study is provided in Section V. A method for the verification of correctness, based on LOTOS language and a BPEL to LOTOS mapping is covered in Section VI. Quality metrics to assess transformation results are described in Section VII. Conclusions and plans for future research are given in Section VIII.

II. Related Work

Transformational implementation of software is not a new idea. The approach was developed many years ago within the context of monolithic systems, with the use of several executable specification techniques. The formal foundation was based on problem decomposition into a set of concurrent processes, use of functional languages [7] and formal modeling by means of Petri nets [8].

An approach for transformational implementation of business processes was developed in [9]. This four-phase approach is very general and not tied to any particular technology. Our method, which can be placed in the fourth phase (implementation), is much more specific and focused on the implementation of runnable processes described in BPMN and BPEL.

BPMN defines a model and a graphical notation for describing business processes, standardized by OMG [3]. The reference model of SOA [10,11] and the specification of BPEL [5] are standardized by OASIS. An informal mapping of BPMN to BPEL was defined in [3]. A comprehensive discussion of the translation between BPMN and BPEL, and of some conceptual discrepancies between the languages, can be found in [12,13]. An open-source tool is available for download at [14].

The techniques of building program dependence graph and program slicing, which we adopted for proving safeness of transformations, were developed in [15,16] and applied to BPEL programs in [17].

Several metrics to measure the quality of parallel programs have been proposed in the literature and studied for many years. A traditional metric for measuring performance of a parallel application is Program Activity Graph, which describes parallel flow of control within the application [18]. We do not use such a graph, nevertheless, our two metrics: Length of thread and Response time, can be viewed as an approximation of Critical path metric described in [18]. Similarly, our Number of threads metric is similar to Available concurrency defined in [19].

To the best of our knowledge, our work on the implementation of business processes in service oriented architecture is original. Preliminary results of our research were published in [1]. An extended version, including a revised algorithm for building program dependence graph and an original method for the verification of transformation correctness are introduced in this paper.

III. The Semantics of a Business Process

A business process is a collection of logically related activities, performed in a specific order to produce a service or product for a customer. The activities can be implemented on-site, by local data processing tasks, or externally, by services offered by a service-oriented environment. The services can be viewed from the process perspective as the main business data processing functions.

A specification of a business process can be defined textually, e.g., using a natural language, or graphically, using BPMN. An example BPMN process, which executes a simplified processing of a bank transfer order is shown in Fig. 1. The process begins and waits for an external invocation from a remote client (another process). When the invocation is received, the process extracts the source and the target account numbers from the message, checks the availability of funds at source and splits into two alternative branches. If the funds are missing, the process prepares a negative acknowledgement message, replies to the invoker, and ends. Otherwise, the alternative branch is empty. Then, the process invokes the withdraw service at source account, invokes the deposit service at target account, packs the results returned by the two services into a single reply message, replies to the invoker and ends. This way, the process implements a service, which is composed of another services.

BPMN specification of a business process can be automatically translated into a BPEL program, which can be used for a semi-automatic implementation.

BPEL syntax is composed of a set of instructions, called activities, which are XML elements indicated in the document by explicit markup. The set of BPEL activities is rich. However, in this paper, we focus on a limited subset of activities for defining control flow, service invocation, and basic data handling.

The body of a BPEL process consists of simple activities, which are elementary pieces of computation, and structured elements, which are composed of other simple or structured activities, nested in each other to an arbitrary depth. Simple activities are <assign>, which implements substitution, <invoke>, which invokes an external service, and <receive>, <reply> pair, which receives and replies to an invocation. Structured activities are <sequence> element to describe sequential execution, <flow> element to describe parallel execution and <if> alternative branching. An example BPEL program, which implements the business process in Fig. 1, is

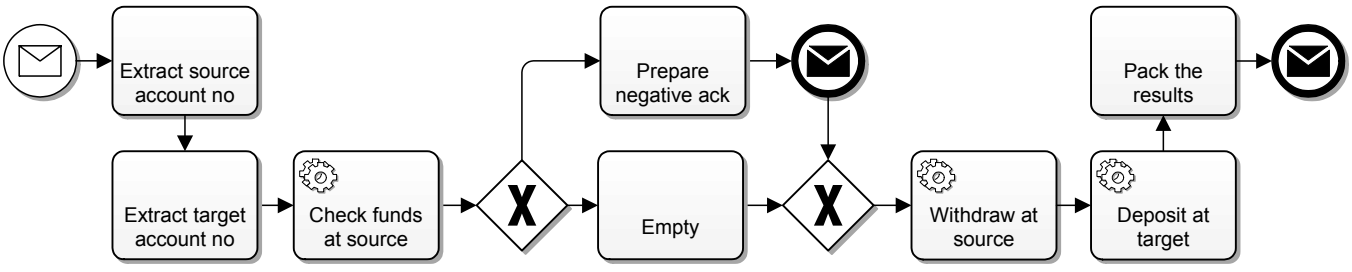

Figure 1. BPMN specification of a business process

```
<sequence>
    <receive name="rcv" variable="transfer"/>
    <assign name="src">
        <copy> <from variable="transfer" part="srcAccNo"/>
        <to variable="source" part="account"/> </copy>
        <copy> <from variable="transfer" part="srcAmount"/>
        <to variable="source" part="amount"/> </copy>
    </assign>
    <assign name="dst">
        <copy> <from variable="transfer" part="dstAccNo"/>
        <to variable="target" part="account"/> </copy>
        <copy> <from variable="transfer" part="dstAmount"/>
        <to variable="target" part="amount"/> </copy>
    </assign>
    <invoke name="verify" inputVariable="source"
        outputVariable="fundsAvailable"/>
    <if> <condition> $fundsAvailable.res </condition>
        <empty name="empty"/>
    <else> <sequence>
        <assign name="fail">
            <copy> <from> 'lack of funds' </from>
            <to variable="response" part="fault"/> </copy>
        </assign>
        <reply name="nak" variable="response"/>
        <exit name="exit"/>
    </sequence> </else> </if>
    <invoke name="withdraw" inputVariable="source"
            outputVariable="wResult"/>
    <invoke name="deposit" inputVariable="target"
            outputVariable="dResult"/>
    <assign name="success">
        <copy> <from variable="wResult" part="res"/>
        <to variable="result" part="withdraw"/> </copy>
        <copy> <from variable="dResult" part="res"/>
        <to variable="result" part="deposit"/> </copy>
    </assign>
    <reply name="ack" variable="result"/>
</sequence>
```

Figure 2. A skeleton of a BPEL program of a bank transfer (Fig. 1)

shown in Fig. 2. Name attribute will be used to refer to particular activities of the program in the subsequent figures.

The first executable activity of the program is <receive>, which waits for a message that invokes the process execution and conveys a value of the input argument. The last activity of the process is <reply>, which responds to the invocation and sends a message that returns the result. The activities between <receive> and <reply> execute a business process, which invokes other services and transforms the input into the output. This is a typical construction of a BPEL process, which can be viewed as a service invoked by other services.

SOA services are assumed stateless [20], which means that the result of a service execution depends only on values of data passed to the service at the invocation, and manifests to the outside world as values of data sent by the service in response to the invocation. Therefore, we assume that the observable behavior of a process in a SOA environment consists of data values, which the process passes as arguments when it invokes external services, and data values, which it sends in reply to the invoker.

A. Program Dependence Graph

To capture the influence of a process structure into the process behavior, we use a technique called program slicing [15,16], which allows finding all the instructions in a program, which influence the value of a variable in a specific point of the program. For example, finding the instructions that influence the value of a variable that is used as an argument by a service invocation activity or by a reply activity of the process.

The conceptual tool for the analysis is Program Dependence Graph (PDG), whose nodes are activities of a BPEL program, and edges reflect dependencies between the activities. An algorithm for constructing PDG of a BPEL program consists of the following steps:

1. Define nodes of the graph, which are activities at all layers of nesting.
2. Define control edges (solid lines in Fig. 3), which follow the nested structure of the program, e.g., an edge from <sequence> to <if> shows that <if> activity is nested within the <sequence> element. Output edges of <if> node are labeled "Yes" or "No", respectively.
3. Define dataflow edges (dashed lines in Fig. 3), which reflect dataflow dependencies between the activities, e.g., an edge from activity "rcv" to activity "src" shows that an output variable of "rcv" is used as input variable to "src".
4. Add dataflow edges from <receive> activity, which is nested within a <sequence> element, to each subsequent activity of this <sequence> such that no paths from <receive> to this activity exists (there are no such items in Fig. 3).
5. If an <exit> activity is nested within a <sequence>, then:
   a. remove all the activities, which are subsequent to <exit>, together with all the input and output edges,

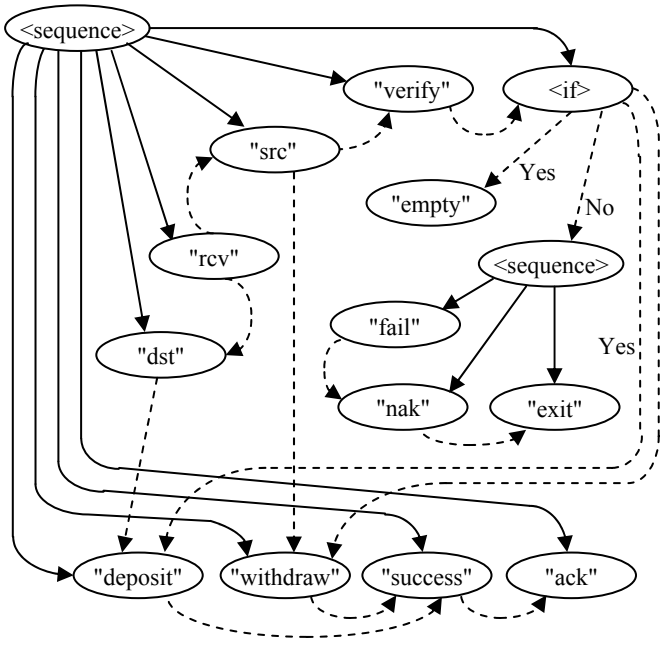

Figure 3. Program dependence graph of the bank transfer process

b. for each antecedent activity with no path to <exit>, add a dataflow edge from this activity to <exit> ("nak" to "exit" edge in Fig. 3).

6. If an <if> element is nested within a <sequence> and there is an <exit> within "Yes" ("No") branch of <if>, then add "No" ("Yes") edges from <if> to subsequent activities with no path from <if> (<if> to "deposit" and <if> to withdraw edges in Fig. 3).
7. Convert "Yes" and "No" edges that output <if> activities into dataflow edges.

Dataflow edges within a program dependence graph reflect the dataflow dependencies between subsequent activities, which determine values of the program variables. The edges added in step 4 reflect the semantics of the process as a service, which starts after receiving an invocation message. The edges added in steps 5 and 6 reflect the semantics of <exit>, which stops the program and prevents execution of all the subsequent activities. Dataflow edges introduced in step 7 reflect the semantics of <if> statement, which outgoing branches may execute only after evaluating the condition. An example program dependence graph of the business process in Fig. 2 is shown in Fig. 3. It can be noted, that the flow of control within the original BPEL program complies with dataflow edges of its program dependence graph.

In the rest of this paper, we adopt a definition that a transformation preserves the process behavior, if it keeps the set of messages sent by the process as well as the data values carried by these messages unchanged. Such a definition neglects the timing aspects of the process execution. This is justified, given that it does not change the business requirements. There are many delays in a SOA system and the correctness of software must not relay on a specific order of activities, unless they are explicitly synchronized.

A transformation that preserves the process behavior is called safe.

Definition (Safeness of a transformation)

A transformation is safe, if the set of messages sent by the activities of a program remains unchanged and the flow of control within the transformed program complies with the direction of dataflow edges within the program dependence graph of the reference process. □

The set of activities executed within a program may vary, depending on decisions made when passing through decision points of <if> activities. To fulfill the above definition, the set of messages must remain unchanged, for each particular combination of these decisions.

A path composed of dataflow edges in a program dependence graph reflects the dataflow relationships between the activities, and implies that the result of the activity at the end of the path depends only on the preceding activities on this path. If the succession of activities executed within a program complies with the dataflow edges, then the values of variables computed by the program remain the same, regardless of the ordering of other activities of this program.

Safeness of a transformation guarantees that the transformation preserves the behavior of the transformed program as observed by other services in a SOA environment. Safeness is transitive and a sequence of safe transformations is also safe. Therefore, a process resulting from a series of safe transformations applied to a reference process preserves the behavior of the reference process.

IV. SAFE TRANSFORMATIONS

The body of a BPEL process consists of simple activities, e.g., <assign>, which define elementary pieces of computation, and structured elements, e.g., <flow>, which is composed of other simple or structured activities. The behavior of the process results from the order of execution of activities, which stem from the type of structured elements and the positioning of activities within these elements. A transformation applies to a structured element and consists in replacing one element, e.g., <flow>, by another element, e.g., <sequence>, or in relocation of activities within the structured element. If the behavior of the transformed element before and after the transformation is the same, then the behavior of the process stands also unchanged.

Several transformations have been defined. The basic ones: simple and alternative displacement, parallelization and serialization of the process operations, and process partitioning are described in detail below. All the transformations are safe, according to definition of safeness given in Section III. As pointed out in Section III, a safe transformation does not change the behavior of a process, which is composed of stateless services. A problem may arise, if the services invoked by a process have an impact on the real world. If this is the case, a specific ordering of these services may be required. In our approach, a designer can express the necessary ordering conditions adding supplementary edges to the program dependence graph.

Transformation 1: Simple displacement

Consider a <sequence> element, which contains n arbitrary activities executed in a strictly sequential order. Transformation 1 moves a selected activity A from its original position i, into position j within the sequence.

***Theorem* 1.** Transformation 1 is safe, if no paths between activity A and the activities placed on positions i+1, … j in the sequence existed in the program dependence graph of the transformed program.

Proof: Assume that $i < j$ (move forward). The transformation has no influence on activities placed on positions lower than i or higher than j. However, moving activity A from position i to j reverts the direction of the flow of control between A and the activities that are in-between. This could be dangerous if a dataflow from A to those activities existed. However, if no dataflow paths from A to the activities placed on positions i+1, … j existed in the program dependence graph, then no inconsistency between the control and data flow can exist.

If $j < i$ (move backward), the proof is analogous. The lack of dataflow path guarantees lack of inconsistency between the data and control flows within the program. □

Transformation 2: Pre-embracing

Consider a <sequence> element, which includes an <if> element preceded by an <assign> activity, among others. Branches of <if> element are <sequence> elements. Transformation 2 moves <assign> activity from its original position in the outer <sequence>, into the first position within one branch of <if> element.

***Theorem* 2.** Transformation 2 is safe, if neither a path from the moved <assign> to an activity placed in the other branch of <if>, nor a path from the moved <assign> to the activities positioned after <if> in the outer sequence, existed in the program dependence graph of the transformed program.

Proof: The transformation has no influence on activities placed prior to <if> element in the outer <*sequence*>. Moving <assign> activity to one branch of <if> removes the flow of control from <assign> to activities in the other branch of <if> and – possibly – to activities placed after <if>. But according to the assumption of this theorem, there is no data flow between these activities. Therefore, no inconsistency between the control and data flow can exist. □

Transformation 3: Post-embracing

Consider a <sequence> element, which includes an <if> activity followed by a number of another activities. Branches of <if> element are <sequence> elements, one of which contains <exit> activity. Transformation 3 moves the activities, which follow <if>, from its original position in the outer <sequence> into the end of the second <sequence> of <if> element.

***Theorem* 3.** Transformation 3 is safe.

Proof: Activities, which are placed after an <if> element in the reference process, are executed only after the execution of <if> is finished. The existence of <exit> in one branch of <if> prevents execution of these activities when this branch is selected. The activities are executed only in case the other branch is selected. Therefore, neither the flow of control nor the flow of data is changed in the program, when the activities are moved to the other branch of <if>, i.e., the branch without <exit> activity. □

Transformation 4: Parallelization

Consider a <sequence> element, which contains *n* arbitrary activities executed in a strictly sequential order. Transformation 4 parallelizes the execution of activities by replacing <sequence> element by <flow> element composed of the same activities, which – according to the semantics of <flow> – are executed in parallel.

***Theorem* 4.** Transformation 4 is safe, if for each pair of activities A_i, A_j neither a path from A_i to A_j nor a path from A_j to A_i existed in the program dependence graph of the transformed program.

Proof: The transformation changes the flow of control between the activities of the transformed element. The lack of dataflow paths between these activities means that no inconsistency between the control and data flow can exist. □

Transformation 5: Serialization

Consider a <flow> element, which contains *n* arbitrary activities executed in parallel. Transformation 5 serializes the execution of activities by replacing <flow> element by <sequence> element, composed of the same activities, which are now executed sequentially.

```
<invoke name="xxx"                                        (a)
   inputVariable="source"  outputVariable="target"
/>

<sequence>                                                (b)
   <invoke name="xxx_i"  inputVariable="source"/>
   <receive name="xxx_r"  variable="target"/>
</sequence>
```

Figure 4. Synchronous (a) and asynchronous service invocation (b)

***Theorem* 5.** Transformation 5 is safe.

Proof: The proof is obvious. Parallel commands can be executed in any order, also sequentially.

Transformation 6: Asynchronization

Consider a two-way <invoke> activity, which sends a message to invoke an external service and then waits for a response (Fig. 4a). Transformation 6 replaces the two-way <invoke> activity with a sequence of a one-way <invoke> activity followed by a <receive> (Fig. 4b). This way, a synchronous invocation of a service is converted into an asynchronous one.

Transformation 6 can be proved safe, if we add a dataflow edge from <invoke> node to <receive> node in the program dependence graph of each program, which includes an asynchronous service invocation shown in Fig. 4b.

***Theorem* 6.** Transformation 6 is safe.

Proof: The transformation has no influence on activities executed prior to <invoke> activity. Dataflow edges from these activities to <invoke> remain unchanged. The transformation has no influence on activities executed after <invoke>, as well. Dataflow edges to these activities from <invoke> are redirected to begin at node <receive>. Hence, there is a one-to-one mapping between the sets of dataflow paths, which exist in program dependence graph of a program before and after the transformation. Therefore, no inconsistency between the control and data flow can exist.

Transformations 1 through 6 can be composed in any order, resulting in a complex transformation of the process structure. Transformations 7 and 8 play an auxiliary role and facilitate such a composition. These transformations are safe,

```
<sequence>          (a)          <flow>              (b)
   <sequence>                       <flow>
      <C1> </C1>                       <C1> </C1>
      .....                            .....
      <Ck> </Ck>                       <Ck> </Ck>
   </sequence>                      </flow>
   <sequence>                       <flow>
      <Ck+1> </Ck+1>                   <Ck+1> </Ck+1>
      .....                            .....
      <Cn> </Cn>                       <Cn> </Cn>
   </sequence>                      </flow>
</sequence>                      </flow>
```

Figure 5. Sequential (a) and parallel (b) partitioning of commands

because they do not change the order of execution of any activities within a BPEL program. □

Transformation 7: Sequential partitioning

Transformation 7 divides a single <sequence> element into a nested structure of <sequence> elements (Fig. 5a).

Transformation 8: Parallel partitioning

Transformation 8 divides a single <flow> element into a nested structure of <flow> elements (Fig. 5b).

V. CASE STUDY

Consider a process of transferring funds between two different bank accounts, shown in Fig. 1, implemented by a BPEL process. A skeleton of the simplified BPEL program of this process is shown in Fig. 2.

The process body is a sequence of activities, which starts at <receive>. Then, it proceeds through a series of steps to process the received bank transfer order and to invoke services offered by the banking systems to verify availability of funds at source account, to withdraw funds and to deposit the funds at the destination account. Finally, it ends after replying positively, if the transfer has successfully been done, or negatively, if the required amount of funds was not available at source.

PDG of this program is shown in Fig. 3. The first two <*assign*> activities process the contents of the received message in order to extract the source and destination account numbers and the amount of money to transfer. Therefore, there are dataflow edges from "rcv" to "src" and to "dst" nodes in PDG. The next consecutive <invoke> activity uses the extracted source account number and the amount of money to invoke the verification service, and the response of the invocation is checked by <if> activity. Therefore, two dataflow edges from *src* to *verify* and from *verify* to <if> exist in the graph. Similarly, the <invoke> activities named "withdraw" and "deposit" use the account numbers calculated by "src" and "dst", respectively. Two dataflow edges from "withdraw" and "deposit" nodes to "success" node, and then an edge from "success" to "ack", reflect the path of preparing the acknowledgement message that is sent to the invoker when the transfer is finished.

The analysis of the program dependence graph in Fig. 3 reveals that no dataflow path between activity named "dst" and the next two activities "src" and "verify" exists in the graph. Therefore, these activities can be executed in parallel. Similarly, there is no dataflow path between two consecutive <invoke> activities "withdraw" and "deposit". These two activities can also be executed in parallel.

To perform these changes, we can partition the outer <sequence> element using transformation 6 three times, and then parallelize the program structure using transformation 4 twice. A skeleton of the resulting BPEL program is shown in Fig. 6. Only names of the activities are shown in Fig. 6. The variables used by the activities are omitted for brevity.

However, this is not the only way of transformation. Alternatively, the designer can displace "dst" forward, just before <if> activity, and then use transformation 2 in order to enter "dst" to the inside of <if> in place of <empty> activity. Next, transformation 3 can be used to embrace the last three activities of the outer <sequence> element into the first branch of <if> element, consecutively following "dst". Then, the designer can move "dst" forward, adjacent to "deposit", partition the inner sequence of <if> using transformation 6, and parallelize the program structure using transformation 4. A skeleton of the resulting BPEL program is shown in Fig. 7. We removed "exit" activity from the final program, because it is obviously redundant at the end of the program.

```
<sequence>
   <receive name="rcv">              - receive transfer order
   <flow>
      <assign name="dst">            - extract destination no
      <sequence>
         <assign name="src">         - extract source no
         <invoke name="verify">      - verify funds at source
      </sequence>
   </flow>
   <if>
      <condition> ... </condition>   - check availability
         <empty name="empty">        - do nothing if available
      <else> <sequence>
         <assign name="fail">        - set response
         <reply name="nak">          - reply negatively
         <exit name="exit">          - end of execution
      </sequence> </else>
   </if>
   <flow>
      <invoke name="withdraw">       - withdraw funds
      <invoke name="deposit">        - deposit funds
   </flow>
   <assign name="success">
   <reply name="ack">                - reply positively
</sequence>
```

Figure 6. A skeleton of the transformed bank transfer process – variant I

```
<sequence>
   <receive name="rcv">                  - receive order
   <assign name="src">                   - extract source no
   <invoke name="verify">                - verify funds
   <if>
      <condition> ... </condition>       - check availability
      <sequence>
         <flow>
            <invoke name="withdraw">     - withdraw funds
            <sequence>
               <assign name="dst">       - extract dst. no
               <invoke name="deposit">   - deposit funds
            </sequence>
         </flow>
         <assign name="success">
         <reply name="ack">              - reply positively
      </sequence>
      <else> <sequence>
         <assign name="fail">            - set response
         <reply name="nak">              - reply negatively
      </sequence> </else>
   </if>
</sequence>
```

Figure 7. A skeleton of the transformed bank transfer process – variant II

The main advantage of the transformed process over the original one is higher level of parallelism, which can lead to better performance of the program execution. If we compare the two alternative designs, then intuition suggests that the structure of the second process is better than of the first one. In order to verify this impression, the reference process and the transformed processes can be compared to each other, with respect to a set of quality metrics. Depending on the results, the design phase can stop, or a selected candidate (a transformed process) can be substituted as the reference process for the next iteration of the design phase.

VI. VERIFICATION OF CORRECTNESS

The correct-by-construction approach is appealing for the implementation designer because it can open the way towards automatic process optimization. However, the approach has also some practical limitations. It is possible that small changes to a process behavior can be acceptable within the application context. If this was the case, then a verification method is needed, capable not only of verifying the process behavior, but also showing the designer all the potential changes, if they exist. In this section, we introduce LOTOS language, which is used as a formal basis for such a verification method.

A. The language LOTOS

Language of Temporal Ordering Specification (LOTOS) is one of the formal description techniques developed within ISO [21] for the specification of open distributed systems. The semantics of LOTOS is based on algebraic concepts and is defined by a labeled transition system (LTS), which can be built for each LOTOS expression.

A process, or a set of processes, is modeled in LOTOS as a behavior expression, composed of actions, operators and parenthesis. Actions correspond to activities, which constitute the process body. Operators describe the ordering of actions during the process execution. The list of operators, together with an informal explanation of their meaning is given in Table I. We use μ to denote an arbitrary action and δ to denote a special action of a successful termination of an expression or sub-expression.

LOTOS expression can be executed, generating a sequence of actions, which is called the execution trace. An expression that contains parallel elements can generate many traces, each of which describes an acceptable ordering of actions. Not all of the actions that are syntactic elements of an expression are directly visible within the execution trace. These actions are called observable actions and are denoted by alphanumeric identifiers, e.g., *g*1, *g*2, etc. Only observable actions are counted as members of an execution trace of the expression. Other actions cannot be identified when observing the trace. These actions are called unobservable actions. Unobservable actions are denoted by letter ***i*** and are not counted as members of an execution trace.

Formally, unobservable actions are those that are listed within the **hide** clause of LOTOS. In this paper, we omit this clause to help keeping the expressions simple.

The operational semantics of LOTOS provides a means to derive the actions that an expression may perform from the structure of the expression itself. Formally, the semantics of an expression *B* is a labeled transition system $< S, A, \rightarrow, I >$ where:

S – is a set of states (LOTOS expressions),
A – is a set of actions,
$\rightarrow$ – is a transition relation, $\rightarrow \subseteq S \times A \times S$,
B – is the initial state (the given expression).

The transition relation is usually written as $B \xrightarrow{\mu} B'$. For example, the semantics of expression (*g*; *B*1) can be described by a labeled transition:

$$g; B1 \xrightarrow{g} B1$$

This means that expression (*g*; *B*1) is capable of performing action *g* and transforming into expression *B*1.

The semantics of a complex expression consists of a directed graph (a tree) of labeled transitions, which root is the expression itself, and which edges are the labeled transitions. Each path from the root node to a leaf node of the graph defines a sequence of actions, which is an execution trace of the expression.

LOTOS expression can serve as a tool for modeling the set of traces of execution of a BPEL process. To use the tool, we can model BPEL activities as observable actions in LOTOS, and describe the ordering of activities during the process execution by means of a LOTOS expression.

Simple activities of BPEL are mapped to observable actions of LOTOS, followed by **exit** symbol. For example:

<assign name="*ass*"> is mapped to *ass*; **exit**
<invoke name="*inv*"> is mapped to *inv*; **exit**

Exceptions are BPEL <empty>, which is mapped to **exit**, and <exit>, which is mapped to **stop**.

Structured activities of BPEL are translated into LOTOS expressions according to the following rules:

TABLE I. EXPRESSIONS IN BASIC LOTOS

Syntax	Explanation
stop	inaction, lack of action
μ; *B*	action μ precedes execution of expression *B*
*B*1 [ ] *B*2	alternative choice of expressions *B*1 and *B*2
*B*1 |[*g*1,…*gn*]| *B*2	parallel execution of *B*1 and *B*2 synchronized at actions *g*1,…,*gn*
*B*1 ||| *B*2	parallel execution with no synchronization between *B*1 and *B*2
exit	successful termination; generates a special action δ
*B*1 >> *B*2	sequential composition: successful execution of *B*1 enables *B*2
*B*1 [> *B*2	disabling: successful execution of *B*1 disables execution of *B*2
hide *g*1,…,*gn* **in** *B*	hiding: actions *g*1,…,*gn* are transformed into unobservable ones

- <sequence> element is mapped into sequential composition (>>),
- <flow> element is mapped to parallel execution (|||),
- <if> element is mapped to alternative choice ([ ]).

The semantics of parallelism in LOTOS is interleaved. Parallel execution of activities that are nested within <flow> element of a BPEL process is modeled by the possibility of executing the corresponding LOTOS actions in an arbitrary order. The semantics of choice is exclusive. When one branch of <if> element begins execution, then the other branch disappears. Special action δ generated by **exit** is not counted in the execution traces because it is an unobservable action.

Consider, for example, BPEL process in Fig. 2. If we map the process activities according to the above rules, then the resulting LOTOS expression looks as follows:

rcv;**exit** >> *src*;**exit** >> *dst*;**exit** >> *verify*;**exit** >>
(**exit** [ ] *fail*;**exit** >> *nak*;**exit** >> **stop**) >>
withdraw;**exit** >> *deposit*;**exit** >> *success*;**exit** >> *ack*;**exit**

The trace set generated by the labeled transition system of this expression consists of two traces composed of the following observable actions:

rcv; *src*; *dst*; *verify*; *withdraw*; *deposit*; *success*; *ack*
rcv; *src*; *dst*; *verify*; *fail*; *nak*

B. The Verification Method

The verification follows a two-phase approach illustrated in Fig. 8, where B2L acronym stands for: BPEL-to-LOTOS mapping. In the first phase, dataflow dependencies between the activities of the reference process are analyzed using the Program Dependence Graph (PDG) and all the unnecessary sequencing constraints on these activities are removed. The resulting reduced program dependence graph reflects all the dataflow dependencies between the activities of the reference process and is free from the initial process structuring. If we preserve the dataflow dependencies during the process transformation, then the values computed by all the activities remain unchanged. In particular, the values that are passed between the processes by means of the inter-process communication activities: <invoke> in one process and <receive> <reply> pair in the other one, remain also unchanged. The reduced program dependence graph is then transformed into a LOTOS expression, which is called a Minimal Dependence Process (MDP). The labeled transition system of the minimal dependence process defines a set of traces that define the behavior of all processes, which comply with dataflow dependencies defined within the reference process. The first phase is performed only once for a given reference process.

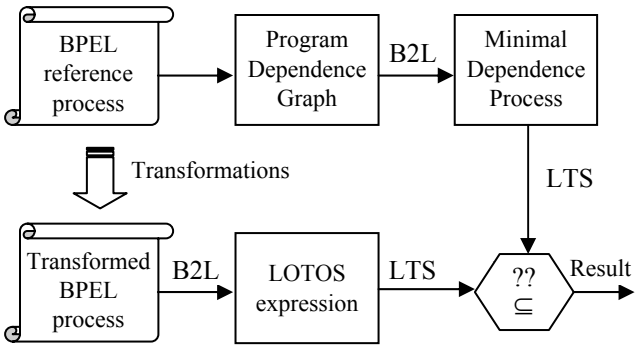

Figure 8. Verification of a process behavior

The second phase is performed repetitively during the transformational implementation cycle. A transformed BPEL process is mapped into a LOTOS expression, as described in the previous subsection. The set of traces generated by the labeled transition system of this expression is compared with the set of traces generated by the labeled transition system of the minimal dependence process. If the trace set generated by the expression is within the trace set of MDP, then the behavior of the transformed BPEL process is safe in that it preserves the behavior of the reference process.

C. The Reduced Program Dependence Graph

A dataflow edge between two nodes in a program dependence graph implies that the result of the activity at the end of the edge depends on the result of the activity at the beginning of this edge. Therefore, the arrangement of activities during the program execution, reflected by the succession of activities in an execution trace, must comply with the direction of dataflow edges. Any change to this arrangement may lead to a change in the program behavior.

Structured nodes <sequence> and <flow>, as well as control edges connected to these nodes, reflect the structure and the flow of control within the reference process. Both of the two can be changed during the process transformation. Therefore, <sequence> and <flow> nodes are removed from the program dependence graph. The reduced program dependence graph of the reference process in Figs. 2 and 3 is shown in Fig. 9. An algorithm for removing the nodes consists of the following steps:

1. Remove all <sequence> and <flow> nodes, which are not directly nested within an <if> element. Redirect control edges, which output each removed node, to the direct predecessor node if one exists, or remove otherwise.
2. If a <sequence> node is nested within an <if>, then:
   a. Remove <sequence> node together with the input "Yes" ("No") edge.
   b. Add dataflow edges labeled "Yes" ("No") from <if> node to each member of <sequence> such that no path from <if> to this node exists (<if> to "fail" edge in Fig. 9).

The services invoked by a process can have an impact on the real world. If this is the case, a specific ordering of these services can be required, regardless of the dataflow relation between the invoking activities. A designer can reflect this requirement adding supplementary edges between the appropriate nodes of the reduced program dependence graph.

D. Minimal Dependence Process

Let $G_P = (N_P, E_P)$ be a reduced program dependence graph of a BPEL process P. It can be proved that graph G_P is acyclic. We say that node n_i precedes node n_j, denoted

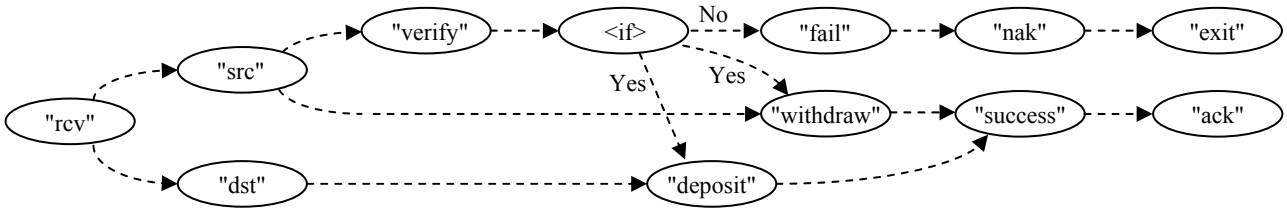

Figure 9. The reduced program dependence graph of the process in Figs. 2 and 3

$n_i < n_j$, if there exists a path from n_i to n_j in the reduced program dependence graph. Precedence relation is a strict partial order in N_P.

An execution of a BPEL program can be modeled as a process of traversing through the program dependence graph, starting at the initial node and moving along the directed edges. The process stops when the last node of the graph is reached. Because the ordering of nodes is only partial, then the succession of visited nodes and edges may vary. For example, the first node in Fig. 9 is *rcv*. After visiting this node, data can be passed along the edge to *src* or along the edge to *dst*. If the former is true, then in the next step either node *src* can be visited or data can be passed along the edge to *dst*. However, node *dst* could not be visited before the data were passed through its incoming edge.

Nodes and edges of a program dependence graph can be mapped to LOTOS actions in such a way that a visit to a node is mapped to an observable action, while moving along an edge is mapped to an unobservable action. A sequence of execution steps is mapped to a sequence of LOTOS actions. An example mapping of nodes and edges is shown in Fig. 10.

A visit to a node enables visiting all the succeeding nodes. However, the way of reaching this node (described by an expression *B*1) has no influence on the other part of execution after visiting the node (described by another expression *B*2), and vice versa. This means that actions performed before the visit (within *B*1) and actions performed after the visit (within *B*2) are independent. However, finishing the visit and passing data along the output edges of the visited node make a synchronization point between the two. This informal description can be expressed formally in LOTOS using the operator of parallel execution of *B*1 and *B*2 synchronized at action assigned to the output edge.

Minimal dependence process is a LOTOS expression that defines the set of traces, which are compliant with dataflow dependencies described by the program dependence graph. This way, minimal dependence process defines the semantics of a BPEL reference process. The algorithm for building MDP searches through the reduced program dependence graph, starting at the initial node. LOTOS expression is constructed iteratively, by appending a new sub-expression to the existing part of MDP in each visited node.

For example, the first action in the graph in Fig. 10 is *rcv*, followed by one of the actions *a* or *b*. Hence, the appropriate LOTOS expression begins with:

rcv; (*a*|||*b*) …

Passing data along one of the output edges enables traversing through the other parts of the graph. Action *a* enables *src*, while action *b* enables *dst*. Both of the enabled actions are independent and can be executed in parallel. Hence, the next part of the LOTOS expression is:

((*rcv*; (*a*||*b*)) |[*a*]| *a*; *src*;…) |[*b*]| *b*; *dst*;…

Formally, the algorithm for constructing MDP of a BPEL program described by a reduced program dependence graph consists of the following steps:

1. Assign an observable LOTOS action to each node of the reduced program dependence graph, except of <if> nodes. The action is identified by the name attribute of the node (nodes in PDG are BPEL activities).
2. Find paths in the reduced program dependence graph, such that the first node of a path has one output edge, the last node has one input edge and each other node has one input and one output edge. Substitute each path with a single node, and assign to this node LOTOS expression composed of actions, which were assigned to the removed nodes, separated by semicolons.
3. Assign an unobservable LOTOS action to each edge of the graph. The actions should be distinct, except of the edges, which output the alternative nodes of an <if> activity and input the same node. These actions should be equal.
4. Initiate graph search from the initial node. Create LOTOS expression, denoted MDP', composed of:
   - the expression assigned to the initial node,
   - semicolon and parallel composition of actions assigned to the output edges.
5. Search through the nodes of the reduced program dependence graph in a sequence complying with the precedence relation (n_i is visited before n_j, if $n_i < n_j$). For each node, place parentheses around the MDP' and append the following expressions:
   - parallel composition synchronized on actions assigned to the input edges,
   - a sequence of actions assigned to the input edges, separated by semicolons,
   - semicolon and LOTOS expression assigned to the node (empty for <if> node),
   - semicolon, and parallel composition of actions assigned to the output dataflow edges or an alternative selection of actions assigned to the output control edges (the case of <if> activity).
6. When the algorithm stops, after visiting the last node, MDP' becomes the minimal dependence process MDP.

For example, let us consider the reduced program dependence graph in Fig. 9. The steps of assigning LOTOS expressions to nodes (step 1), removing paths (step 2), and assigning unobservable actions to edges (step 3) change the graph as shown in Fig. 10.

The minimal dependence process derived from the graph in Fig. 10 takes the form of the following LOTOS expression:

(((((((*rcv*;(*a*|||*b*)) |[*a*]| *a*;*src*;(*c*|||*d*)) |[*b*]| *b*;*dst*;*e*)
|[*c*]| *c*;*verify*;(*y1*;*y2*[ ]*n*)) |[*d*,*y1*]| *d*;*y1*;*withdraw*;*f*)
|[*e*,*y2*]| *e*;*y2*;*deposit*;*g*) |[*f*,*g*]| *f*;*g*;*success*;*ack*)
|[*n*]| *n*;*fail*;*nak*;*exit*

The labeled transition system of this expression generates a set of 13 traces, each of which is a sequence of observable actions:

{ *rcv*; *dst*; *src*; *verify*; *fail*; *nak*; *exit* ,
rcv; *src*; *dst*; *verify*; *fail*; *nak*; *exit* ,
rcv; *src*; *verify*; *dst*; *fail*; *nak*; *exit* ,
rcv; *src*; *verify*; *fail*; *dst*; *nak*; *exit* ,
rcv; *src*; *verify*; *fail*; *nak*; *dst*; *exit* ,
rcv; *src*; *verify*; *fail*; *nak*; *exit*; *dst* ,
rcv; *dst*; *src*; *verify*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *verify*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *dst*; *verify*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *dst*; *verify*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *verify*; *withdraw*; *dst*; *deposit*; *success*; *ack* }

The trace set of the reference process in Fig. 2 consists of 2 traces:

{ *rcv*; *src*; *dst*; *verify*; *fail*; *nak*; *exit* ,
rcv; *src*; *dst*; *verify*; *withdraw*; *deposit*; *success*; *ack* }

The trace set of the first transformed process in Fig. 6 consists of 9 traces:

{ *rcv*; *dst*; *src*; *verify*; *fail*; *nak*; *exit* ,
rcv; *src*; *dst*; *verify*; *fail*; *nak*; *exit* ,
rcv; *src*; *verify*; *dst*; *fail*; *nak*; *exit* ,
rcv; *dst*; *src*; *verify*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *dst*; *src*; *verify*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *dst*; *verify*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *dst*; *verify*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *verify*; *withdraw*; *dst*; *deposit*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *deposit*; *withdraw*; *success*; *ack* }

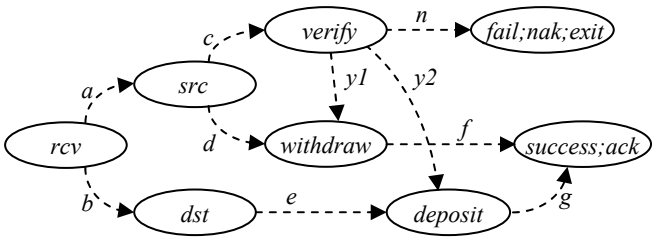

Figure 10. Construction of MDP: The reduced program dependence graph (Fig. 9) after step 3

The trace set of the second transformed process in Fig. 7 consists of 4 traces:

{ *rcv*; *src*; *verify*; *fail*; *nak* ,
rcv; *src*; *verify*; *dst*; *withdraw*; *deposit*; *success*; *ack* ,
rcv; *src*; *verify*; *dst*; *deposit*; *withdraw*; *success*; *ack* ,
rcv; *src*; *verify*; *withdraw*; *dst*; *deposit*; *success*; *ack* }

Obviously, the trace set of MDP includes the trace sets of the reference process as well as of the transformed processes. This proves that both transformations are safe.

VII. QUALITY METRICS

Many metrics to measure various characteristics of software have been proposed in literature [18,19]. In this research, we use simple metrics that characterize the size of a BPEL process, the complexity and the degree of parallel execution. The value of each metric can be calculated using a program dependence graph.

The size of a process is measured as the number of simple activities in a BPEL program. More precisely, the value of this metric equals the number of leaf nodes in the program dependence graph of a BPEL process. For example, the size of the processes shown in Figs. 2 and 6 is 12, while the size of the process in Fig. 7 equals 10.

Leaf nodes are simple activities, which perform the processing of data. Therefore, the value of the process size metric could be considered a measure of the amount of work, which can be provided by the process. However, smaller number of this metric may result from removing excessive, unstructured activities, like <empty> and <exit>. This is the case of program in Fig. 7.

The complexity of a process is measured as the total number of nodes in PDG. For example, The complexity of the process shown in Fig. 2 is 15, the complexity of the process in Fig. 6 is 18, and the complexity of the process in Fig. 7 is 16.

The number of nodes in PDG, compared to the size of the process, describes the amount of excess in the graph, which can be considered a measure of the process complexity.

The number of threads is measured as the number of items within <flow> elements of a BPEL program, at all levels of nesting. A problem with this metric is such that the number of executed items can vary, depending on values of conditions within <if> elements. Therefore, the metric is a vector of values, computed for all combinations of values of these conditions. The algorithm of computation assigns weights to nodes of the program dependence graph of the process, starting from the leaves up to the root, according to the following rules:

- the weight of a simple BPEL activity is 1,
- the weight of a <flow> element is the sum of weights assigned to the descending nodes (i.e., nodes directly nested within the <flow> element),
- the weight of a <sequence> element is the maximum of weights assigned to the descending nodes (i.e.,

TABLE II. NUMBER OF THREADS METRIC

if - condition	Process in Fig. 2	Process in Fig. 6	Process in Fig. 7
YES	1	2	2
NO	1	2	1

nodes directly nested within the <sequence> element),

- the weight of an <if> element is the weight assigned to the activity in this branch of <if>, which is executed according to a given value of condition within the <if> element.

The number of executed items can be influenced also by the presence of <exit> activity, which ends the process execution. Therefore, the nodes directly nested within a <sequence> element are ordered in compliance with the order of execution. Nodes subsequent to a node, which is, or which comprises, <exit> activity, are not taken into account in the computation.

The metric value equals the weight assigned to the top <sequence> node of PDG. Values of the metric for the processes in Figs. 2, 6, and 7 are shown in Table I. Program dependence graph and calculation of the metric for the program in Fig. 7 is shown in Fig. 11 (grey numbers right to the nodes).

The length of thread is measured as the number of sequentially executed activities within a BPEL program. Because the number of executed items can vary, depending on values of conditions within <if> elements, the metric is a vector of values, computed for all combinations of values of these conditions. The algorithm of computation assigns weights to nodes of the program dependence graph of the process, starting from the leaves up to the root, according to the following rules:

- the weight of a simple BPEL activity is 1,
- the weight of a <flow> element is the maximum of weights assigned to the descending nodes (i.e., nodes directly nested within the <flow> element),
- the weight of a <sequence> element is the sum of weights assigned to the descending nodes (i.e., nodes directly nested within the <sequence> element),
- the weight of an <if> element is the weight assigned to the activity in this branch of <if>, which is executed according to a given value of condition within the <if> element.

Nodes directly nested within a <sequence> element are ordered in compliance with the order of execution. Nodes subsequent to a node, which is, or which comprises, <exit> activity, are not taken into account in the computation.

The metric value equals the weight assigned to the top <sequence> node of PDG. Values of the metric for the processes in Figs. 2, 6, and 7 are shown in Table II.

TABLE III. LENGTH OF THREAD METRIC

if - condition	Process in Fig. 2	Process in Fig. 6	Process in Fig. 7
YES	9	7	7
NO	7	6	5

TABLE IV. RESPONSE TIME METRIC

if - condition	Process in Fig. 2	Process in Fig. 6	Process in Fig. 7
YES	36	25	25
NO	16	15	14

The response time is measured as the sum of estimated execution times of activities, which are sequentially executed within a BPEL program. Because the number of executed items can vary, depending on values of conditions within <if> elements, the metric is a vector of values, computed for all combinations of values of these conditions The algorithm of computation is identical to the algorithm of computation of the length of thread metric, except of the first point, which now reads:

- the weight of a simple activity is the estimated execution time of this activity,

In the simplest case, the estimated execution time can just differentiate between local data manipulation activity and a service invocation. Values of the metric for the processes in Figs. 2, 6, and 7, calculated under an assumption that a local data manipulation time equals 1, while a service execution time equals 10, are shown in Table III. Program dependence graph and calculation of the metric for the program in Fig. 7 is shown in Fig. 11 (numbers left to the nodes).

Comparing the values of metrics calculated for the processes considered in the case study in Section V, one can note that both transformed processes are faster than the original reference process (smaller value of the response time

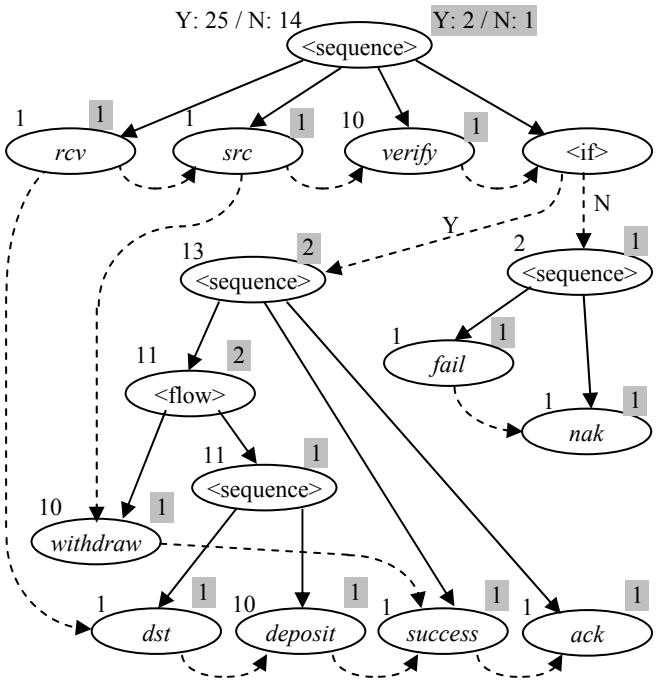

Figure 11. Program dependence graph of the program in Fig. 7 and calculation of metrics: Number of threads (grey numbers right to the nodes) and length of execution (left to the nodes)

metric). Speeding up the process execution is a benefit from parallel invocation of services in a SOA environment. Comparing the variants of the transformed bank transfer process (Fig. 6 and Fig. 7), one can note that the second variant is a bit faster and simpler (smaller values of the size metrics). This variant can be accepted by the customer or used as a new reference process in the next transformation cycle.

VIII. CONCLUSION AND FUTURE WORK

Defining the behavior of a business process is a business decision. Defining the implementation of a business process on a computer system is a technical decision. The transformational method for implementing business processes in a service oriented architecture, described in this paper, promotes separation of concerns and allows making business decisions by business people and technical decisions by technical people.

The transformations described in this paper are correct by construction in that they do not change the behavior of a transformed process. However, the transformations change the process structure in order to improve efficiency and benefit from the parallel execution of services in a SOA environment. The quality characteristics of the process implementation are measured by means of quality metrics, which account for the process size, complexity and the response time of the process as a service. Other quality features, such as modifiability or reliability, are not covered in this paper.

The correct-by-construction approach opens the way towards automatic process optimization. However, the approach has also some practical limitations. If the external services invoked by a process have an impact on the real world, as is usually the case, a specific ordering of these services may be required, regardless of the dataflow dependencies between the service invocation activities within a program. In our approach, a designer can express the necessary ordering conditions adding supplementary edges to the program dependence graph. Therefore, the approach cannot be fully automated and a manual supervision over the transformation process is needed.

It is also possible that small changes to a process behavior can be acceptable within the application context. Therefore, part of our research was aimed at finding a verification method capable not only of verifying the process behavior, but also of showing the designer all the potential changes, if they exist. A decision on whether to accept the changes or not is made by a human.

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Automated Tailoring of Application Lifecycle Management Systems to Existing Development Processes

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***Abstract*—Application lifecycle management approaches are used to tame the increasing complexity, size and number of development artifacts. Throughout the application lifecycle, a number of tools are used to create a diversity of development artifacts. It is widely believed that the efficiency of development can be improved by the integration of these tools. However, such integrated solutions are not accepted by practitioners if the solutions are not aligned with the established development culture, processes and standards. Thus, application lifecycle management needs to be tailored to the specific corporate needs. The tailoring, however, is typically performed manually and is thus resource intensive. We propose a cost efficient tailoring approach for application lifecycle management, which is based on reuse and automation. We explore to what extent existing process models can be reused for automatically configuring the application lifecycle management system, so it is aligned with the development process. We identify a number of relationship patterns between the development process and its supporting tool chain and show how the patterns can be used for constructing a tool chain. In three case studies, we examine the practical applicability of the approach.**

Keywords-Application Lifecycle Management; Process Modeling; Tool Integration; Tool Chain; Generative Approach; Model Driven Development.

I. INTRODUCTION

The development of software-intensive products, such as embedded systems, produces a large number of diverse development artifacts, such as documents, models and source code. The artifacts are produced and used throughout the product lifecycle and are ideally managed systematically in an application lifecycle management (ALM) system [1]. In this article, we focus on one specific aspect of application lifecycle management systems – the aspect of tool integration. Currently available commercial application lifecycle management systems do not provide adequate tool integration, as shown in a recent analysis [2]. Tool integration is an essential aspect of ALM, since the development artifacts in the ALM system are typically developed with a number of different development tools. The development tools ideally interoperate seamlessly, however, the tools are often "island solutions" and a considerable engineering effort is necessary to make a specific set of tools interoperate. Thus, tool integration is realized externally to the development tools, in the form of tool chains. A *tool chain* can be regarded as an integrated development environment consisting of several development tools, which is intended to increase the efficiency of development by providing connections between the tools used in a development process [3].

To be effectively used, tool chains need to be customized to a specific selection of development tools and a specific development process. For example, a company might select IBM DOORS for requirements management, Enterprise Architect for UML modeling and MATLAB/Simulink for designing and simulating control algorithms. The tool chain needs to include these development tools. The way in which these tools are connected, is determined by the development process, which might prescribe that a connection between requirements and UML models is needed, and a connection between UML models and MATLAB/Simulink models.

Building automated tool chains that fit the individual needs is an expensive and time-consuming task. In Section II, we describe the challenges involved in building such customized tool chains and study the perspective of involved stakeholders. If a systematic and automated development approach for tool chains was available, tool chains could be efficiently developed for each new development context. We introduce a domain-specific modeling language for tool chains in Section III. The language allows us to express the essential design decisions for creating a tool chain. In Section V, we propose a systematic development process for building tool chains with this language, including the design phase, analysis phase, verification phase and implementation phase of tool chains. In Section IV, we focus in-depth on the relationship between process models and tool chain models and ways of leveraging this relationship in the conceptual design and verification phases of tool chain construction. We describe the relationship between process and tool chain in the form of patterns, implement them as model transformations and leverage these patterns for design and verification. We apply the approach in three case studies in Section VI. In the remaining Sections VII - IX, we relate our approach to other work in the field, sketch future work and consider the implications of this work.

II. Challenges

To develop modern software-intensive systems, such as an embedded system, a large number of development tools are used. Each of these tools can help us to be more productive, manage knowledge, and manage the complexity of development. The use of single, specialized tools has the potential to improve the efficiency of the development process, improve knowledge management, and improve complexity management, depending on the degree of automation they provide [4]. Multiple tools have the potential to improve the productivity in the development process, depending on how well they are integrated with each other and their degree of automation [3]. The reasons for using *multiple* tools can be found in the high degree of specialization of the tools, which is necessary to support the different engineering disciplines and the different engineering phases. The engineering of a software intensive system requires experts from a number of different engineering disciplines, such as control, hardware, software and mechanics. Each engineering discipline prefers a different set of development tools that excel in that particular discipline [5]. Throughout the different phases of the development process, specific tools are used, such as tools for prototyping, requirements engineering, design, implementation, verification and testing. In addition, crosscutting tools are used that support the process as a whole, such as repositories or tools for data management. The used tools are for the largest part commercial-off-the-shelf tools. The tools can thus not be changed and have to be used as they are.

Since engineers use the various tools to develop a single system, they need to relate the data that is captured in different tools, exchange data for reusing it in another tool or even to automate tasks that involve different tools. Most development tools do not interoperate well with one another, this is why additional software external to the tools – a tool chain – is needed as the glue to facilitate the integration.

Tool chains can provide different coverage of the development process; therefore, we distinguish between task-oriented tool chains with a small coverage and lifecycle-oriented tool chains with a larger coverage. Many existing tool chains cover only one task in the development process, e.g., the tool chain between source code editor, compiler and linker. We call these tool chains task-oriented. The tools are used in a linear chain, so that the output of one tool is the input for the next tool. These tool chains have a relatively small scope and integrate a small number of tools from within one phase in the lifecycle. Characteristic for these traditional tool chains are their linear connections, using a pipes and filter design pattern [6].

Along with the efforts to capture the complete application lifecycle in systems for ALM, there is a need for tool integration with a larger scope. Lifecycle-oriented tool chains support data exchange, tracing, and automation across the complete development lifecycle, from requirements engineering over verification, design and implementation to maintenance. When creating software-intensive systems, such tool chains may span multiple disciplines such as software engineering, hardware engineering and mechanical engineering and integrate a large number of different development and lifecycle management tools. In addition, modern development processes put new demands on the tool chain: processes might be agile, iterative or model-driven, which implies that the supporting tool chain cannot be linear.

With the large number of alternative development tools available in the marketplace and the large number of company-specific development processes, there is an even larger number of potential, different development processes that need to be supported by tool chains. A static, one-size-fits-all application lifecycle management system cannot fulfill these needs. Ideally, a tailor-made, customizable solution is available that addresses the individual needs. Since there is limited methodological and tool support and little reuse of tool chain parts, either one-size-fits-all tool chains are used despite their suboptimal support or customized tool chains are built, in a mostly manual way, which requires a tremendous development effort and investment.

In this article, we present one approach for solving this issue: by providing cost-efficient methods for building tool chains, the individual development of tailored tool chains becomes feasible. The approach manages to be cost-efficient by reuse of existing information and automation of development activities. The approach thus provides an opportunity to bring tailored tool chains within the reach of industrial application.

A. Stakeholders

As part of the description of challenges, some of the most important stakeholders of tools and tool chains are introduced, as depicted in Figure 1, including their roles as *users* or *creators* of tools and tool chains. The embedded systems developers work with multiple development tools and take on the role of the *users of tools*. In addition, the embedded systems developers take on the role of the *users of tool chains*, motivated by the expected efficiency gains in development provided by tool chains. The vendors of tools for embedded systems development take on the role of the *creators of tools*. IT infrastructure deploys the development tools. Process engineers have the big picture of the development process, which is hopefully consistent with the actual development practices of the embedded developers. Tool integration specialists are the only ones who know the integration technologies and conventions. A challenge is the effective communication between the stakeholders, as it requires a description of the different needs and possibilities of the stakeholders on the appropriate level of abstraction.

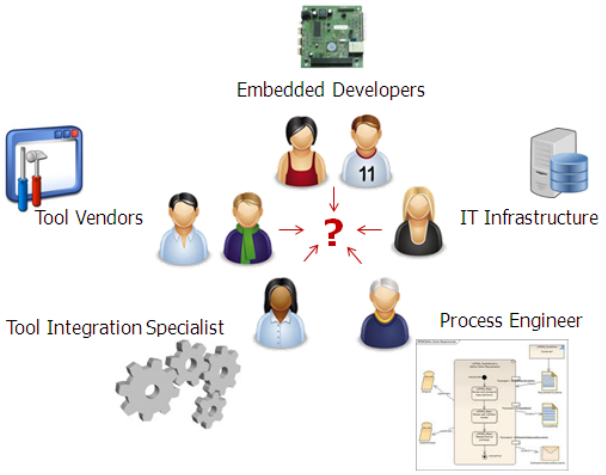

Figure 1. Stakeholders of tool chain development

Each one of the different stakeholders for tool chain development provides some important information for building a tool chain. Based on observations and interactions with industry in the research projects iFEST [7] and CESAR [8], the assignment of the role of the *creator of tool chains* is not clearly defined in industry. The role might be assigned to third party tool integration developers, but also to embedded systems developers or to tool vendors, which is problematic. Tool vendors are mostly interested in connecting only their tools to other tools, resulting in a limited scope of the integration. For embedded systems developers, the implementation of a tool chain is an additional burden that distracts them from their primary task of developing an embedded system. The observed constellation of stakeholders requires an approach for describing and communicating tool chains both in early design phases and in later phases, when more precision is needed.

III. Modeling the Design of Tool Chains

We need an early design model that describes all important design decisions of a tool chain. Such a design model can also serve as a boundary object [9] for the communication between different stakeholders. We chose to use the Tool Integration Language (TIL) [10], a domain specific modeling language for tool chains. TIL allows us not only to model a tool chain, but also to analyze it and generate code from it. The implementation of a tool chain can be partly synthesized from a TIL model, given that metamodels and model transformations are provided. Here we can only give a short overview of TIL, for an elaborated description of concrete graphical syntax, abstract syntax and semantics we refer to [10].

The graphical concrete syntax of each language concept is introduced by a simple example in Figure 2, the concrete mapping function, which maps abstract to concrete syntax, is defined by corresponding circled numbers ⓪..⑦ in Figure 2 and the following text. This section also briefly and informally introduces the semantics of TIL concepts.

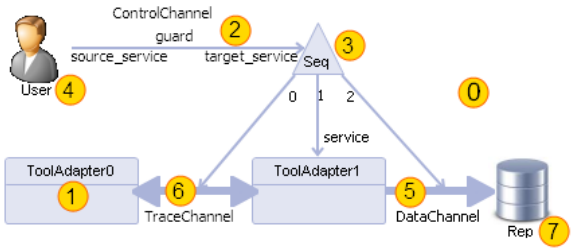

Figure 2. A simple TIL model illustrating the graphical concrete syntax of the language concepts

A **ToolChain** ⓪ provides a container for instances of TIL concepts. An instance of the ToolChain concept describes the tool chain by the composition of its contained instances of TIL concepts.

A **ToolAdapter** ① is a software component that describes the role of a tool in the tool chain by exposing the services and data of the tool, which are relevant for the specific role. Exposing the services of a tool enables control integration. Exposing the data of a tool enables data integration. A ToolAdapter makes two kinds of adaptation: (1) It adapts between the technical space of the tool and the technical space of integration for both data and services. (2) It adapts the structure of data and the signature of services available in the development tool to the data structure and service signatures defined by the ToolAdapter metamodel.

Each ToolAdapter has two associated *ToolAdapter metamodels*: one that specifies the structure of the exposed tool data and another that specifies the signature of the exposed services. In addition to the services defined in the metamodel, all ToolAdapters provide the default services *activate* to start the tool, *injectData* to load data (which is an instance of the ToolAdapter data metamodel) into the tool and *extractData* to access the tool data (as an instance of the ToolAdapter data metamodel). The ToolAdapter metamodels serve as an interface specification for the ToolAdapter and describe which data and services of the tool are exposed. More information on the structure of the ToolAdapter metamodels is provided in [10], [11].

Subtypes of ToolAdapters are defined, such as a **Repository** ⑦, which provides storage and version management, e.g., a ToolAdapter for Subversion [12].

A **DataChannel** ⑤ describes the possibility to transfer and transform data from a source ToolAdapter to a target ToolAdapter at the run-time of the tool chain; it is a directed connection. The data originates from the *source_service* of the source ToolAdapter (default service: *extractData*), is transformed and is finally received by the *target_service* of the target ToolAdapter (default service: *injectData*). A

model transformation is attached to the DataChannel; the source and target metamodels of the transformation need to match the respective data metamodels of source and target ToolAdapters.

A **TraceChannel** ⑥ describes the possibility to establish trace links between the data of two ToolAdapters at the run-time of the tool chain; it is an undirected connection. A TraceChannel is a design-time representative for a number of trace links at run-time. At design-time one can specify the type of data that can be linked by traces. The endpoints of the traces can be restricted to a subset of the tool data by specifying the *source_service* and *target_service* (default service: *extractData*), which provide the data. At run-time, these services provide a list of all the source and target elements that are offered as endpoints for specifying a trace.

A **ControlChannel** ② describes an invocation or notification, it is a directed connection originating from a *source* component and ending in a *target* component. If the target of the ControlChannel is a ToolAdapter, the ControlChannel denotes the invocation of a tool service; if the target is a DataChannel, the data-transfer is executed; if the target is a TraceChannel, a dialog for creating traces is presented. If the target is a User, it denotes notification of the User. A condition for the execution of the ControlChannel can be specified by a guard expression. A service of the source component, called *source_service* (default value: *activate*), can be specified as the event that triggers the ControlChannel. The invoked service in the target component is specified as the *target_service* (default value: *activate*) of the ControlChannel.

A **Sequencer** ③ describes a sequence of invocations or notifications. When a Sequencer is activated by an incoming ControlChannel, it activates the outgoing ControlChannels in the specified order. The order is specified by the events (0..n), which are specified as the *source_service* in the outgoing ControlChannels from the Sequencer. Only after the service executed by the previous ControlChannel is finished, will the next ControlChannel be activated.

A **User** ④ represents a real-world tool chain user. The concept is used to describe the possible interactions of the real-world users with the tool chain. Outgoing ControlChannels from the User denote the invocation of tool chain services by the real-world user. Incoming ControlChannels to a User denote a notification sent to the real-world user, e.g., by e-mail.

By default, all TIL concepts describe parts of an automated tool chain, however some parts of the tool chain may not need to be automated and are manually integrated. TIL allows marking ControlChannels, DataChannels and TraceChannels as manually executed, in which case they are depicted by dashed lines.

The semantics of TIL is defined in the text above, in addition, compatible formal semantics of the behavior of TIL can be described by a mapping of TIL concepts to networks of finite state machines (FSMs) [13].

IV. Relationship between Process and Tool Chain

When building a tool chain, it is important to study which development tools need to be connected. This information about the relationship between development tools is often already available in a process model. Process models exist for a variety of reasons, i.e., for documenting, planning or tracking progress in a development project. The Software & Systems Process Engineering Metamodel (SPEM) [14] is the standardized formalism by the OMG for this purpose. A SPEM model might already be available independently from a tool integration effort, e.g., as it is the case in development with the Automotive Open Software Architecture (AUTOSAR) [15]. The information available in process models forms the skeleton of a tool chain, i.e., which tools are involved and how they are connected in the process. To construct an executable tool chain as a software solution, additional details are needed, e.g., information about the data of tools, how to access it, how to convert it and how to describe the relation between data of different tools. In this Section we evaluate, to what extent information from existing SPEM models can be used for constructing a tool chain.

Ideally, connections for all tools used throughout the development process are provided; and in this case the tool chain supports the development process. The process provides constraints and requirements for the construction of the tool chain. While generic process models are available, e.g., the SPEM models for the Rational Unified Process (RUP) [16] or for AUTOSAR [15], companies also create individual process models for various purposes, e.g., to customize these generic models to their individual environments, to document the development process, to plan the development process, to track the progress in the development or to document their selection of tools.

If both the process is described as a model and the tool chain is described as a model, information from the process model can be reused for constructing a tool chain model. This approach ensures that the tool chain and the process are aligned. Alignment decreases the friction experienced when using the development tools according to the process model. Process models only contain some, but not all information necessary for specifying tool chains. Especially the type of the connection between tools needs to be added later on.

1) Modeling the Product Development Process: In this section, we introduce a modeling language that is used for describing the development process. There are both formal and informal processes in companies, documented to different degrees and there is an increasing trend to model processes. Several established languages exist for modeling processes or workflows. These languages have various purposes, for example BPMN [17] and BPEL [18] describe

business processes and SPEM describes development processes. We apply SPEM, since it is a standardized and relatively widespread language for modeling development processes with mature and diverse tool support. A SPEM model describes both the product development process and the set of tools used and can thus be applied to describe the process requirements of a tool chain. An example model is provided in Figure 5.

A number of concepts are defined in SPEM, we introduce here the core concepts that are relevant in the context of tool chains: a *Process* is composed of several *Activities*; an *Activity* is described by a set of linked *Tasks*, *WorkProducts* and *Roles*. A number of relationships, here represented by $\ll . \gg$, are defined between the concepts of the metamodel: a *Role*, typically an engineer or software, can $\ll perform \gg$ a *Task* and a *WorkProduct* can be marked as the $\ll input \gg$ or $\ll output \gg$ of a *Task*. A *WorkProduct* can be $\ll managed\ by \gg$ a *Tool* and a *Task* can $\ll use \gg$ a *Tool*.

A. Development Process Model as Requirements for Tool Chains

In general, a requirement is a documented need of the nature or behavior of a particular product or service. Requirements can have different degrees of formalization and structure. In the context of developing tool chains, the tool chain is the product. The nature or behavior of a particular tool chain is documented by process models, which thus can be interpreted as the requirements. Process models contain the selection of tools and the description of the connections between the tools. Since process models describe the process in a structured and formalized form, the requirements of a tool chain are formalized and structured, which we will use for describing the relationship between process and tool chain and using this relationship for efficiently constructing and verifying tool chains.

B. Relationship Patterns between Process and Tool Chain

If both the process and tool chain are described as a model, we can also model the relationship between them. A process described in SPEM might provide several opportunities for tool integration. Such an opportunity involves two tools and a direct or indirect connection between them. The tools and the connections found in SPEM are included into the tool chain architecture as ToolAdapters and Channels. The direction of the DataChannel can be determined by the involved work products, which have either the role of input or output of the task. Tasks connected to only one tool or tasks dealing with work products connected to the same tool do not require support from a tool chain; in these tasks engineers work directly with this tool, e.g., by using the GUI of the tool.

The challenge is to identify those parts in a SPEM model that are relevant for tool integration. The relationship cannot be described by mapping single metaclasses, as in Table I, instead the relationship needs to be described by combinations of several connected metaclasses, which we call patterns. To describe this relationship in more detail, we list patterns of both SPEM and TIL models and their correspondences.

Table I
CORRESPONDENCES BETWEEN SPEM AND TIL METACLASSES

SPEM Metaclass	TIL Metaclass
Role	User
Tool	ToolAdapter
Task	Channel

The relationship patterns consist of a SPEM part, which matches a subgraph of a process model in SPEM, and a TIL part, which will become a new subgraph in the tool chain model in TIL. The mapping is established by pairs of model elements from both SPEM and TIL, whose name attribute is equivalent and whose types are mapped according to the correspondences of metaclasses presented in Table I. In the following, we show four SPEM patterns that describe tool integration related activities, they are illustrated in the top part of Figure 3, and the corresponding TIL pattern is illustrated in the bottom.

1) *Task-centered Integration Pattern:* For each *Task* in SPEM that has associated *WorkProducts* as input and output, where the input *WorkProduct* has a different associated *Tool* than the output *WorkProduct*, this pattern produces *ToolAdapters* and a *Channel* between them in the TIL model. The pattern is shown in (1) and can be observed in case study 1 in Figure 5 for the *Task TraceReq2UML* connecting the *WorkProduct RequirementsDatabase* and the *WorkProduct UMLFile*.
2) *Multi-tool Task-centered Integration Pattern:* For each SPEM *Task* with two SPEM *Tools* associated with it, this pattern produces *ToolAdapters* and two *Channels* between them in the TIL model, since no directionality is modeled in SPEM. This pattern is theoretically possible according to the SPEM metamodel, but we have not observed it in practice. The pattern is illustrated in (2).
3) *WorkProduct-centered Integration Pattern:* For each SPEM *WorkProduct* that is both input and output of its associated *Tasks*, which have a different associated *Tool*, this pattern produces *ToolAdapters* and a *Channel* between them in the TIL model. The pattern is illustrated in (3) and can be observed in case study 2 in Figure 7 for the *WorkProduct ECU-ConfigurationDescription*, which is output of the *Task GenerateBaseECUConfiguration* and input to the *Task GenerateRTE*.
4) *Multi-tool WorkProduct-centered Integration Pattern:* For each SPEM *WorkProduct* in that is associated to two different *Tools*, this pattern produces *ToolAdapters*

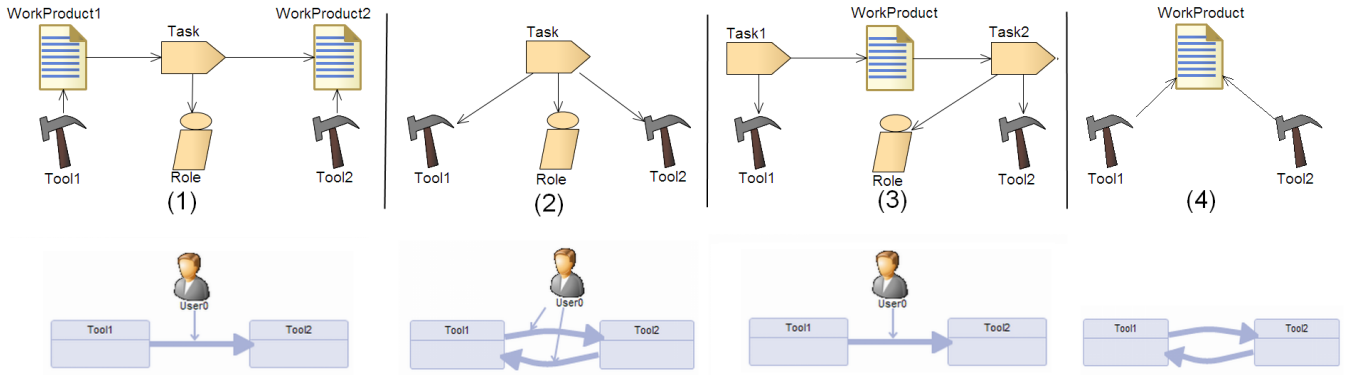

Figure 3. SPEM and TIL Patterns

and two *Channels* between them in the TIL model, since no directionality is modeled in SPEM. This pattern is theoretically possible according to the SPEM metamodel, but we have not observed it in practice. The pattern is illustrated in (4).

For all relationship patterns, the following constraints need to be fulfilled: For each *Role* in SPEM that is connected to the *Task*, we create a *User* model element in the TIL model, which means that the Role in SPEM and the User in TIL are optional parts in the patterns of Figure I. If a *ToolAdapter* corresponding to the *Tool* already exists in the TIL model, the existing *ToolAdapter* is connected, otherwise a new *ToolAdapter* is produced.

C. Implementation as Model Transformations

The implementation of the patterns offers possibilities for automation of the pattern usage. We implement the relationship patterns as model transformations, with SPEM as the source metamodel and TIL as the target metamodel. We chose the model-to-model transformation language in QVT-R, with the mediniQVT engine, and the Eclipse Modeling Framework (EMF) for realizing the metamodels. We use a simplified SPEM metamodel in EMF, and for the visualization of SPEM models we use Enterprise Architect. For modeling and visualization of TIL, we use the TIL Workbench described in [10].

Patterns (1) to (4) in Figure 3 are graphical representations of the relational QVT model transformation rules. Since QVT relational is a declarative language, the implementation describes the source patterns and the corresponding target patterns in the form of rules. Additionally, the attributes between source and target pattern are mapped, as described in Table I.

D. Usage of Relationship Patterns

The relationship patterns can be used in different ways. Here, we apply the relationship patterns for constructing the initial design of a new tool chain starting from a process model. Other forms of using the relationship patterns are possible, but are not considered in depth here. We can use the patterns, e.g., for verification: based on a process model and a tool chain model we check if the requirements provided by the process are realized by the tool chain model.

In the following, we focus on the application of the relationship patterns to create an initial tool chain design in TIL based on the process requirements expressed in the SPEM model. The patterns can be applied to a SPEM model that is complete and contains all necessary references to *Tools*. The patterns ensure that the design of the tool chain is aligned with the process, a necessity for acceptance of the tool chain with practitioners. This design of the tool chain can be created in an automated way and might need to be iteratively refined by adding details.

The process model only provides the skeleton for the specification of a tool chain, such as the selection of tools, the connections between the tools and the user role working with the tools. The process model does not provide the nature of the connections and the exact execution semantics of the automated tool chain. The nature of the connection can be data exchange, for creating trace links between tool data or for accessing specific functionality of the tool. This information needs to be added manually by configuring and choosing the right type of channel in TIL, a DataChannel, TraceChannel or ControlChannnel. Also, events need to be specified that trigger the data transfer or activate the tracing tool. For each ToolAdapter, a metamodel describing the data and functionality of the tool need to be added to the TIL model. For each DataChannel, a model transformation needs to be added.

To handle these cases, we add a refinement step, which complements the automated construction. Once this information is added, the TIL model can be used as input to a code generator for tool chains, as detailed in [11].

After focusing on the initial conceptual design phase for tool chains in this section, we explain the complete development process for tool chains in the following section.

V. Tool Chain Development Process

When developing tool chains, two processes are relevant: (1) the process for developing the embedded system as a product, called PDP (Product Development Process) and (2) the process for developing a tool chain (TCDP). The TCDP is followed at design-time of the tool chain to ensure that the developed tool chain can support the PDP at run-time by automating its integration-related tasks. In this section we address the TCDP.

A. Overview

In Figure 4, the TCDP – the process for developing a tool chain with TIL – is illustrated using the SPEM [14] notation. The development process for tool chains with TIL is structured into five phases: requirements engineering, conceptual design, detailed design, analysis and implementation. These phases are presented according to the order in which they are traversed during tool chain development. The complete tool chain development process has the following phases:

1) The requirements of the tool chain are elicited from the selection of tools and from the dependencies of tasks and tool usages in the product development process.
2) In the conceptual design phase, a conceptual model of the tool chain is described using TIL based on the requirements stipulated by the product development process. The conceptual model conveys the overall architecture of the tool chain, including the existing ToolAdapters, Users and connections between the ToolAdapters.
3) The alignment of the conceptual TIL model with the process model can be verified to highlight any intended or unintended discrepancies between tool chain design and the requirements stipulated by the product development process. Depending on the outcome of the analysis, the conceptual design phase can be iterated in order to create a conceptual model which is better aligned with the requirements.
4) In the detailed design phase, the conceptual TIL model is refined by different types of Channels and ToolAdapter metamodels. ToolAdapter metamodels are attached to each ToolAdapter in the TIL model to describe the data and services of the tool, which are exposed by the ToolAdapter. The connections between ToolAdapters and other components are refined by choosing the type of the connector (ControlChannel, DataChannel or TraceChannel). A model transformation is attached to each DataChannel in the TIL model; it describes the translation of data from the source tool to the target tool. The model transformation can be specified in different ways, either manually or computed based on the information in an ontology or weaving model). The conceptual TIL model with attached metamodels and model transformations yields a complete TIL model.

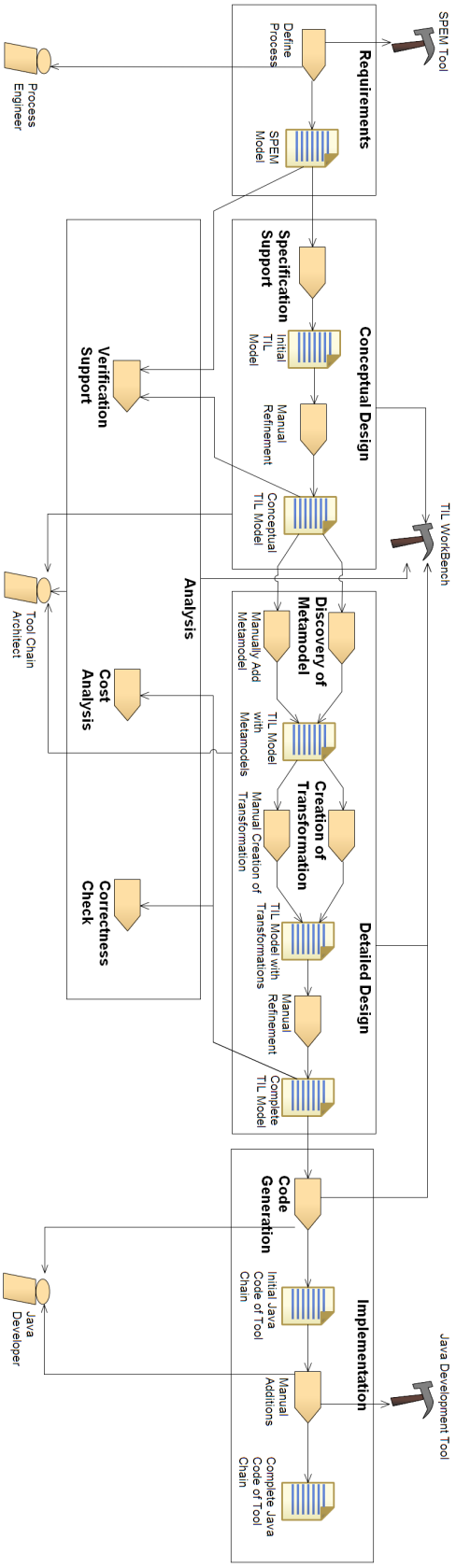

Figure 4. Process for developing a tailored tool chain with semi-automated support based on TIL, illustrated using SPEM [14] notation

5) Additional analyses are possible based on the detailed design. The syntactic correctness of the model can be checked and non-functional properties, such as the development cost of the tool chain, can be estimated. Depending on the outcome of the analyses, the tool chain design can be corrected before proceeding to the implementation phase.
6) In the implementation phase, the TIL model can serve as a blueprint for implementing the tool chain. The code of the tool chain is compiled and deployed.
7) At run-time[1] of the tool chain, the embedded developers use the deployed tool chain, which integrates several embedded systems tools.

There are different stakeholders of the tool chain, who are in contact with the tool chain at different points in the lifecycle of the tool chain. For this purpose, a distinction is made between the design-time of a tool chain and the run-time.

At design-time of the tool chain, the tool chain development process is executed, which involves a process engineer, tool chain architect and tool chain developers. A *process engineer* may model the product development process that is supported by the tool chain. The *tool chain architect* defines the conceptual and detailed design of the tool chain. One or several *tool chain developers* implement the tool chain as software based on the tool chain design.

At run-time, the tool chain software is executed to realize the data-transfer, traceability, invocation and notification to support the *product development process* of the embedded system. The *embedded systems developers* have the role of *tool chain users*.

The role of the *tool chain architect* has been explicitly introduced to cover the responsibility of specifying, refining and analyzing the architecture of the tool chain. Since TIL allows the tool chain to be described independently of implementation technology, the role of the tool chain architect can be separated from that of the tool chain developer. As the tool chain users, embedded systems developers are familiar with the requirements for the tool chain, but not with their implementation. Thus, embedded systems developers may be suitable candidates to take on the role of the tool chain architect and leave the implementation to dedicated tool chain developers. This separation of responsibilities is one attempt to resolve the unclear responsibility for the creation of tool chains observed in industry (cf. Section II-A).

B. Requirements Engineering

As described in Section IV-A, the product development process constitutes an important part of the requirements for the tool chain. By modeling the product development process in SPEM, we capture and model the requirements of the tool chain. We are thus in the situation to have semi-formal requirements for the tool chain.

[1]Strictly speaking, the run-time is outside the scope of the development process but has been added here for illustrating the connection between the tool chain and the embedded systems developers.

C. Conceptual Design

In the early design phase of the tool chain development process, a conceptual TIL model is created, which only describes the components and connections of the tool chain without any additional details. The conceptual model of the tool chain should be aligned to the product development process and the choice of development tools, so the tool chain can support the integration-related tasks in the development process. Development processes can be modeled for different purposes [19], however, here we focus on process models that have been created as a means for documentation, and are expressed by the Software and Process Engineering Metamodel (SPEM) [14].

If in addition to describing the tool chain as a model (e.g., using TIL), the process is also modeled (e.g., using SPEM), the relationship between the process model and tool chain model can be described. Possible relationships between SPEM and TIL models are identified and expressed by a mapping of a pattern of SPEM metaclasses to a pattern of TIL metaclasses. This mapping is implemented as a model transformation. Using the transformation and an existing process model, an initial conceptual design model of the tool chain is created. The main benefit of an automated mapping between process models and tool chain models is that an alignment between the design of the tool chain and the process can be achieved. This approach was described in detail in Section IV.

D. Refinement and Detailed Design

The conceptual TIL model needs to be refined by adding ToolAdapter metamodels that describe the data and the services exposed by each ToolAdapter and thus serve as interface specifications. If the ToolAdapter is to be newly implemented, the ToolAdapter metamodels need to be manually specified.

If an existing, already deployed ToolAdapter is to be reused and integrated into a tool chain, such as an existing ToolAdapter provided by a third party, the integration of the ToolAdapter would be possible on implementation level. In this approach, however, we explore the *integration at model level*, since a complete model of the tool chain enables correctness checks, analysis of the tool chain and complete synthesis of the implementation. The integration on model-level entails representing the interface of the remotely deployed ToolAdapter by ToolAdapter metamodels. This work explores, how the ToolAdapter metamodels of the remotely deployed ToolAdapter can be automatically discovered and integrated into a comprehensive TIL model of the tool chain.

The approach allows for the efficient reuse of deployed ToolAdapters in a new tool chain, ensures the consistency

between the ToolAdapter metamodel and the deployed implementation, and the consistency between the ToolAdapter metamodel and the TIL model, enabled by the representation of all relevant information on the model level. This approach is further detailed in [20].

The conceptual TIL model needs to be further refined with detailed specifications for each DataChannel. DataChannels denote the transfer of data from a source ToolAdapter to a target ToolAdapter. The tool data is exposed by the ToolAdapter in the form of a model that conforms to the ToolAdapter metamodel. If the metamodels of source and target ToolAdapters are the same, the data can be simply copied between the ToolAdapters. In the more common case that the metamodels are different, the data needs to be transformed before it can be transferred to the target ToolAdapter. For this purpose, TIL offers the possibility to link a model transformation to each DataChannel. The model transformation converts the data between the metamodels of source and target ToolAdapters.

Typically, the details of a DataChannel are manually specified in the form of a model transformation, which requires time and effort. Especially if the requirements for the tool chain are still changing and prototypes of a tool chain are developed, an automated approach for the specification of model transformations can be valuable. In this setting, the intention is to rapidly and automatically create a first prototype of a model transformation, which can be manually refined later on.

Under certain conditions it might be possible to provide support for specifying a prototype model transformation automatically. The TIL model contains relevant information for generating the transformation, such as its execution direction and both its source and target metamodels. This information is not sufficient for an algorithmic approach, but a heuristic approach for prototyping model transformations can be realized. With the assumption that similar metaclasses of the metamodels of source and target ToolAdapters should be mapped, a model transformation can be computed using heuristics. As a measure for the similarity of the metaclasses, the similarity of the reference structure and the names of the metaclasses are used. The automatic refinement of the tool chain model by generating the information in DataChannels is described in [21].

E. Verification and Analysis

The analysis of a tool chain design is intended to support the *tool chain architect* when designing a tool chain. An advantage of using an explicit model-based description of the tool chain is the possibility for early analysis. Early analysis allows for evaluating different designs of the tool chain and especially allows finding problems during design that would be more expensive to correct if discovered later [22]. Instead of applying generic, existing analysis techniques, we here focus on *domain-specific analyses* that make use of the additional knowledge of the domain of tool integration, which is encoded in TIL models.

1) Correctness Checks of the Tool Chain Design: Correctness checks are used to detect specification errors in TIL models. Syntactic correctness of the TIL model is checked by the TIL Workbench when a TIL model is created. In addition, the following checks for semantic correctness are performed. A TIL model provides language concepts for both specifying service signatures and invoking the services. All service calls need to be consistent with their respective specification. Correctness checks compare the usage with the specification. The services and data structures are specified in the ToolAdapter metamodels and are used in the ControlChannels. The TIL model is checked for correctness by analyzing whether all service usages in the ControlChannels comply with their definitions in the ToolAdapter metamodels. The correctness check in the current implementation checks whether the used services are defined in the ToolAdapter metamodels by using the name of the services. Future work on the implementation could also take the parameters of the services into account.

2) Early Structural Design Verification of Tool Chain Design: In general, design verification checks if the design fulfills the specified requirements. The requirements for a tool chain are provided by the selection of tools, the product development process and additional information. Here the verification effort focuses on *structural design verification*, which is concerned with the extent to which the structure of the design of the tool chain is aligned to the structure required by the product development process. Early verification of tool chain design can detect possible misalignments between the structure of the product development process and the structure of the tool chain, when corrections are still relatively simple and cheap. By automating the early verification of tool chain design, it can be performed repeatedly with little effort, supporting the iterative refinement of tool chains.

The alignment of the design provided by a TIL model is checked against the requirements provided by a SPEM model [23]. This alignment can be expressed by a mapping of a pattern of SPEM metaclasses to a pattern of TIL metaclasses. Even if the conceptual model has been constructed based on a SPEM model, unintended changes might have been introduced by manual refinements. The verification produces a list of misalignments and a measurement indicating the degree of alignment between the tool chain and the product development process using precision/recall metrics [24], where a tool chain that is well-aligned to the process model has both a high degree of precision and a high degree of recall.

Structural design verification is only one part of a comprehensive design verification, since other requirements besides the structure, such as the behavior and non-functional requirements, need to be checked as well. Even a comprehen-

sive design verification is a complement – not a replacement – to testing and verification of the final implementation.

F. Implementation

To support the implementation phase of the tool chain development process, the TIL approach provides a code generator. For any correct TIL model the code generator synthesizes a corresponding implementation automatically. TIL is designed to be independent of any particular implementation technology and thus code for different implementation technologies could be generated for a TIL model. For the purpose of showing that code generation is feasible, a particular implementation technology was chosen as a target platform and a code generator was built for it.

Code generation can produce a large part of the implementation automatically, however, it needs to be complemented with some manual implementation for interfacing the APIs of the integrated tools. We refer to [10] and [11] for a detailed description of the support for the implementation phase and code generator.

VI. Case Studies

In this section, we apply the identified relationship patterns between a process model and a tool chain (see Section IV) in two industrial case studies and a case study that recursively applies the approach to the development of tool chains. The tool chain development process (see Section V) and the tool integration language (see Section III) are used as enabling technologies. The variety of case studies gives us the opportunity to study different ways of using the patterns and to explore the impact of different modeling styles.

A. Case Study 1: Conceptual Design of a Tool Chain Model for a Hardware-Software Co-Design Process

This case-study deals with an industrial development process of an embedded system that is characterized by tightly coupled hardware and software components. The development process for hardware-software co-design is textually described in the following:

- The requirements of the embedded system are captured in the IRQA[2] tool. The system architect designs a UML component diagram and creates trace links between UML components and the requirements.
- The UML model is refined and a fault tree analysis is performed by the safety engineer. When the results are satisfactory, the control engineer creates a Simulink[3] model for simulation and partitions the functionality for realization in software and hardware.
- The application engineer uses Simulink to generate C code, which is refined in the WindRiver[4] tool. The data from UML and Simulink is input to the IEC-61131-3 conform ControlBuilder tool. The data from ControlBuilder, Simulink and WindRiver is integrated in the Freescale development tool for compiling and linking to a binary for the target hardware.
- A hardware engineer generates code in the hardware description language VHDL from Simulink and refines it in the Xilinx ISE[5].

Based on the description of the process, we have created the corresponding SPEM model visualized in Figure 5.

We apply the model-to-model transformation that realizes the relationship patterns on the SPEM model in Figure 5. This yields a tool chain model that is aligned with the process, as shown in Figure 6. By applying the task-centered integration pattern shown in (1), we identify integration tasks that are linked to two work products that in turn are linked to different development tools (e.g., the task *Trafo_UML2Safety*). Some other tasks are not concerned with integration, they are related to one tool only (e.g., the task *Use_UML*).

The TIL model resulting from application of the relationship patterns is internally consistent; this means that there are no conflicts, missing elements or duplications in the model. All tools mentioned in the SPEM model are also present in the TIL model as ToolAdapters and all ToolAdapters are connected. In addition, the approach ensures that the design of the tool chain matches the process.

Since the tool chain is modeled, we can easily change, extend and refine the initial model before any source code for the tool chain is developed. The TIL model is relatively small compared to the SPEM model, thus hinting at its effect to reduce complexity. When using the simple complexity metric of merely counting model elements and connections, we see that in the TIL model their number is reduced by $2/3$ compared to the SPEM model (cf. Table II).

Table II
Size of the SPEM and TIL Model of Case Study 1

Count	Model Elements	Connections
SPEM Model	43	71
TIL Model	13	26

The important architectural design decisions of the tool chain (such as the adapters and their connections) can be expressed in TIL, while the complexity has been decreased compared to a SPEM model (cf. Table II). The tool chain model can be analyzed and - after additional refinement with tool adapter metamodels and transformations - can be used for code generation, as detailed in [11], [10]. Moreover, the presented model-driven construction of the tool chain ensures that the tool chain is aligned with the process.

[2]http://www.visuresolutions.com/irqa-web
[3]http://www.mathworks.com/products/simulink
[4]http://www.windriver.com
[5]http://www.xilinx.com/ise

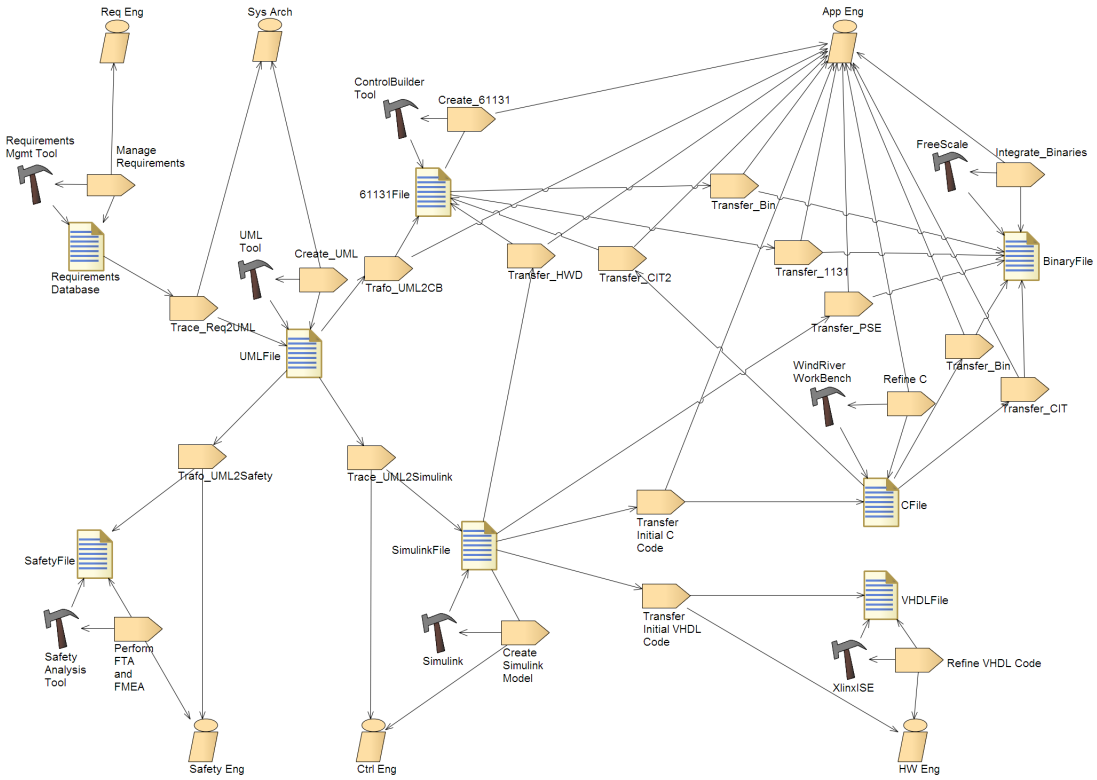

Figure 5. Case Study 1: Product Development Process of the Case Study as a SPEM Model

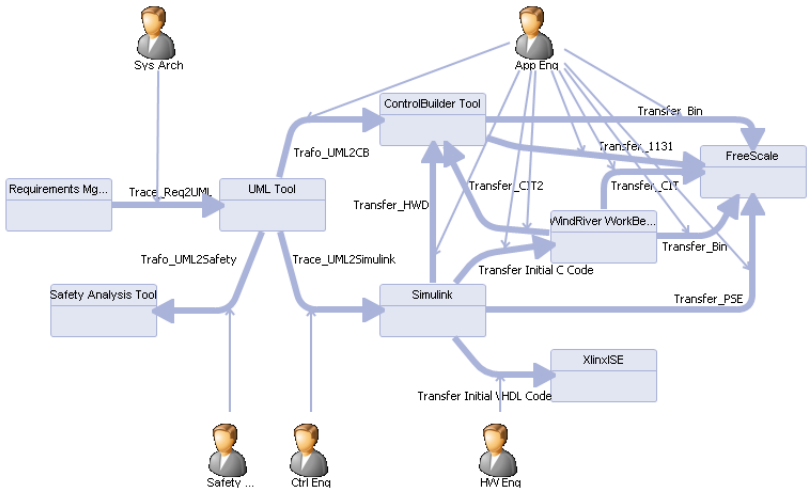

Figure 6. Case Study 1: Tool Chain of the Case Study as a TIL Model

B. Case Study 2: Verification of a Tool Chain Model for AUTOSAR ECU Design

In this case study, we model a tool chain for AUTOSAR. AUTOSAR is developed by the automotive industry and defines an architectural concept, a middleware and in addition a methodology for creating products with AUTOSAR. The AUTOSAR methodology describes process fragments, so called capability patterns in SPEM. Generic AUTOSAR tool chains are implemented in both commercial tools and open frameworks, however, it is a challenge to set up tool chains consisting of tools from different vendors [25] and tool chains customized to the needs of a particular organization.

The SPEM process model is provided by the AUTOSAR consortium and is publicly available, which contributes to the transparency of this case study. An excerpt of this model that is relevant for the design of a ECU, is depicted in Figure 7. We use this excerpt of the SPEM model to initialize a tool chain. Applying the patterns creates the tool chain model in TIL, illustrated in Figure 8. Out of the four different SPEM parts of the relationship patterns (1) - (4), only the workproduct-centered integration pattern (3) matched several times in the SPEM model. This is due to the modeling style used in the AUTOSAR methodology, where *WorkProducts* are used as an interface for integrating tools.

The generated skeleton of the tool chain lays the foundation for ensuring that the AUTOSAR methodology can be realized by this tool chain. The skeleton can now be refined with metamodels, model transformations and the behavior.

C. Case Study 3: A Tool Chain for Developing Tool Chains

To create a tool chain for developing tool chains, we apply the approach recursively onto itself: the tool chain is the product that will be developed according to the process for developing the tool chains. Using the terminology introduced in Section V, this process is called tool chain development process (TCDP) illustrated in Figure 4. We now interpret the TCDP as the PDP and thus as the basis for tool chain creation: the TCDP is interpreted as a description of the requirements of the tool chain.

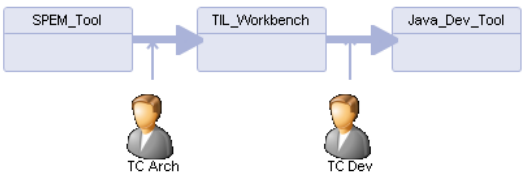

Figure 9. The tool chain for developing tool chains.

Only three tools are involved in the TCDP, and the tool chain is a straightforward pipe-and-filter architecture. The tool chain in TIL, which results from applying the patterns described in Section IV-B, is depicted in Figure 9. For each ToolAdapter, the metamodels are already defined and can be reused: The SPEM metamodel is defined [14] the TIL metamodel is defined [10] and the metamodel for Java is simply text in this context. The model transformations that need to be associated with the DataChannels are also defined: the model transformation from SPEM to TIL is described in Section IV-B in the form of patterns, the model transformation from TIL to Java code is described in paper [10]. With these cornerstones, it is thus perfectly feasible to apply the approach onto itself. This exercise can also be seen as an additional form of validation for the approach.

VII. Related Work

Related work can be found in the areas tool integration and process modeling. There are a number of approaches for tool integration, as documented in the annotated bibliographies [26], [27]. Most of the approaches do not take the process into account; in this section, we focus on those approaches that do.

Different process metamodels have been compared in [28] and specifically process models based on UML [29]. These approaches are usually focused on the description and documentation of processes. The execution of process models can range from simple workflow systems to more elaborate automation models. An example of an approach in the latter category is the PM+FDT approach [30]. It is based on a formalism for activity diagrams and uses model transformations to realize activities for transitioning from one formalism to another one. While dealing with multiple formalisms through transformations is possible, the connection to industrially used development tools is out of scope.

In the following, we classify approaches for process modeling according to two dimensions: The first dimension comprises different execution mechanisms, which can be interpretation vs. compilation. The second dimension comprises different process modeling languages, which can be proprietary vs. standardized.

Interpretation-based approaches [31], [32], [33] use the process definition for tool integration. This technique is also known as enactment of process models. Since the description of the process is identical to the specification of the tool chain, no misalignment between process and tool chain is possible. There are two preconditions for this approach: the process model needs to be executable and the access to data and functionality of the development tools needs to be possible. The use of a proprietary process model for interpretation in tool chains is introduced in [34], as the process-flow pattern. Approaches that extend SPEM make the process model executable [31], [32]. The orchestration of tools by a process model is shown in [33]. However, the interpretation of integration related tasks is often not possible, since the interfaces to the development tools are not standardized. Thus, the use of process enactment to build tool chains is limited.

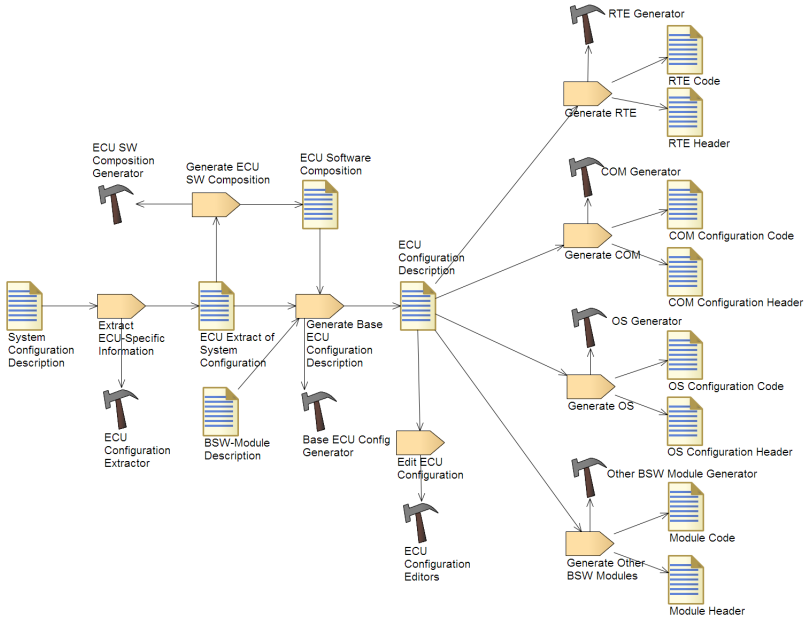

Figure 7. Case Study 2: Excerpt of the AUTOSAR Methodology for Designing an ECU [15].

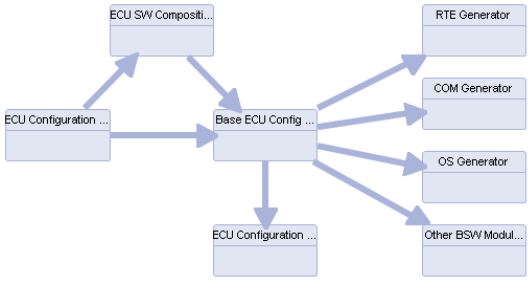

Figure 8. Case Study 2: AUTOSAR Tool Chain for Designing an ECU as a TIL Model

Compilation-based approaches transform the process model into another format, where the process model serves as a set of requirements. Proprietary process models provide great flexibility to adapt them to the specific needs of tool integration. An integration process model is developed in [35], where each process step can be linked to a dedicated activity in a tool. For execution, it is compiled into a low-level process model. The proprietary process model needs to be created specifically for constructing a tool chain. In this work, we use the standardized process metamodel SPEM [14], which allows us to reuse existing process models as a starting point for building tool chains and as a reference for verification for tool chains.

VIII. Future Work

This approach assumes that an appropriate process model for tool chains is available. We assume that the process model does not contain any integration related overhead, i.e., explicit representation of a model transformation tool and intermediate data model. We assume that tools have been assigned to process activities. The choice for certain tools is usually independent of automating the tool chain, the choice merely needs to be documented in the process model. SPEM offers several ways for describing tool integration. Future work can identify additional SPEM patterns for describing tool integration. Future work can also identify possible uses of additional SPEM constructs for describing tool integration, such as the the SPEM work breakdown structure.

The use of the presented patterns is limited to processes represented in SPEM and tool chains modeled in TIL. However, the patterns could be adapted to similar process metamodels, as long as the required concepts are present. In the future, we would like to experiment with additional languages for describing the process model, such as BPMN. This might help us to further generalize the patterns.

We have evaluated the approach in two case studies from the area of embedded systems and one case study from software development. We do not see any reason why the

patterns could not be applied for creating tool chain from process models in other application areas in the future and are thus generalizable. For further validation, we thus plan to apply the presented techniques in another area of software and systems engineering.

IX. Conclusion

In modern development processes, tools are no longer used in a linear sequence, but as networks of interacting tools. The tool chain represents this network of interacting tools that needs to be tailored to the the development process. Processes are increasingly described as process models, which exist for a variety of reasons, i.e., for documenting, planning or tracking progress in a development project. SPEM is the standardized language by the OMG for this purpose. In this article, we recognize the development process modeled in SPEM as a set of requirements for the architecture of tool chains. We devise a number of patterns for creating the skeleton of a tool chain model in TIL, which is aligned with the process. This allows us to automate the creation of an initial tool chain design.

We have further shown how a tool chain model can be systematically developed into a tool chain implementation by following a structured tool chain development process. We have shown that many phases of this tool chain development process can be automated. If this process is followed, a semi-automated construction of tool chain software is possible. The semi-automation makes the construction cost-efficient, which is one of the decisive factors for building and configuring tailored application lifecycle management systems.

The presented cost-efficient construction has the potential to resolves the dilemma faced by industry today: Application lifecycle management can only deliver the promised efficiency improvements and cost savings, if it is tailored to the given set of tools and processes, but tailoring itself is expensive, has a cost and thus reduces the net-value of application lifecycle management. By automating the tailoring, as described in this article, the cost of tailoring is reduced and thus the net-value of application lifecycle management is highly improved.

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Towards an Approach for Analysing the Strategic Alignment of Software Requirements using Quantified Goal Graphs

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***Abstract*—Analysing the strategic alignment of software requirements primarily provides assurance to stakeholders that the software-to-be will add value to the organization. Additionally, such analysis can improve a requirement by disambiguating its purpose and value, thereby supporting validation and value-oriented decisions in requirements engineering processes, such as prioritization, release planning, and tradeoff analysis. We review current approaches that could enable such an analysis. We focus on Goal Oriented Requirements Engineering methodologies, since goal graphs are well suited for relating software goals to business goals. However, we argue that unless the extent of goal-goal contribution is quantified with verifiable metrics, goal graphs are not sufficient for demonstrating the strategic alignment of software requirements. Since the concept of goal contribution is predictive, what results is a forecast of the benefits of implementing software requirements. Thus, we explore how the description of the contribution relationship can be enriched with concepts such as uncertainty and confidence, non-linear causation, and utility. We introduce the approach using an example software project from Rolls-Royce.**

Keywords—Requirements Engineering; Strategic Alignment; Quantified Goal Graphs; Requirements Traceability

I. INTRODUCTION

This paper describes in more detail the concepts and the technique originally presented at the 7th International Conference on Software Engineering Advances [1]. It extends the work namely through a more comprehensive literature review, and the introduction of multi-point goal contribution.

The growth of the strategic importance of IT [2] necessitates the need to ensure that software to be developed or procured is aligned with the strategic business objectives of the organization it will support [3]. Attaining this alignment is a non-trivial problem; firstly, decisions in the Requirements Engineering (RE) phase are some of the most complex in the software development or procurement lifecycle [4], and secondly, there is a gulf of understanding between business strategists and IS/IT engineers [5]. If alignment were trivial and easy, then it would not have been the "top ranking concern" of business executives for the last two decades [6], over 150 papers would not have been published on the topic [7], and perhaps there would be less software features implemented but never used (currently half of all features [8]).

Decisions made in the requirements phase greatly affect the value of the resulting software, e.g., in requirements prioritisation, the selection of the least important requirements allows costs to be cut by trading off the development of those requirements. The correctness of any such decision depends entirely on the availability of information about the choices available to the decision maker [9]. In this context, information about the value of a requirement, in particular, the causes and dependencies of value creation, is highly useful. Goal graphs are of great interest because they are well suited for visualising cause-effect, dependency, and hierarchical relationships between requirements [10].

This paper explores the suitability of goal graphs for demonstrating a software requirement's strategic alignment. Current Goal Oriented Requirements Engineering (GORE) approaches primarily take a qualitative or subjective approach to describing goal contribution, such as GRL's {--,-,+,++} or [-100,100] scores [11]. As a result, any strategic alignment proposed by the use of goal graphs is not specific, measurable or testable. Proposed extensions by Van Lamsweerde [12] do not consider that a chain of linked goals may contain a variety of metrics that need to be translated in order to demonstrate strategic alignment. Additionally, the certainty, confidence, and credibility of the predicted contribution is not explored. A probabilistic layer for goal graphs is proposed in [13], which recognises that goals are often only partially satisfied by software requirements. However, the (often non-linear [14]) effects of the incomplete goal satisfaction on an organisation's various levels of business strategy are not explored. Furthermore, current methods do not consider how goal contribution scores are elicited [15], and how their calculation affects the credibility and accuracy of the claimed benefits. This paper attempts to demonstrate how the above problems can be addressed, thereby improving the applicability of goal graphs for the problem of analysing the strategic alignment of software requirements. By making assumptions about business value explicit, our approach complements Value-Based Software Engineering (VBSE) [16].

We have developed and implemented our approach in partnership with an industrial partner (Rolls-Royce) to ensure its usability and utility in real world settings. We use examples in the context of a software project for a Business Unit (BU) responsible for part of a Gas Turbine (GT) engine, henceforth referred to as GT-BU. The software will automate geometry design and analysis for engine components, as well as for their manufacturing tools such as casting molds. Simply put, engineers will input the desired design parameters and the software will output the component's geometry. At the time of our involvement with the project, some high level

software requirements had already been elicited and defined according to the Volere template [17].

In Section II, we describe the problem that this paper addresses. Then, in Section III, we define and describe the essential terminology and concepts, while in Section IV, we present and evaluate the extent to which existing solutions address it. Section V presents our approach and tool in order to address the gaps outlined in Section IV. We conclude in Section VI with the paper's contributions and future work.

II. The Problem

Stakeholders responsible for a software project's funding need to be able to demonstrate that the software they want to develop or purchase will be beneficial. Decision makers require granularity at the requirement level, rather than the project level, since individual software functionalities or qualities may significantly affect the benefit or cost of the software's development or procurement. Furthermore, stakeholders performing requirements engineering processes where the benefit of a requirement is questioned (e.g., in prioritisation, release planning, trade-off, etc.) need to know how benefit is defined by the stakeholders, and then how the requirements (and their alternatives) contribute to it.

As an example of the problem that this paper examines, we introduce the following high-level software requirement taken from our example project: "While operating in an analysis solution domain and when demanded, the system shall run analysis models". The rationale attached to this requirement is "So that structural integrity analysis models can be solved as part of an automated process". Although the rationale hints at automation, the requirement's benefit to the business and the potential for alignment with business strategy are unclear. In order to understand the latter (i.e., the alignment with business strategy), the extent to which the organisation wants to reduce the problems related to manual structural integrity analysis needs to be understood (i.e., it's business objectives). In order to understand the former (i.e., the business value), the extent of the requirement's contribution to the problem-to-be-solved needs to be made clear, e.g., the extent that automation is likely to solve the problems related to manual structural integrity analysis. For example, if the manual process costs the business in terms of employee time and computing time, how much time is consumed, and at what cost? Then finally, to what extent will the software requirement's successful (or partially successful) implementation reduce the time consumption and cost?

To paraphrase Jackson & Zave [18], for every stated benefit (or an answer to "why?"), there is always a discoverable super benefit (i.e., benefit that arises from that benefit). For example, the slow and human resource intensive process may constrain the designer's ability to innovate (by not being able to analyse new design ideas), which may ultimately harm the organisation's competitive advantage. Many levels of benefit follow a requirement's implementation. Each level provides the possibility of contributing to a business objective at a different level of the organisation. There are arguably more levels of benefit than it would be sensible to express within a requirement, since several requirements may achieve the same benefit, but their contribution will vary.

III. Background Terminology

A. Software Requirements

In 1977, Ross and Schoman stated that software requirements "must say why a system is needed, based on current or foreseen conditions" as well as "what system features will serve and satisfy this context" [19]. Robertson & Robertson later expanded the concept of a "feature" by defining a requirement as: "something that a product must do or a quality that the product must have" [17], otherwise known as functional and non-functional requirements, respectively. It is worth noting here that, according to the "what, not how" [20] paradigm, software requirements are often incorrectly specified in practice (i.e., they often describe *how* features should work, rather than *what* features should be implemented). Consequently, implementation bias may occur, unnecessarily constraining the design space. Practitioners are not entirely to blame however, since the *what* and *how* separation is confusing. This is because a requirement describes both concepts at the same time, but at different levels of abstraction. For example, "print a report" is what the system should do, but also how the system should "make the report portable" – which again, is what the system should do, but also how the system should "make reports shareable". The *how* and *why* aspects of a *what* statement are simply shifts in the level of the statement's abstraction (down, and up, respectively).

Popular requirements engineering templates (e.g., Volere [17] and IEEE Std 830-1998 [21]) and meta models (e.g., SysML [22] and the Core Metamodel [23]) tend not to focus on the *why* aspect, typically addressing it by stipulating that rationale be attached to a requirement. However, rationale is not always an adequate description of why the requirement is valuable. If only one *why* question is asked about the requirement then the rationale can still be distant from the true problem to be solved (i.e., the essence of the requirement), and it may be defined without consideration of its wider implications. A stakeholder's "line of sight" (i.e., the ability to relate low level requirements to high level business goals), and thus, the ability to determine the value of a requirement, depends on their ability to find answers to enough recursive *why* questions. Anecdotally, empirical studies at Toyota determined that the typical number of *why* questions required to reach the root cause of a problem is five (thus spawning the "five why's" method popularised by Six Sigma) [24].

B. Strategic Alignment

Singh and Woo define business-IT strategic alignment as "the synergy between strategic business goals and IT goals" [7]. In the IT context, Van Lamsweerde defines the term "goal" as a prescriptive, optative statement (i.e., desired future state) about an objective that the system hopes to achieve [25]. In the business context, a goal is defined as an abstract indication of "what must be satisfied on a continuing basis to effectively attain the vision of the business" [26]. In order to relate the goals of the system to those of the business, an integrated definition of the terms used by business strategists and software developers is required. Furthermore, the first definition does not make "objective" distinct from "goal". The Object Management Group (OMG) defines such

terms in its Business Motivation Model (BMM) [26]. There, an objective is defined as a specific "statement of an attainable, time-targeted, and measurable target that the enterprise seeks to meet in order to achieve its goals". According to the definitions of goals and objectives provided by the BMM, the difference between a goal and an objective lies in the goal's hardness (i.e., whether the goal's satisfaction can be determined). Therefore, from now on, we use the terms "hard goal" and "objective" interchangeably.

Finally, the BMM defines that a collection of business objectives forms a business strategy [26], thus satisfaction of objectives leads to the satisfaction of the strategy. It logically follows that the extent to which a software requirement aligns to business strategy depends on the extent to which the requirement contributes to the satisfaction of the strategy's objectives. Attempting to demonstrate a requirement's strategic alignment to soft goals (e.g., "maximise profit") would be inappropriate, since it would not be possible to describe the extent of the requirement's contribution to the goal. Therefore, when demonstrating strategic alignment, requirements should be related to objectives rather than goals.

IV. Related Work

The following areas of research are related to analysing the strategic alignment of software requirements: (A) Value Based Software Engineering, (B) Goal Oriented Requirements Engineering, (C) Strategic Alignment Approaches, (D) Quantitative Requirements and Metrics, and (E) Requirements Traceability Approaches.

A. *Value Based Software Engineering*

The Value Based Software Engineering (VBSE) agenda is motivated by observations that most software projects fail because they don't deliver stakeholder value, yet, much software engineering practice is done in a value-neutral setting (e.g., where project cost and schedule is tracked rather than value) [27]. Value Based Requirements Engineering (VBRE) takes the economic value of software systems into perspective through activities such as stakeholder identification, business case analysis, requirements prioritisation, and requirements negotiation [28]. The primary VBRE activities are Business Case Analysis (BCA) and Benefits Realization Analysis (BRA) [16]. Other VBRE activities such as prioritisation are considered secondary to these, since they depend on (and often start with) benefit estimation [29].

In its simplest form, BCA involves calculating a system's Return on Investment (ROI) - which is the estimated financial gain versus cost, defined in present value. While simple in definition, accurately calculating ROI is complex, since the validity of any concise financial figure depends on assumptions holding true, e.g., that independent variables remain within expected intervals (e.g., time saved is between [x,y]). Estimating benefit involves further intricacies such as uncertainty and the translation of qualitative variables (e.g., the software user's happiness) to quantitative benefits (e.g., sales revenue) - none of which are made explicit by BCA. An advancement from BCA in descriptiveness, e^3value modelling seeks to understand the economic value of a system by mapping value exchanges between actors, ultimately leading to financial analysis such as discounted cash flow [30]. However, it does not address how economic value creation is linked to requirements, nor are links between value creation and business strategy attempted.

BRA's fundamental concept is the Results Chain [2], which visually demonstrates traceability between an initiative (i.e., a new software system) and its outcomes (i.e., benefits) using a directed graph, where nodes represent initiatives, outcomes, and assumptions, while edges represent contribution links. BRA's contribution links allow one initiative to spawn multiple outcomes, but the links are not quantitative, e.g., outcome: "reduced time to deliver product" can contribute to outcome: "increased sales" if assumption: "delivery time is an important buying criterion" holds true – but the quantitative relationship between "delivery time" and "sales increase" is not explored. This is problematic when outcomes are business objectives, since their satisfaction depends on the extent that they are contributed to, e.g., in the case of a cost reduction objective, the primary concern is the amount of reduction that is contributed by the actions.

In summary, neither BCA nor BRA estimates the benefit of individual requirements, but rather for whole systems. A similar criticism also applies to the majority of requirements prioritisation methods, as a systematic literature review "found no methods which estimate benefit for [primary] individual requirements" [29], nor were any found which derive the benefits of secondary requirements from their contribution to primary requirements. In this context, primary refers to stakeholder requirements or business objectives while secondary refers to those derived from the primary requirements (e.g., a refined functional requirement).

B. *Goal Oriented Requirements Engineering (GORE)*

GORE seeks to provide answers to "why?" software functionality should exist. The most well-known GORE methodologies include KAOS [31], i* [32] and GRL [33]. Such methodologies produce goal graphs whereby goals at a high level represent the end state that should be achieved and lower level goals represent possible means to that end. A goal graph is traversed upwards in order to understand why a goal should be satisfied and downwards to understand how that goal could be satisfied. In this context, a requirement is a low level goal, which is simply a means to achieving an end (a high level goal). Other related concepts such as resources, beliefs and obstacles are typically related to goals to describe what a goal's satisfaction requires, while agents (or actors) indicate which stakeholders are responsible for (or depend on) a goal's satisfaction. Relationships between goals are typically represented by means-end links, where optional AND/OR constraints represent alternative options for satisficing a goal. Contribution links are enhanced means-end links, in that they describe the extent to which a goal contributes to the achievement of another. However, "extent" is usually defined in terms of sufficiency and necessity (logic), not as in the quantitative extent of the contribution [34].

i. *Goal-Goal Contribution Links*

Contribution links are usually annotated with a score or a weight, to represent the degree of contribution made by the

goal. Three approaches for applying scores to contribution links in goals graphs are described by Van Lamsweerde [12]:

1. Subjective qualitative scores e.g., --, -, +, ++.
2. Subjective quantified scores e.g., -100 to 100.
3. Objective gauge variable (i.e., a measured quantity predicted to be increased, reduced, etc.).

After evaluating the above approaches, Van Lamsweerde concludes that the specification of contribution scores with objective gauge variables (the third option) is the most appropriate for deciding among alternatives, due to its verifiability and rooting in observable phenomena. Of course, the subjective approaches are no doubt quicker to use, but their sole use risks misunderstanding the actual contribution mechanism. A comprehensive comparison of the qualitative contribution reasoning techniques can be found in [35].

Just as objective contribution scoring adds rigour and testability to the task of deciding between alternatives, the same applies to the task of demonstrating alignment to business objectives. Thus, contribution scores should be quantified in terms of the contribution likely to be made to the objective. Our rationale is that, by definition, objectives are quantitatively prescribed, and reasoning qualitatively about degrees of satisfaction of a quantitative target is highly ambiguous. Additionally, this will allow the contribution scores to be verifiable so that they (as predictions) may be later compared to actual results in the evaluation stage of the project. It must be noted here, however, that this option is not without its disadvantages - empirical studies in requirements prioritisation show that practitioners find providing subjective data far easier than objective data [36]. A parallel can be drawn here to the decision analysis field, where inferior (i.e., qualitative) processes have found favour with decision makers because "they do not force you to think very hard" [9].

Van Lamsweerde goes on to explain how alternative goal (i.e., requirement) options can be evaluated by predicting contributions made by goals to soft goals (which define the qualities to be used for comparison) [12]. However, in the prescribed approach, the relationship between the soft goals and the predicted benefit to be gained by their achievement is not made explicit. In other words, the contribution scores are not abstracted to different levels of benefit such that they may eventually relate to business objectives. Each of these potential benefit abstractions require that the metrics used to measure contribution (and satisfaction) are translated (e.g., from time saved to money saved). Furthermore, the expected values allocated to the objective gauge variables are single-point representations of inconstant and variable phenomena. For example, when estimating the number of interactions required to "arrange a meeting via email" – an alternative requirement option taken from the paper's meeting scheduling system example – a single number does not describe the possible variance, or how that variance can affect the desired end. This is important for predicting strategic alignment, since variance in a requirement's satisfaction is likely [13], and it will affect the satisfaction of the related business objective(s).

GORE approaches typically describe a goal's benefit relative to other goals with an importance or weight attribute [12], where importance is a qualitative label (e.g., high, medium, low) and weight is a percentage (where the total of all assigned weights is 100%). Both of these approaches are ambiguous and subjective, and are not traceable to observable benefits, e.g., alignment with business objectives.

A probabilistic layer for quantified goal graphs is proposed in [13] to represent the variance of goal contributions in terms of probability density functions (pdf's). However, effects of the variance on the satisfaction of high level goals, or business objectives, are not described. To use the example provided in the paper, the effects of an ambulance arriving at a scene within 8, 14, or 16 minutes (i.e., satisfaction of the target exceedingly, completely, or partially) are not described in the context of the benefits of doing so – i.e., to what extent will some problem(s) be affected given these possible goal satisfaction levels. If this is not explored, then it might be that there are no significant benefits to be gained at certain intervals of goal satisfaction levels (note that this point is more significant for non-life-threating systems). Thus, if a goal is defined with a specific target (e.g., target arrival time) in mind, without the rationale for doing so explored as further goal abstractions, then satisfying that goal may not be worthwhile - "wrong decisions may be taken if they are based on wrong objectives" [13]. Furthermore, probabilistic approaches have limited applications (pdf's are not often available and are time consuming to construct), and do not capture stakeholder "attitude, preference and likings" [15].

ii. The Goal-oriented Requirements Language (GRL)

Given the choice of GORE methodologies, we chose to focus on and adopt GRL [33] for the following reasons:

1. GRL's diagrammatic notation is well known within the RE community (since it originates from i*) [33].
2. i* (GRL's primary component) has been shown to be the most suitable for modelling Information System (IS) strategic alignment according to the strategy map concept (GRL not included in review) [37].
3. GRL has an ontology describing its modelling concepts (where others are described informally) [34].
4. GRL was recently made an international standard through ITU specification Z.151 [11].

GRL integrates the core concepts of i* and the NFR Framework [33] (where i* inherits the qualitative goal contribution mechanism from NFR [32]), but GRL adds to i* the capability to express contributions quantitatively. Thus, goal contributions in GRL can be specified with either subjective numeric scores (interval [-100,100]) or qualitative labels (one of {--,-,+,++}) [33], i.e., the first and second options outlined in Van Lamsweerde's paper [12]. For example, a time reduction goal might contribute to an overall-cost saving goal with a contribution weight of 67 out of 100 with positive polarity (+). Such a contribution score is untestable and not grounded by observable phenomena. Moreover it is not refutable, which, according to Jackson [38], means that the description is inadequate because no one can dispute it. The only way such scales could be testable is if the goals were specified with fit criterions (e.g., a cost to be saved), which mapped to the scale, e.g., that they implied percentage satisfaction (which they do not). In which case, a 50/100 contribution might imply that 50% of a £20,000 annual cost saving will be achieved. However, this is only applicable for

goals whose satisfaction upper bound is 100% (since the scale's upper bound is 100), which is not the case for goals involving increases (e.g., where a mean's contribution to an end exceeds the end's target level).

Recently, the jUCMNav tool allowed goals to relate to Key Performance Indicators (KPIs) in GRL, in order to map a goal's satisfaction value to real world numbers [39]. However, subjectivity still exists in goal chains (i.e., >1 link), since KPIs do not affect the way in which goal contribution is specified further up the goal chain (i.e., as low level benefits are translated to high level business objectives, e.g., converting time to cost). Also, the interaction between KPIs is not considered, e.g., composition via hierarchy or non-linear causation. Since the publication of our original work, Horkoff et al. have improved GRL's integration with indicators to consider the hierarchy of KPIs alongside a goal model [40]. However, their approach is concerned with improving Business Intelligence (BI), rather than aligning software requirements to strategic business goals. Thus, several areas are still lacking when applied to our problem. Means are not distinguished from ends (i.e., business objectives and software requirements), making it difficult to know which sets of goals should be aligned, or how those goals should be defined or organised differently. Also, stakeholder utility and confidence through the range of possible goal satisfaction levels (i.e., KPIs in the approach) is not specified – making it hard to know the effects of partial requirement satisfaction, or the credibility of the estimated alignment. Furthermore, non-linear relationships in the associated KPI hierarchy (i.e., diminishing returns in achieving an objective) are not amenable to algebraic description [14] (i.e., "business formulae", as termed in the approach) – making their definition and communication difficult. Finally, potential fluctuation or uncertainty (i.e., the range of possibilities) in goal contribution is not described, as is done with *usage profiles* in [41] .

As an additional concern, a contribution link is underpinned by assumptions which can either make or break the satisfaction of the end goal. For example, a reduction in task time will only reduce costs if associated costs are actually cut (e.g., by billing work to a different project, or through redundancies). GRL's belief elements (otherwise known as "argumentation goals") could be used to express such assumptions in order to provide an integrated view, despite their inferiority in richness to satisfaction arguments [42]. However, in the case of this particular assumption, it seems more semantically appropriate to model it as a necessary action for the end-outcome, just as the BRA's Results Chain [2] does.

C. Strategic Alignment Approaches

The Balanced Scorecard and Strategy Maps (SMs) approaches [43] offer guidance on formulating and relating business goals to each other under four perspectives: financial, customer, internal processes, learning and growth. In order to improve traceability between these perspectives, SMi* combines SMs with i* goal models [44]. While this approach does not directly relate to software requirements, goals could be categorised by the four perspectives to ensure coverage.

The most suitable framework for relating software requirements to business strategy is B-SCP [45], due to its tight integration with the OMG's Business Motivation Model (BMM) and the explicit treatment of business strategy that this affords [7]. B-SCP decomposes business strategy towards organisational IT requirements through the various levels of the BMM (i.e., the vision, mission, objective, etc.). However, B-SCP cannot show the extent to which a requirement satisfies a strategy, since no contribution strengths are assigned to links between requirements and the strategy's objectives. Moreover, B-SCP's methodology refines business strategy top-down towards IT requirements, which means that completeness of the model is dependent on the completeness of the business strategy, i.e., there is no opportunity to refine software functionality upwards to propose new business strategy. Additionally, B-SCP does not consider rich GORE concepts (e.g., AND/OR, actors), as found in GRL.

D. Quantitative Requirements and Metrics

The contribution that a requirement's implementation makes to a business objective depends on the extent of the requirement's satisfaction (i.e., partially or completely). In order to understand the extent of a requirement's satisfaction, the desired outcome of the requirement must first be made explicit. Although its practicality is debated [46], it is considered best practice to describe a requirement's desired outcome using quantitative measures [47]. In [48], Gilb describes the steps that requirements quantification should entail. Firstly, the desired level of achievement should be elicited. Then secondly, the capabilities of the various alternative design solutions should be estimated against that desired level. Finally, the delivered solution should be continuously measured against that desired level. Unfortunately, these steps are rarely followed in practice [47], [48].

As a result of a career training practitioners to quantify requirements, Gilb concludes that there are two main obstacles to quantifying requirements [48]. Primarily, practitioners find defining quantitative scales of measure for a requirement difficult, often believing that it is impossible to quantify all requirements due to their sometimes qualitative nature (which, according to Gilb is incorrect). Secondly, practitioners encounter difficulty in finding ways of measuring numeric qualities of a software product which are practical to use (i.e., meters in Planguage), and at the same time, measure real qualities. Besides, even if a requirement is quantified, its quality is not necessarily improved; a related survey revealed that precisely quantifying requirements can lead to long project delays and increased costs if the quantifications are unrealistic [49]. This is problematic, since it is not straightforward to determine what is realistic with current technology in order to set the desired level of achievement. Despite the difficulties in expressing a requirement's fit criterion quantitatively, qualitative descriptions (e.g., "good uptime") are too ambiguous to be useful – in both trying to achieve that requirement, and in analysing the effect of its implementation on the (quantitatively defined) business objectives. The only caveat to this is that qualitative terms such as "good" can be suitable if they have been defined as fuzzy numbers [50].

The Volere [17] template stipulates that a Fit Criterion be attached to a requirement in order to make its satisfaction empirically testable (i.e., the first step of Gilb's requirement

quantification steps). Planguage [51] similarly provides a template for describing how a requirement's satisfaction should be tested, and what the result of the test should be. Planguage's fit criterions are more descriptive than Volere's, since multiple levels of quantitative fit criterion are specified, e.g., for what must be achieved (minimum), what is planned to be achieved (likely), what is wished to be achieved (best case), and what has been achieved in the past (benchmark).

GQM+Strategies™ [52] was developed to extend the Goal Question Metrics methodology by providing explicit support for the traceability of software metrics measurement effort at the project level (e.g., measuring the impact that pair programming has on quality) to high-level goals at the business level (e.g., increasing the software user's satisfaction). In [53], the approach is used to show the alignment of software project goals to high level business goals by using a 2d matrix. The approach's main benefits are that goals are defined quantitatively using a tried and tested metrics template, and, that assumptions which underpin goal to goal contributions are made explicit, much like GRL's belief element allows for. However, the approach focuses on decisions at the project level, rather than the requirements level (i.e., which projects, rather than requirements, should be implemented?), so is not directly applicable to the problem – a large and variable number of goal abstractions can be required to link a requirement (a means) to a project goal (an end). Additionally, the approach falls short in areas similar to the other methodologies reviewed. Firstly, when a link exists between two goals, the effects of the first goal's satisfaction on the second goal are not explored. Thus, although each goal has a target satisfaction level (e.g., 5% profit increase), the predicted contributions that its child goals (e.g., software requirements) make toward it are not represented (along with forecast related information such as confidence, evidence, stakeholder agreement, etc.). Therefore, although GQM+Strategies™ achieves traceability between project goals and business goals, it is not possible to analyse the *extent* of the strategic alignment of software requirements, since, as aforementioned, requirements often partially satisfy goals [13], i.e., the effect of a requirement's partial satisfaction is not described in the context of business objectives. Finally, the approach lacks concepts found in GORE which contextualise goals and support decision analysis (e.g., actors, obstacles, AND/OR links).

E. Requirements Traceability Approaches

Several approaches exist which allow means to be traced to ends, typically by constructing a 2d comparison matrix where rows list means and columns list ends. Such traceability allows questions such as "what ends will be affected if this means is affected?" Additionally, it is usually possible to answer the question "how well does this means satisfy the end we want?" One of the most popular tools to trace (and then compare) product features (i.e., means) to customer requirements (i.e., ends) is the House of Quality (HoQ) [54]. Numbers are assigned (e.g., 1-9) to each means-end relationship based on the strength that the means contributes to the end. A drawback to the HoQ is that the numerical score values used to measure the strength of the contribution are subjective (e.g., strong, medium, weak). Additionally, since the HoQ is constructed using a 2D grid, only two dimensions can be compared in the same grid, i.e., requirements can be related to software goals, but if those software goals are to be related to stakeholder goals or business goals, then additional grids will be required for each extra dimension. If these dimensions are not explored (e.g., if the software project goals are not abstracted to business goals), then the goals that the alternative solutions will be evaluated against may be incorrect (e.g., solution specific or aiming to solve the wrong problem). Despite the drawbacks to using grids, they are argued to be the best means of visually displaying traceability for large numbers of traced entities [55], since they avoid diagrammatic "spaghetti", and perhaps most importantly, they visualise the lack of traceability with empty cells (e.g., means which do not contribute to an end).

To complement Planguage, Gilb proposes an approach called impact estimation [51], which estimates the impact of alternative system options (i.e., means) against a set of requirements (i.e., ends) using a 2d grid. This approach is very similar to the approach used by Van Lamsweerde to evaluate alternative design options [12], as previously discussed in subsection IV.B.i, and as such, it shares the same problems for application to our problem. The main contribution (related to our problem) of the impact estimation method is that it allows the practitioner to represent their confidence (interval [0,1]) in their prediction of the effect a means has on an end.

V. Proposed Approach

We propose that GRL goal graphs can be used to demonstrate strategic alignment by linking requirements as tasks (where the task is to implement the requirement) and business objectives as hard goals (where the hard goal brings about some business benefit) with contribution links (where the requirement is the means to the objective's end). The requirements should be abstracted (asking "why?") until they link to business objectives. Business objectives then link to higher objectives, until the business strategy is represented.

A. Constructing the Goal Graph

Before looking at how software requirements and business objectives can be connected with goal graphs, we must first explain how we represent the individual concepts.

We define business objectives using an adaption of the GQM+Strategies formalisation template [56], as in Table 1. Requiring a description of a goal using a metrics template encourages more descriptive goal models, e.g., "improve component lifespan" is defined rather than "improve engine".

TABLE 1: EXAMPLE GQM+STRATEGIES FORMALISATION

Activity	Reduced	
Object	GT-BU Fabricated Structures (FS)	
Focus	Average Manufacturing Lead Time	
Magnitude	Target: 3 months [reduction] Threshold: 2 months [reduction]	As-Is: 6 months
Scale	Average time in months required to have FS parts manufactured from the inception of a new engine	
Timeframe	1 year after system deployment	
Scope	Gas Turbine Components X,Y & Z	
Author	John Smith (Component Engineer, GT-BU)	

Our modifications to the textual template attempt to improve integration with visual GRL diagrams through:

1. The addition of the most important concept [47] from Planguage - the scale, which specifies exactly what is to be measured, and the unit of measure.
2. The addition of scale qualifiers [51] to better describe the magnitude, e.g., "threshold" separates acceptable from unacceptable [39]. When we refer to the magnitude of an objective, we refer to the target.
3. The specification of the objective's activity attribute in the past tense, since objectives represent desired outcomes rather than an activities.
4. The removal of the constraints and relations fields - these can be expressed diagrammatically with obstacles and links (e.g., dependencies), respectively.
5. The addition of the author field so that newly proposed objectives can be identified and traced.

For our reference implementation, we used the Volere template to define the attributes of a requirement, primarily because it requires a fit criterion for testing the satisfaction of a requirement. Similarly, an objective can be considered satisfied when the specified magnitude is achieved within the specified timeframe (since benefits are not realised instantly).

Figure 1 shows an example diagram produced following the approach to explore and visualise the strategic alignment of three high-level software requirements.

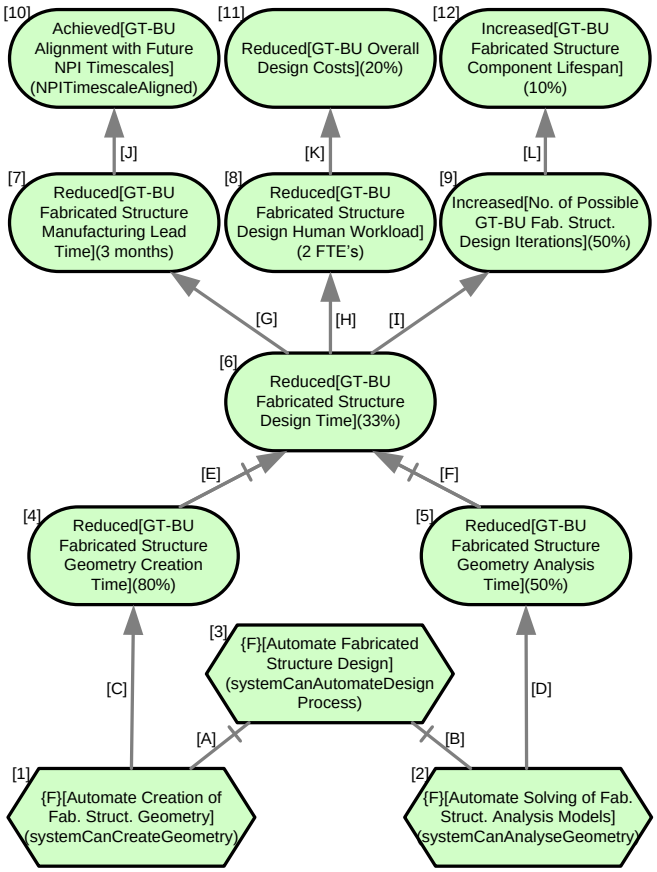

Figure 1: Example Strategic Alignment Diagram using GRL

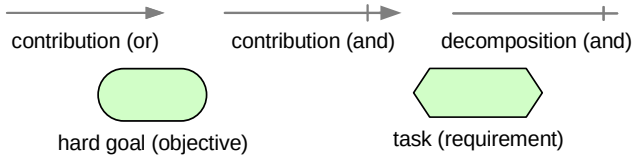

Figure 2: Key for Figure 1 - GRL Elements Used

We represent software requirements as GRL tasks (i.e., the task of implementing the requirement) using the naming syntax: "{F/NF}[Requirement](Fit Criterion)", where "F/NF" is either Functional or Non-Functional, "Requirement" is a short headline version of the requirement description, and "Fit Criterion" is the short-hand version of the metric used to test the requirement's satisfaction. In order to visualise the objectives (specified by the GQM+Strategies template) in a goal graph, we use GRL hard goals with the naming syntax: "Activity[Object Focus](Magnitude)".

Soft goal elements (e.g., goals and visions from the BMM) are not defined in the goal graph for the purpose of demonstrating strategic alignment. This is because their satisfaction criteria is undefined and thus immeasurable. Therefore, it is nonsensical to consider that a requirement may either partially or completely satisfy a goal or a vision. However, since objectives exist to quantify goals, and since goals exist to amplify the vision [26], non-weighted traceability between an objective and its goals (and their related vision) should be maintained for posterity and for impact analysis.

A contribution link between a requirement and an objective specifies that the requirement's satisfaction will achieve some satisfaction of the objective. The extent of the satisfaction is defined by the contribution score specified by the link, and is defined in terms of the objective's scale. A link between two objectives is similar, except that the satisfaction of an objective is measured by its magnitude rather than by a fit criterion. If the contributions of the child elements additively amount to meet the parent element's specified magnitude, then the model suggests that the parent element will be satisfied.

An "OR" contribution specifies that if there are multiple "OR" links, a decision has to be made about which should be satisfied. An "AND" contribution specifies that all "AND" links are required for the objective to be satisfied. The contribution links (E & F) are of the "AND" type, since both objectives (4 & 5) are required if objective (6) is to be satisfied. Decomposition links can be used to refine a requirement into more specific requirements, much like SysML's "hierarchy" link stereotype [22]. The high-level software requirement (3) is decomposed to two lower level requirements (1 & 2) to represent the hierarchy of requirement abstraction. The decomposed requirements (1 & 2) then link to objectives (4 & 5) with contribution links in order to represent what those requirements hope to achieve. The decomposition of requirements continues until the lowest level of requirements are represented. For example, requirement (2) is decomposed to specify which type of analysis should be automated (e.g., structural integrity, cost, etc.). Then, these decompositions contribute to more specific objectives (e.g., "reduce the average time taken to assess structural integrity").

B. *Single-Point Goal Graph Quantification*

Both requirements and objectives have target levels of satisfaction (e.g., the fit criterion and magnitude). This target level is a single point of possible satisfaction, where multiple points refer to satisfaction better or worse than the target level. We will now explain how a contribution relationship is described for a single point of goal or requirement satisfaction.

TABLE 2: QUANTIFIED LINK CONTRIBUTION PREDICTIONS

Link	[Contribution] [Activity] [Scale]	Confidence
C (1⟶4)	[80%] [Reduction] in [Geometry Creation Time]	1
D (2⟶5)	[50%] [Reduction] in [Geometry Analysis Time]	0.75
E (4⟶6)	[20%] [Reduction] in [Time Required to Design]	1
F (5⟶6)	[13%] [Reduction] in [Time Required to Design]	0.75
G (6⟶7)	[3 months] [Reduction] in [Manufacturing Lead Time]	0.75
H (6⟶8)	[2 FTE's] [Reduction] in [Human Workload]	1

Table 2 shows a sample of the quantifications that complement Figure 1 in order to make contributions testable (the numbers are now fictional due to commercial sensitivity).

The quantified contribution for link (C) tells us that objective (4) will be satisfied if requirement (1) is satisfied, since objective (4)'s required magnitude of reduction (80%) will be contributed by the complete satisfaction of requirement (1). It is important to note that where percentages are used as contribution scores on links, this does not infer that a certain percentage of the objective's magnitude will be achieved (in this case, 80% of 80%). Instead, the focus of the objective (e.g., geometry creation time) will be affected by that percentage in the context of the activity (e.g., a reduction by 80%). Contribution links between pairs of objectives are read in the same way; link (E) specifies that the satisfaction of objective (4), determined by its magnitude attribute, will lead to some contribution toward objective (6).

This abstraction of objectives to higher level objectives allows the benefits to be expressed in terms of high-level business objectives. This is done in order to disambiguate the predicted business value by placing the quantifications into context (i.e., a large saving from a small cost may be less than a small saving from a large cost). It must be noted that a contribution link should represent causation rather than correlation, and thus care should be taken to separate the two as far as possible (guidance on this can be found in [14]).

C. *Multi-Point Goal Graph Quantification*

Our approach so far represents the contribution that objectiveX makes to objectiveY when objectiveX's magnitude is completely satisfied (objectiveX is interchangeable with requirementX in this statement). However, it is likely that objectives and requirements will only be partially satisfied, i.e., their required magnitude will likely not be fully achieved. Thus, pessimistic, realistic, and optimistic views (i.e., multiple points of goal satisfaction) of strategic alignment are not currently possible. Also, it is not possible to understand the pareto optimality of software requirements (e.g., where most of the benefit is achieved and where diminishing returns starts to occur). Additionally, the potential for benefit caused by a software feature is finite, e.g., a reduction in Full Time Employees (FTE's) can be gained by task automation – up to a point. Furthermore, conflated goal contribution links whose polarity is mixed can remain hidden until multi-point contribution is modelled. Checking if the relationship between two goals is hump or U-shaped (i.e., not monotonic) will indicate that the causal pathway is more complex than is modelled, and thus the goal graph should be expanded. This separation of causal pathways is advocated both in utility theory for systems engineering in [57], and business system dynamics in [14] - which gives the example: the relationship between "increase pressure to finish work", positively, and then negatively contributes to the goal "increase employee output", as fatigue eventually overcomes motivation.

In order to understand the effects of partial satisfaction on the chain of goals, it is important to know the contribution objectiveX makes to objectiveY at various levels of objectiveX's satisfaction. This is represented by defining a *table function* [14], i.e., pairs of objectiveX and objectiveY values, together with a chosen interpolation method (linear, step-after, cardinal, monotone, etc.). Table functions are used as opposed to analytic (i.e., algebraic) functions since analytic functions are difficult to design, experiment with, and most importantly, communicate to stakeholders [14]. The table function should span the worst-case to best-case range for each objective. If the value of objectiveX lies outside the table function, i.e., objectiveX's value is extreme, then ideally the table function should be updated to cover the extreme value, since the worst or best case points are no longer representative. Alternatively, the slope of the last two points could support extrapolation, or the minimum and maximum values of the table function could be mapped to all values lower and higher (respectively) than the table function's range.

To illustrate a multi-point quantified contribution link, Figure 3 visualises link (H) between objective (6) and (8).

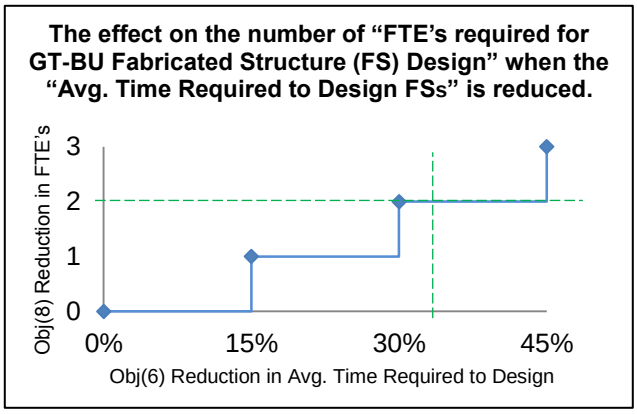

Figure 3: Link (H)'s Quantitative Contribution Relationship

Link (H), as shown in Figure 3, is comprised of 4 pairs of values, and, in this case, step-after interpolation to represent integer increments (in other organisations or projects, linear

interpolation and rounding may be more fitting). In this contribution link, extreme values of objective(6) are mapped to the minimum and maximum data point specified by the table function, to represent finite benefit realisation. Improvements to the reusability and robustness of the relationship, currently in the form of $Y = f(X)$, could be made by normalising the function such that the input and output of the function are dimensionless, i.e., independent of the unit of measurement used (e.g., to define time or human resource usage). Guidance on constructing non-linear functions can be found in [14].

The visualisation appropriate to depict a contribution link depends on the type of numerical data (i.e., discrete or continuous) used by an objective's scale or a requirement's fit criterion. Thus, either a bar chart or a line chart can be used. For functional requirements, the former should be used, since they have two states (i.e., implemented or not), whereas non-functional requirements should be represented using the latter, since they have infinite states of satisfaction. Note that the dashed green lines on the axes represent the magnitudes (targets) required by the respective objectives, as specified by the goal formalisation template (as in Table 1).

D. Describing Confidence in Quantifications

Contribution links in goal graphs are predictions of a causality relationship between two goals. Epistemological uncertainty (caused by a lack of knowledge) about a contribution link therefore must exist to some degree, since we cannot have perfect knowledge about future events. Before we look to describe confidence in goal contribution links, we must first distinguish *uncertainty* from *confidence*.

When predicting unknown quantities, uncertainty refers to beliefs about possible values for the unknown quantity, while confidence refers to the belief that a given predicted value is correct [58]. For example with reference to contribution link (H), uncertainty represents the range of possible values of FTE reduction (e.g., an interval [0, maxWorkloadInFTE's]) that could reasonably occur given a reduction in design time of 33%, i.e., the satisfaction of objective (8). In terms of Figure 3, uncertainty would affect the thickness of the line (i.e., lack of precision) used to represent the causation. Confidence, on the other hand, represents the belief that the chosen prediction (e.g., 2 FTE's, according to Table 2, and/or Figure 3) is the correct one. Thus in summary, a stakeholder's confidence is influenced by the salient factors that they believe to affect the correctness of their prediction, while a stakeholder's uncertainty is influenced by the number of different prediction options that could be correct [58].

In the decision analysis field, it is well recognised that confidence plays an essential part in determining optimal decisions, especially where a choice has to be made between two options which seem to provide similar benefits [9]. Furthermore, the description of confidence will indicate the risk that the modelled strategic alignment may not occur in practice. In this paper, we focus on confidence, since empirical studies have shown that while practitioners can judge which of their predictions are more uncertain, they find quantifying the uncertainty interval difficult [59]. However, if a stakeholder were reluctant to provide a single value to quantify the contribution, the contribution could be specified in more uncertain terms, such as: 2 ± 1 FTE's for link (H), i.e., an *interval estimate* [60]. It is important that the range is restricted as far as possible to avoid ambiguity in the contribution description, since the utility of a prediction is diminished by imprecision. If the range of uncertainty is wide, it should be expressed with a probability density function (pdf) to show which points in the range are more or less certain [13]. For a single-point contribution relationship (where it is assumed that the target of the first objective will be met), a pdf would describe the distribution of belief over the range of possible values for objectiveY, given a specific value of objectiveX (i.e., objectiveX's target). However, many values of objectiveX (i.e., the x-axis in Figure 3) are possible, leading to many possible pdf's to describe - reducing the usability of the approach. Thus, stakeholders should be encouraged to specify a single value of objectiveY that they are most certain of, i.e., a *point estimate* [60], rather than a range of least to most certain values. An interesting and more manageable source of uncertainty stems from the observation that a requirement's benefit depends on the system's environment (i.e., context or scenario of use) [47]. Thus, contribution scores could be associated to those environments. We further describe and exemplify this concept (usage profiles) in [41].

The confidence level representation concept we adopt is similar to that used by Gilb for impact estimation [51], so, in Table 3, we enumerate confidence levels using a similar scale. Mapping textual descriptions to confidence values (interval [0,1]) allows stakeholders to more easily select a value based on the quality of the supporting evidence (i.e., salient factors).

TABLE 3: CONFIDENCE LEVEL ENUMERATIONS

Confidence	Description
0.25	Poor credibility, no supporting evidence or calculations, high doubt about capability
0.5	Average credibility, no evidence but reliable calculations, some doubt about capability
0.75	Great credibility, reliable secondary sources of evidence, small doubt about capability
1	Perfect credibility, multiple primary sources of evidence, no doubt about capability

Basic confidence adjustment can be performed by multiplying contributions by their associated confidence level so that users are reminded of the impact confidence has on predictions, as in [51]. For example, when confidence levels are taken into consideration in Table 2, the satisfaction of requirement (1) still leads to the full satisfaction of objective (4). However, when confidence levels are considered for links (E & F), the satisfaction of objective (6) is in doubt, since (20*1) + (13*0.75) is less than the 33% required by the objective's magnitude attribute. Adjusting contributions to account for confidence in this way is similar to calculating the expected value of a random variable. However, since the mapping between the textual statements and the numbering in Table 3 (adapted from [51]) is not grounded by evidence or heuristics, a contribution score which is adjusted for confidence using them should not be treated as an expected value, but rather as an indication of the effects of confidence. If we wanted to better approximate the expected value, a number based on probability should be used to represent confi-

dence [58], i.e., the answer to such a question: if the requirement were implemented a large number of times, what percentage of those times would the stated contribution be contributed? Formulating an answer to such a question depends on the experiences of the stakeholders in implementing similar requirements in similar projects in a similar environment. Similarity in this sense is difficult to achieve, since there are many socio-technical variables that can affect the benefits realised by a software project or a particular feature.

Additional confidence levels could be associated to the user's predictions to represent how qualified that user is at predicting contribution scores. For example, someone who has implemented similar systems should be able to provide more accurate predictions than someone who has not. The accuracy of a person's previous predictions (i.e., their credibility) could also be considered in order to improve the reliability of the predictions (i.e., calibrated confidence levels).

E. Describing the Utility of a Goal's Satisfaction

One important value consideration is so far, untreated: "what is the benefit in achieving a root goal to various degrees of satisfaction?" i.e., business objectives that do not contribute to other business objectives, such as objective (12). Root objectives exist when the business has not defined any objectives higher than the objective, and where it would not make sense for them to have done so. To address this, we map various levels of a root goal's satisfaction to degrees of *utility* [9], whereby various levels of "goodness" can be achieved. For example, referring to objective (12), various levels of component lifespan improvement map to utility values (interval [0,1]). This allows the representation of non-linear relationships between component lifespan improvement and the associated benefit; perhaps after a 60% improvement on the average component's lifespan, there is no more benefit to be gained since the engine would be retired before the component would fail. Thus, the utility of a 60% improvement would peak at 1. The concept of utility is both subjective and specific to the stakeholder who assigned it. However, capturing it will explain the criticality of a root goal's satisfaction criteria, and differences in utility assignment between stakeholders will be made apparent for conflict resolution before the requirement is implemented.

Note that the maximum utility of some goal satisfaction is defined in isolation from other goals. That is to say that the maximum utility value (i.e., 1) should be defined for each root goal, and then weights can be assigned to those root goals to determine the relative utility of some goal satisfaction, in the context of the system-to-be as a whole. This is done in order to decide on the relative importance of root goals, as in [61]. Pairwise comparison or balance beam diagrams can be used to decide on, and refine the weights [57].

F. Describing & Monitoring As-Is Values for Goals

Wherever the magnitude attribute of an objective (and related contribution scores) is/are specified a percentage, it is especially important that the objective's as-is value is described. Otherwise, it is not possible to later verify that the magnitude (i.e., change) has happened. These values can then be recorded over time in order to evaluate the system (validation) and provide a benchmark for future improvement. Furthermore, prescribed goal satisfaction levels and predicted goal contribution levels, in current and future projects, can then be made more realistic through a feedback mechanism.

G. Describing Assumptions or Necessary Goals

When a contribution link is made between two goals, there may be an implicit assumption behind it, e.g., that some other phenomenon will occur which will enable the contribution. Without this assumption holding true, the contribution made by the contributing goal would be inhibited. For example, Figure 1's contribution link (K) is underpinned by the assumption that, given a reduction in human workload, some design costs can be reduced. While this may seem trivial to highlight, the actual cost reducing mechanism (perhaps redundancy) is often a thorny issue, and it should be communicated as early as possible for conflict resolution. To describe this assumption, either a GRL belief node can be used, or a new task can be added as a decomposition of objective (11); in GRL, decomposition links represent necessity, while contribution links represent sufficiency and polarity (+ive or -ive).

H. Intended Context of Use

We suggest that this approach should be performed after the high-level requirements have been elicited, so that resources are not wasted eliciting lower level requirements that do not align well to business strategy. It is especially important that the strategic alignment of solution oriented requirements (i.e., specified for the machine [38]) is explored, since they do not explain the problem to be solved.

It is important to note that software engineers and business analysts may not know the objectives (or the goals and visions, for that matter) at different levels of the business (i.e., the project, the business unit, the department, the overall business, etc.). Therefore, managers should work with stakeholders to define the business objectives before the requirements can be abstracted toward them. Indeed, it is likely that some software requirements will be abstracted toward business objectives that were not previously elicited.

Users may resist quantifying benefits of requirements, especially for non-functional requirements where the subject may be intangible, however, Gilb has found that it has always been possible to do so in his experience (e.g., by polling customers to quantify customer satisfaction) and has provided guidance on doing so in [51]. Even if the quantifications cannot be elicited at first, providing a scale by which the objective's success will be measured improves the definition of the objective by reducing ambiguity, as aforementioned. Where stakeholders are unable to explain the causal relationship between a requirement and higher goals, the risk that the contribution may not occur as expected will have been indicated.

While we have focused on the benefits of software requirements, both sides of the value equation need to be considered (i.e., costs). Effort estimation models such as COCOMO [62] would be useful in predicting the cost of a requirement.

I. Tool Support

Tool support (GoalViz) has been developed (free to download at [63]) to support the approach through:

- Input support for requirements, objectives, and contribution data (with graphical function input).
- Automatic diagram drawing to focus the user on the approach and data rather than the graph layout.
- Project libraries to facilitate learning about the contributions predicted in previous projects to improve future quantification of confidence assignment.
- Automatic evaluation and summarisation of chains of links to enable efficient understanding.
- What-if analysis allowing comparison of outcomes for different inputs where there is some uncertainty.

VI. Conclusion and Future Work

The presented approach facilitates the disambiguation of a requirement's business value through the enrichment of contribution links in a goal graph. The approach is *descriptive* (a goal is abstracted to describe the underlying problem), *prescriptive* (a certain amount of goal satisfaction is required), and *predictive* (a quantitative goal contribution score predicts how much of the prescription will be achieved by the means). This paper's unique contribution includes:

1. We have argued that the strategic alignment of software requirements depends on the contribution they make to business objectives, and since they are quantitative in nature, reasoning about the contribution made toward them should also be quantitative.
2. We have argued that since strategic alignment is based on predictions of benefit, confidence (and sometimes uncertainty) should be made explicit.
3. We have shown that the non-linear dynamics of contribution links can be explored as quantitative causation relationships (defined with table functions) through more than one level of goal abstraction, in order to understand the effects of partial requirement satisfaction on high level goals.

Future work will evaluate this approach (and those related to it) against required capabilities elicited from our industrial partners. We have outlined two case studies within different industrial settings, such that the benefits and challenges can be evaluated in the context of a range of domains. Feedback resulting from the evaluations in industry will be used to improve the approach and the tool. Planned investigations into optimising the utility and the usability of the approach include empirically evaluating the:

1. extent to which stakeholder utility functions for a goal's satisfaction can be aggregated to represent the preferences and uncertainty of a collective;
2. optimal representation of uncertainty, confidence, and credibility in the causal relationships;
3. optimal way (especially with regards to reusability) to specify the causal relationship between two variables (i.e., gauge variables, KPIs, or goal satisfaction levels), e.g., with causal loop diagrams and dimensionless table functions using Vensim® [14], or specifying "business formulae" as in [40];
4. optimal way to maintain traceability between requirements and design artefacts, perhaps through SysML Requirements [22] and a GRL UML profile.

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Towards the Standardization of Industrial Scientific and Engineering Workflows with QVT Transformations

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Abstract— **Nowadays, design activities in engineering and many other applied science fields require the execution of computational models in order to simulate experiments. This step is usually automated through the execution of the so-called scientific workflows. A large number of different graphic and execution formats are currently in use today, with no clear signs of convergence into a standard format. Things are different in the area of business processes, where many standards have been defined for both the graphical and the execution representation of business process workflows. Significant efforts are currently being carried out to apply business workflow technology into engineering fields. Nevertheless, one of the main obstacles for the industrial adoption of standards is the large base of existing workflows used currently by industry, which cannot be just thrown away. This paper presents a model-to-model transformation using QVT between a widely used industrial metamodel and the BPMN 2.0 standard metamodel. Legacy workflow support is an essential first step to allow the introduction of the use of a business process standard in scientific and engineering industrial applications.**

Keywords – ***BPMN 2.0; business workflow; industrial workflow; transformation; QVT.***

I. INTRODUCTION

Scientific and industrial design activities depend more and more on the execution of computational models in order to run in-silico experiments. These applications are characterized of being computationally intensive and strongly data-driven. Heavy requirements are imposed, not only on the bare computing technology, but also on the high level execution mechanisms [1][2]. The most widely accepted and effective formalism used to represent these computational processes is in terms of scientific and engineering workflows, which provide a declarative way of stating the required high level specifications. In general terms, a scientific or engineering workflow is an automated business process used to execute complex computational processing tasks [3] in scientific or engineering application areas respectively. These kinds of workflows are widely used in natural science, computational simulations, chemistry, medicine, environmental sciences, engineering, geology, astronomy, automotive industry, aerospace, and other industrial fields. Its use has been extended also to optimization tasks, where the development of complex industrial products is modeled as an optimization cycle which includes an engineering process defined in terms of the collaboration of various engineering services with usually large exchange of information between them [4][5].

It is expected that the success of business process technology in business scenarios can contribute to introduce this already mature technology into the field of scientific and engineering workflows. However, it is not yet the case, even if some interesting contributions are indisputable. The main reason is that scientific and engineering workflows require many features that most business process models do not currently support [6][3]. For example, business workflows usually deal with discrete transactions, but engineering and scientific workflows in most cases deal with many interconnected software tools, large quantities of data with multiple data sources and in multiple formats [7]. Also, engineering services usually have a very long execution duration and depend on the execution environment.

Even if scientific and engineering workflows have been used successfully since many years, most of the tools used to define and execute them are not based on standard technologies. The situation is completely different in the area of business processes, where many well-defined standards have been proposed and are widely used. Some attempts to use a business process standard in the domain of scientific and engineering workflows have been performed, though till now, a single standard cannot be used to represent both the abstract view (used by the engineer to represent the process at the scientific domain) and the workflow representation used for execution (at workflow engine level). However, the last definition of the BPMN standard (the release 2.0) from the Object Management Group (OMG) has been developed with broader objectives, overcoming in fact the limitations that prevented the use of previous versions in scientific and engineering applications [8][9]. From now on, all references with the acronym BPMN are intended as references to version 2.0 of the standard. BPMN defines a formal notation for developing platform-independent business processes, contrasting with specific definitions of business processes such as BPEL4WS (Business Process Execution Language

for Web Services) [10]. BPMN defines an abstract representation for the specification of executable business processes within a company, which can include human intervention, or not. BPMN also allows collaboration between business processes of different organizations. The definition of this new standard allows, for the very first time, to extend the use of workflows from the field of business process to the field of science and engineering.

With BPMN, many companies will be tempted to support a standard workflow for scientific and engineering applications. However, it must be considered that there exists a large base of engineering workflows already designed and used currently by industry, which cannot be just thrown away. In order to provide legacy workflow support, we propose a methodology for the transformation of legacy proprietary workflows into BPMN standard workflows. This approach will provide an extra incentive for companies to abandon proprietary workflows and move to standard technologies coming from the field of business processes. However, the transformation is not without pain. The extra data and process requirements in engineering workflows need to be handled properly. Fortunately, BPMN has been defined with an extension facility which allows to add required constructions without breaking standard compliance.

As a part of the methodology, this paper presents a transformation for selected constructions of a widely used industrial engineering workflow to BPMN, in order to present a valid path to perform legacy workflow conversion to a well-defined standard. It is an extension of the work presented in [1], where the basic methodology was presented. In this present paper, transformations of more complex elements based in BPMN extensions are also considered, providing insights on a not-so-easy to handle BPMN construction, which is essential for the support of scientific and engineering workflows. Also, an extended example is presented, together with a more deep explanation of the legacy workflow model and the results of the transformation in terms of XML elements. New sections were added to present the motivations and a discussion on the proposed approach.

The transformation is defined in QVT, a standard relation language for model transformation defined by the OMG with a specification based on MOF and OCL [11]. The language consents to express a declarative specification of the relationships between MOF models and metamodels supporting complex object pattern matching. A QVT transformation defines the rules by which a set of models can be transformed into a different set [12]. Furthermore, it specifies a set of relations that the elements of the implicated models in the transformation must fulfill. The model types are represented by their corresponding metamodels. A relation in QVT specification consists in a set of transformation rules where a rule contains a source domain and a target domain [13]. A domain is a set of variables to be matched in a typed model, with each domain defining a candidate model and also having its own set of patterns [12]. For more details on QVT, the reader is invited to visit the OMG links [11].

The paper is structured in sections. Section II presents related works. The industrial metamodel used as the source model for transformations is described in Section III. Section IV presents an example of the transformation from the point of view of the workflow designer, while Sections V and VI describe the transformation architecture and the transformation between models, respectively. The paper ends with an example in Section VII, and discussions and conclusions in Sections VIII and IX, respectively.

II. RELATED WORK

The use of scientific and engineering workflows for process automation has been widely analyzed in literature [3]. Many commercial and open source implementations do exist. The most widely used by the open source community are Kepler [14], Triana [15], Taverna [16], Pegasus [17] and KNime [18], with many new frameworks appearing continuously. However, all these scientific and/or engineering workflow frameworks are based in proprietary non-standard formats. In the area of commercial tools, there exists many options like for example modeFRONTIER [4] widely used in CAD/CAE engineering optimization. However, again, all of them are based in proprietary formats.

In [1], the authors present a model-to-model transformation using QVT between a widely used engineering workflow and BPMN 2.0, converting successfully data inputs, input sets and input output specifications into the target format. The approach was validated experimentally in the engineering environment supported by a company in the field of multi-objective optimization. This current paper is an extension of [1].

The use of standards like BPMN 1.0 for the abstract representation of scientific workflows, and BPEL or Pegasus for execution were proposed in the past, but never went too far in industry due to the need to support two different standards for the same workflow [17].

Several works in the field of software engineering are related to the concept of transformation between models, and many of them use BPMN to model business process.

Marcel van Amstel et al. [19] investigate the factors that have an impact on the execution performance of model transformation. This research estimates the performance of a transformation and allows to choose among alternative implementations to obtain the best performance. The results of this study can be used by implementers of transformation engines in order to improve the set of currently available tools.

In this same line, a model-to-model transformation between PICTURE and BPMN 1.0 is presented in [20]. PICTURE is a domain-specific process modeling language for the public administration sector. The transformation allows to model administrative processes in PICTURE and to get BPMN models for these processes automatically, helping electronic government by making possible the implementation of supporting processes. In addition, this research contributes to simplify the development process, improves its flexibility and allows meeting organizational

challenges arising in the development of systems that support electronic government.

In [21], three sets of QVT relations are presented as a mean of implementing transformations in a model-driven method for web development. One of them transforms a high-level input model to an abstract web-specific model. The other two transform the abstract web model to specific web platform models.

In [22], the generation of components of the Java EE 6 business platform from technical business processes modeled with BPMN 1.0 was presented. The generation was obtained by performing three transformations in the context of Model-Driven Architecture, performed with QVT Relations and a MOFScript. This research contributed improving the development productivity and reducing design errors.

A solution for the modeling of Clinical Pathways (CP) processes in terms of standard business process models is presented in [23]. To represent a CP as a process workflow, a high-level semantic mapping between the CP ontology and the BPMN ontology was developed. This research shows how a clinical specific process defined in the CP ontology is mapped to a standard BPMN workflow element. This mapping allows healthcare professionals to model a CP by using familiar modeling constructs. Once ready, they can transform this CP to a business process model and thus leveraging the standard definitions of processes to represent and optimize clinical environments by incorporating process optimization tools.

An example application is presented in [24] to demonstrate an automated transformation of a business process model into a parameterized performance model, thus obtaining significant advantages in terms of easy customization and improved automation.

However, to the best of our knowledge, no other research work has considered BPMN as the target model for transformation in the context of industrial scientific or engineering workflows.

III. ESTECO METAMODEL

The metamodel selected as an example is the workflow model used for modeling simulation workflows by ESTECO, a company specialized in industrial multi-objective optimization[4]. The simulated process is represented with a formalism which provides both a representation for the abstract view (used by the engineer to represent the process) and the associated execution model (used for the real simulation). The abstract view is a human-understandable graphic representation, while the execution model is represented with XML. This last model is used by a workflow engine in order to execute the workflow and perform the simulation.

This workflow, which is typical in this kind of environments, includes one task node for each activity and data nodes used to represent input, output and temporary data objects. Data objects can represent simple data like integer, doubles, vectors, matrices or more complex data like files or databases. Activities correspond to the execution of simulators, scripts and other applications in local or remote locations. Usually, each activity is defined through a set of configuration files, which can be large (many gigabytes being common), and a set of inputs and outputs (which can also be very large files or databases). Distributed execution is required, meaning that the activities specified in the workflow can be executed in different nodes (on the grid or the cloud system[25]), requiring data to be passed between them. More information about the ESTECO metamodel can be found in the documentation provided in the web site [4].

The next sections provide a description of the framework used for the transformation by applying it to a small subset of ESTECO's workflow.

IV. TRANSFORMATION EXAMPLE

As it was mentioned before, the ESTECO and the BPMN notations have both a graphical and an XML representation. Usually, the simulation engineer designs the workflow by using a graphical editor, not being at all interested in the associated XML representation, which is used behind the scenes by the editor and the execution engine as the storage and execution format respectively.

This section presents an example of a transformation from the point of view of the designer, who expects to get a BPMN workflow to be obtained from a previously defined ESTECO workflow as a result of the transformation process. Please note that the example presented in this section is intended to present only data handling aspects, and does not include other components, which also need to be considered when performing a full transformation process.

Figure 1 shows an example of a workflow specified in terms of the ESTECO model. It consists of a sequence of two activities, which performs some computation tasks. Execution starts with the node labeled START, which just transfer the execution flow to the first activity (labeled SUM). This first activity receives two inputs and produces a single output as a result of a computational activity. The second activity (labeled MEAN) takes two inputs, one of them being the output of the previous activity, and produces a single output as a result. The workflow terminates successfully when both tasks are executed properly, reaching the node labeled EXIT, or it can generate an exception reaching the node labeled ERROR.

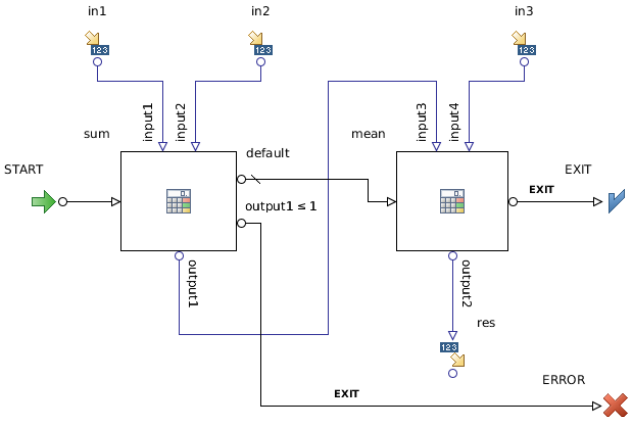

Figure 1. Example of an ESTECO workflow.

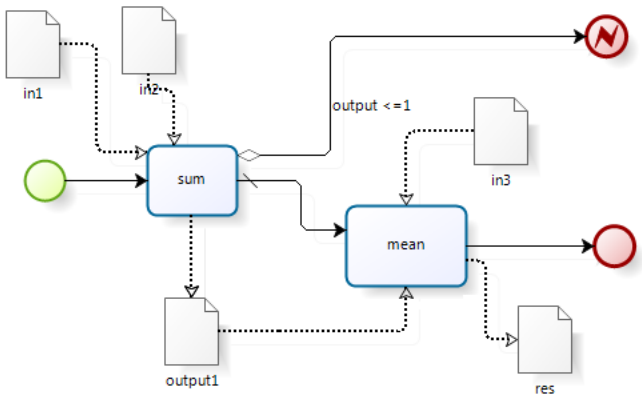

Figure 2. Example of the equivalent BPMN 2.0 workflow.

Figure 2 shows the equivalent BPMN process. Note that the overall graphical structure is not too different between the two workflows. In both of them there is a start node, an end node and an exception event node. There is, however, one extra data object used to transfer intermediate data between the two activities, something that is not required by the ESTECO workflow presented before, which allows direct communication between activities. Note that different kind of arrows and lines are required to indicate the data flow and process flow in BPMN, something that is not so nicely differentiated in the original ESTECO workflow.

An important point to note is that, even if the overall graphical structure is very similar in both workflows, the XML representation is definitely very different. And of course, the transformation process does not take place at the graphical level, but at the XML representation level. This transformation is made possible since both workflow models are defined formally with an XML schema, which provides the basis for a formal transformation process. This transformation process, including selected transformation code in QVT and some examples, is presented in next sections.

V. TRANSFORMATION ARCHITECTURE

Our proposal aims to apply the most recent concepts of business processes to the field of engineering workflows in industrial fields. The use of standards in industry is important since it guarantees portability between tools that support BPMN.

The industrial legacy workflow selected has an XML representation, allowing the use of tools like Medini QVT for transformation [26]. There is no one-to-one correspondence between the different components of ESTECO's workflow and BPMN constructions, since control nodes and data nodes are very differently handled in both models. Also, files and database handling put extra requirements which can only be handled properly with BPMN extensions.

The QVT transformations describe relations between the source metamodel and the target metamodel, both specified in MOF. The transformation defined is then applied to a source model, which is an instance of the ESTECO source metamodel, to obtain a target model, which is an instance of the BPMN target metamodel, as can be seen in Figure 3. The metamodels used in the definition of the transformation are shown at the top level. The specific models to which the transformation defined in the metamodel level is applied in order to obtain BPMN models is shown at the middle level. The lower level represents the instances of the models which can be executed in the corresponding workflow engines.

As mentioned before, activities and processes need data in order to be executed, and in addition, they can produce data during or as a result of their execution. In BPMN, data requirements are captured as *DataInputs* and *InputSets*. The produced data is captured using *DataOutputs* and *OutputSets*. These elements are aggregated in an *InputOutputSpecification* class [2], as can be seen from the UML class diagram presented in Figure 4. The *DataInputs* and *DataOutputs* are additional attributes of the *InputOutputSpecification* element; these elements are optional references to the *DataInputs* and *DataOutputs* respectively. A *DataInput* is a declaration that a particular

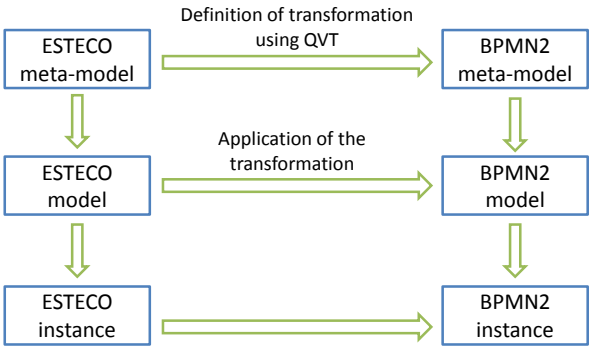

Figure 3. Transformation architecture.

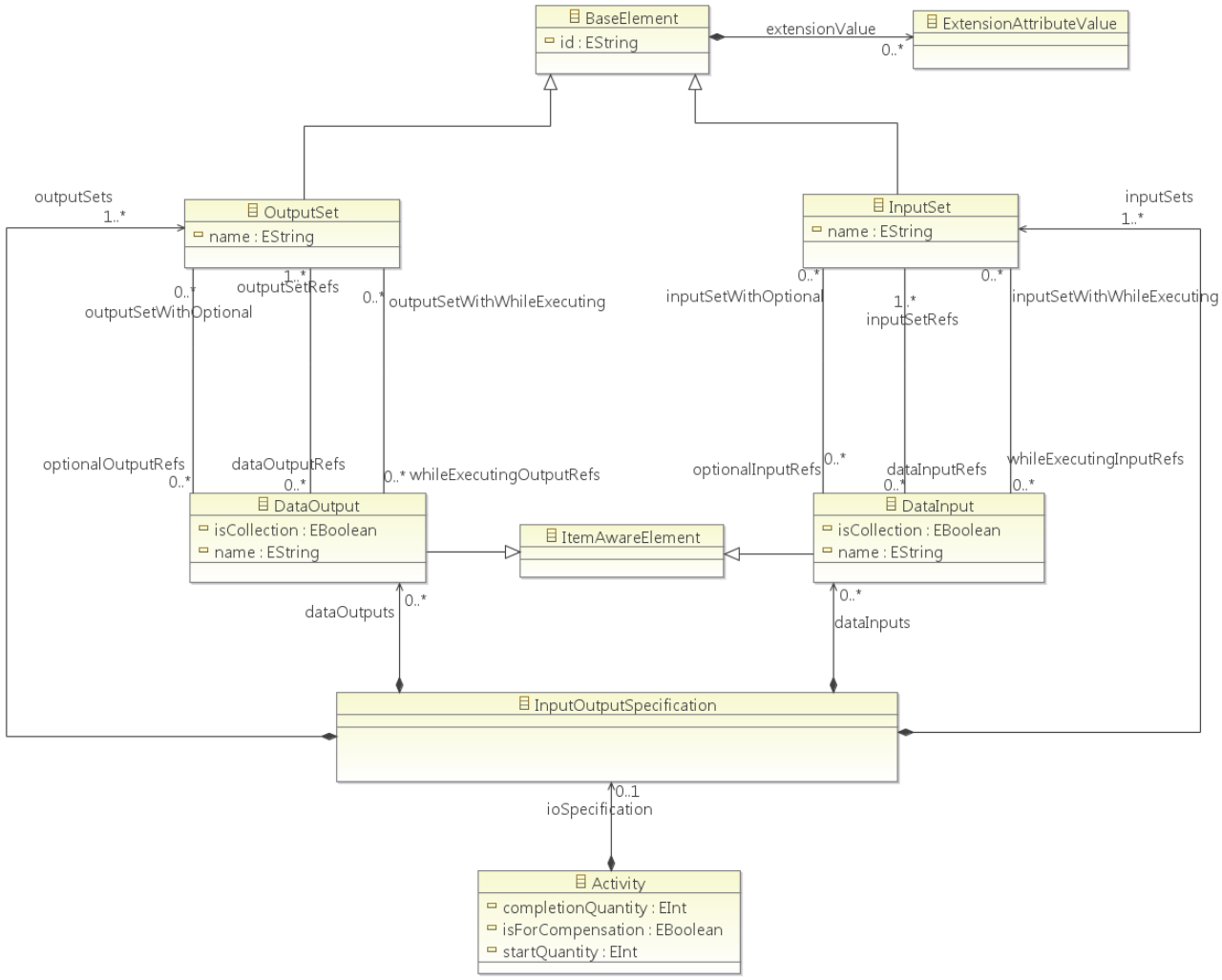

Figure 4. Partial view of the BPMN2 metamodel (from [8]).

kind of data will be used as input of the *InputOutputSpecification*. A *DataOutput* is a declaration that a particular kind of data can be produced as output of the *InputOutputSpecification*. *DataInputs* and *DataOutputs* are *ItemAware* elements. If the *InputOutputSpecification* defines no *DataInput*, it means no data is required to start an Activity. If the *InputOutputSpecification* defines no *DataOutput*, it means no data is required to finish an Activity [8].

The BPMN specification provides an extension mechanism for both the process model and the graphic representation that allows the extension of standard BPMN elements with additional attributes. This mechanism can be used by modelers and modeling tools to add non-standard elements or artifacts to satisfy a specific need. The only requirement is that these extension attributes must not contradict the semantics of any BPMN element [8]. The *ExtensionAttributeValue* class has a relationship with *BaseElement* class, defining a list of attributes or elements that can be attached to any standard BPMN element, as can be seen in Figure 4. As mentioned before, a *DataInput* is an *ItemAwareElement*. All item aware elements inherit the attributes and model associations of *BaseElement*. Therefore, a *DataInput* element inherits the attributes and model associations of *BaseElement*, allowing the extension mechanism to be used by *a DataInput* [8].

A partial view of the ESTECO metamodel with the metaclasses involved in the relations described in this work is shown in the UML class diagram presented in Figure 5. The *TInputDataNode* and *TOutputDataNode* elements inherit the attributes and model associations of *TDataNode*, which in turn, inherits from *TNode*. The *TGeometry* class is the outermost object for all ESTECO elements, i.e., all these elements are contained in a *TGeometry*. The *TInputDataNode* element is a particular kind of *TDataNode* that will be used as input of *TGeometry* to a *Task*. The *TOutputDataNode* element is a particular kind of *TDataNode* which can be produced as output of a *Task* contained in

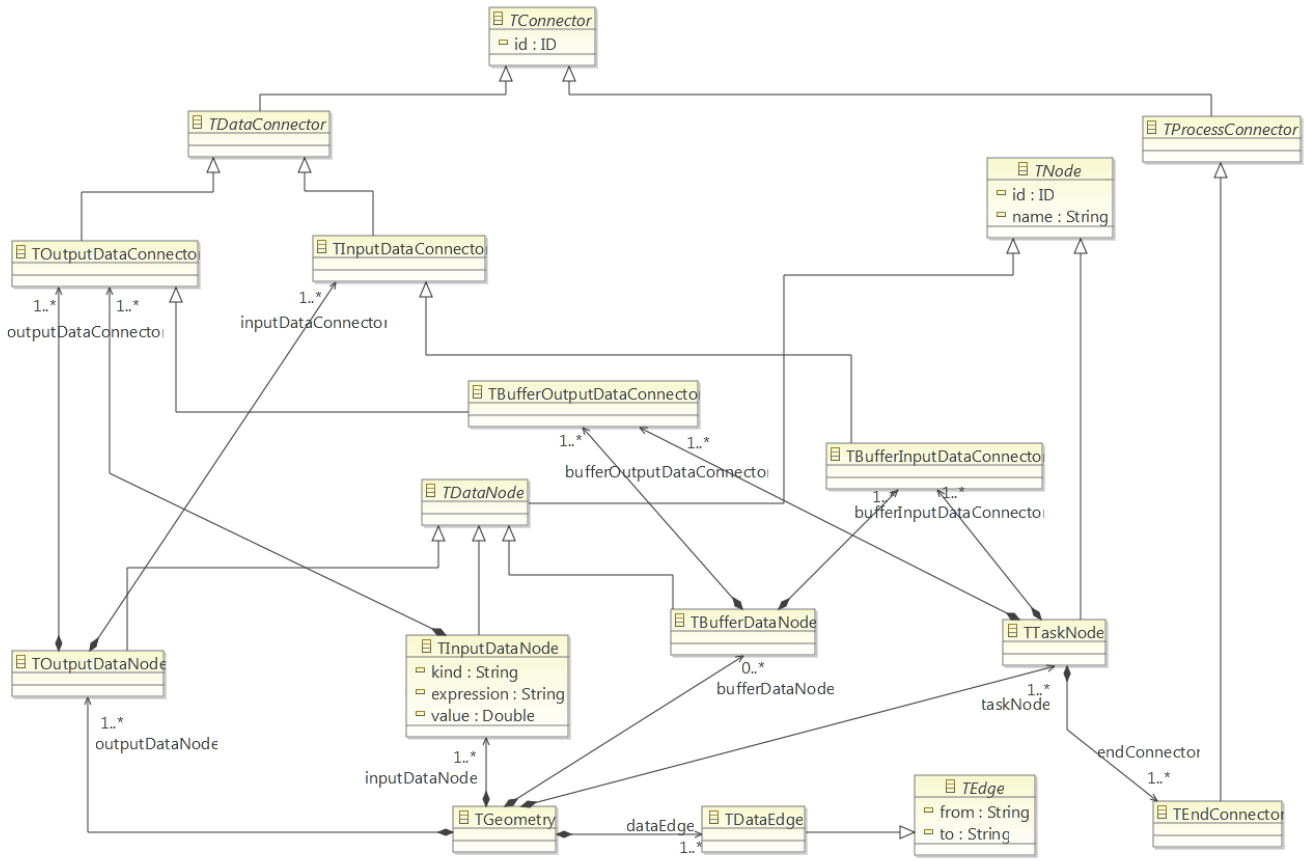

Figure 5. Partial view of ESTECO metamodel (from [4]).

TGeometry. A *TTaskNode* class represents the task that is performed within an industrial workflow.

VI. TRANSFORMATION BETWEEN MODELS

A transformation specifies a group of relations that the elements of the involved models must fulfill. A transformation may have any number of input or output parameters known as domains. For each output parameter, a new model instance is created according to the metamodel of the output metamodel (in this case, the metamodel BPMN).

Each domain identifies a corresponding set of elements defined by means of patterns. A domain pattern can be considered an object template. A relation in QVT defines the transformation rules. A relation implies the existence of classes for each one of its domains. In a relation, a domain is a type that may be the root of a template pattern. A domain implies the existence of a property of the same type in a class. A pattern can be viewed as a set of variables and a set of constraints that model elements must satisfy. A template pattern is a combination of a literal that can match against instances of a class and values for its properties. A domain can be marked as *checkonly* or *enforced*. A *checkonly* domain simply verifies if the model contains a valid correspondence that satisfies the relation. When a domain is *enforced*, if checking fails, the elements of target model can be created, deleted or modified so as to satisfy the relationship.

A relation can contain two sets of predicates identified by a *when* or a *where* clause. The *when* clause specifies the condition that must be satisfied to execute the transformation. The *where* clause specifies the condition that must be satisfied by all model elements involved in the relation, and it may contain any variable involved in the relation and its domains [5]. In the context of transformation, a model type represents the type of the model. A model type is defined by a metamodel and an optional set of constraint expressions. Please note that the definition of these terms can be found in the QVT specification, where the interested reader is referred to [5].

The transformation between ESTECO metamodel and BPMN metamodel is defined as follows:

```
transformation ESTECOToBPMN2(source : esteco_m,
                             target : bpmn2)
```

Note that this transformation takes as input an ESTECO model, which is an instance of the ESTECO metamodel, and produces a BPMN model, that will be an instance of the BPMN metamodel.

Below, the relations which define the mapping between ESTECO metamodel classes and BPMN metamodel classes are presented. This correspondence is not straightforward. As we mentioned in the previous section, the *DataInput*s are captured in *InputSet*s and both are added into an *InputOutputSpecification*. The same happens with the *DataOutput*s. So, in the transformation it is necessary to generate an *IoSpecification* object to aggregate *DataInput*s, *DataOutput*s, *InputSet*s and *OutputSet*s.

The relation used to create an *IoSpecification* object is shown below:

```
relation createIOSpecificationTask {
   checkonly domain source g:esteco_m::TGeometry { };
   enforce domain target t:bpmn2::Task {
   ioSpecification= ioSpecif :
                          bpmn2::InputOutputSpecification {}
  };
  primitive domain id_task:String;
  where {
   getDataInputTask(g,ioSpecif, id_task);
   createInputSetsTask(ioSpecif,ioSpecif);
   getDataOutputTask(g, ioSpecif, id_task);
   createOutputSetsTask(ioSpecif, ioSpecif);
   }
}
```

The relations that are referenced in the previous code, which are used to create InputSets and OutputSets, are the following:

```
relation createInputSetsTask {
  checkonly domain target ioSpecif:
                          bpmn2::InputOutputSpecification {
  };
  enforce domain target ioSpecif :
                          bpmn2::InputOutputSpecification {
       inputSets = input_set :bpmn2::InputSet{
       dataInputRefs= ioSpecif.dataInputs
     }
  };
}

...
```

```
...

relation createOutputSetsTask {
  checkonly domain target ioSpecif:
                          bpmn2::InputOutputSpecification{
  };
  enforce domain target ioSpecif :
                          bpmn2::InputOutputSpecification{
      outputSets = output_set :bpmn2::OutputSet{
      dataOutputRefs= ioSpecif.dataOutputs
    }
  };
```

Note that an *InputSet* is a collection of *DataInput* elements that together define a valid set of data inputs associated to an *InputOutputSpecification*. An *InputOutputSpecification* must define at least one *InputSet* element. An *OutputSet* is a collection of *DataOutput*s elements that together can be produced as output from an Activity. An InputOutputSpecification element must have at least OutputSet element [3].

The relation used to obtain the *DataInputs* of the ESTECO model and the generation of *DataInputs* in BPMN is the following:

```
relation getDataInputTask{
   id_input, name_input : String;
   value_input : Real;
   checkonly domain source g:esteco_m::TGeometry{
     taskNode = t:esteco_m::TTaskNode{
     bufferInputDataConnector = buffer_input :
                    esteco_m::TBufferInputDataConnector {}
     },
     inputDataNode = input : esteco_m::TInputDataNode {
       id = id_input,
       name = name_input,
       value = value_input,
       outputDataConnector = output_data :
                     esteco_m::TOutputDataConnector {}
     },
     dataEdge = data_edge : esteco_m::TDataEdge {}
   };

...
```

```
...

 enforce domain target ioSpecif :
                              bpmn2::InputOutputSpecification  {
        dataInputs = data_input : bpmn2::DataInput {
        id= id_input + '_T',
        name = name_input,
        itemSubjectRef = item : bpmn2::ItemDefinition {
            id = 'DoubleItemDefinition'
        },          extensionValues = extension :
                                        esteco::DocumentRoot{
                default = default : esteco::TDefault {
              simpleValue = simple_value : esteco::TSimpleValue {
                    value = '0'
                }
              }
            }
        }
  };

   primitive domain id_task:String;
   when {
     if (data_edge.from = output_data.id) and
       (data_edge.to = buffer_input.id ) and
       (id_task=t.id) then true else false
  endif;
 }
}
```

Each data input of ESTECO must be transformed into a data input of BPMN. This transformation is straightforward; the QVT code presented before shows the procedure by which the *id*, *name*, *value* and *connectors* are obtained. Note that there is an *extensionValues* attribute referenced in the previous code. This attribute belongs to the *BaseElement* class (Figure 4), which is defined with type *ExtensionAttributeValue*.

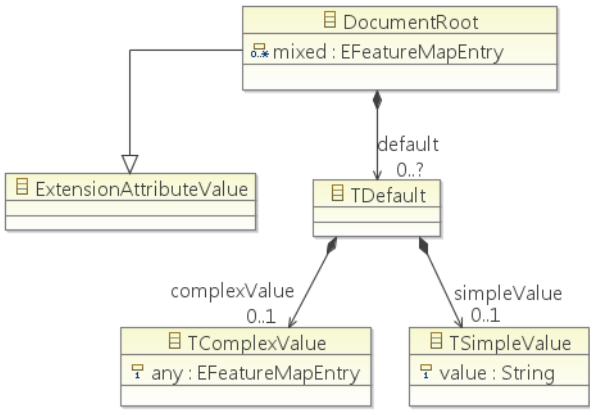

Figure 6. Partial view of the ESTECO XSD definition.

To understand the extensions processing during the transformation process, it is necessary to refer to the definition of types in the ESTECO metamodel. This definition is presented in Figure 6: *DocumentRoot* element inherits the attributes and model associations of *ExtensionAttributeValue*, a class belonging to the BPMN definition, as can be seen in Figure 4. It was necessary to aggregate new attributes: the *Value* attribute, which is contained within *TSimpleValue* and has default value of zero, and the *simpleValue* attribute, which is contained within *TDefault*.

The relation used to obtain the *DataOutput*s of ESTECO model and the generation of *DataOutput*s in BPMN is shown below.

```
relation getDataOutputTask{
   id_output, name_output : String;
   checkonly domain source g:esteco_m::TGeometry {
      taskNode = t:esteco_m::TTaskNode{
      bufferOutputDataConnector = buffer_output :
                    esteco_m::TBufferOutputDataConnector {}
      },
      outputDataNode = output :
                              esteco_m::TOutputDataNode {
        id = id_output, name = name_output,
        inputDataConnector = input_data :
                             esteco_m::TInputDataConnector {}
      },
      dataEdge = data_edge : esteco_m::TDataEdge {}
    };
   enforce domain target ioSpecif :
                             bpmn2::InputOutputSpecification  {
      dataOutputs = data_output : bpmn2::DataOutput {
      id= id_output + '_T',
      name = name_output,
      itemSubjectRef = item : bpmn2::ItemDefinition {
        id = 'DoubleItemDefinition'      }
      }
    };
    primitive domain id_task:String;
    when {
      if (data_edge.from = buffer_output.id) and
        (data_edge.to = input_data.id )  and
        (id_task=t.id) then  true else false
      endif;
   }
}
```

VII. A TRANSFORMATION EXPERIMENT

This section presents an example of a transformation by using the QVT code presented before. The QVT transformations were defined by using Medini QVT, a tool developed by IKV++ technologies with an Eclipse

integration [26]. Medini QVT allows both single direction and bidirectional transformations. The core engine implements the OMG's QVT Relations standard, and is licensed under EPL (Eclipse Public License). The Relations language implicitly creates trace classes and objects to record the events that occurred during a transformation execution.

The QVT Process package contains classes that are used for modeling the flow of Activities, Events, and Gateways, and their sequence within a Process. When a Process is defined it is contained within Definitions [8]. A Process is instantiated when one of its *Start Events* occurs. The *End Event* indicates where a Process will end, finishing the flow of the Process. Data requirements and Data Outputs are contained within an *ioSpecification* object, which defines not only the inputs and outputs, but also the *InputSets* and *OutputSets* for the Process and the Activities [8].

Figure 7 presents the results of the execution of a transformation when applied to one single activity node in the workflow defined in Figure 1. Each box corresponds to an XML element, and the hierarchy between the elements is represented with the tree-like structure. Each task has its own *ioSpecification* object, which contains its own data. Hence, the transformation generates an *ioSpecification* object to combine *DataInputs*, *DataOutputs*, *InputSets* and *OutputSets*, as it was mentioned previously.

Each data input of the ESTECO workflow task is captured as an *inputDataNode* object, which is transformed into a *dataInput* of BPMN. To satisfy specific needs of ESTECO, it has become necessary to use the extension mechanism of BPMN for *DataInput* handling. As it was shown in the previous section, the QVT code for the *getDataInputTask* relation presents the procedure by which the *id*, *name*, *value* and *connectors* are obtained and the

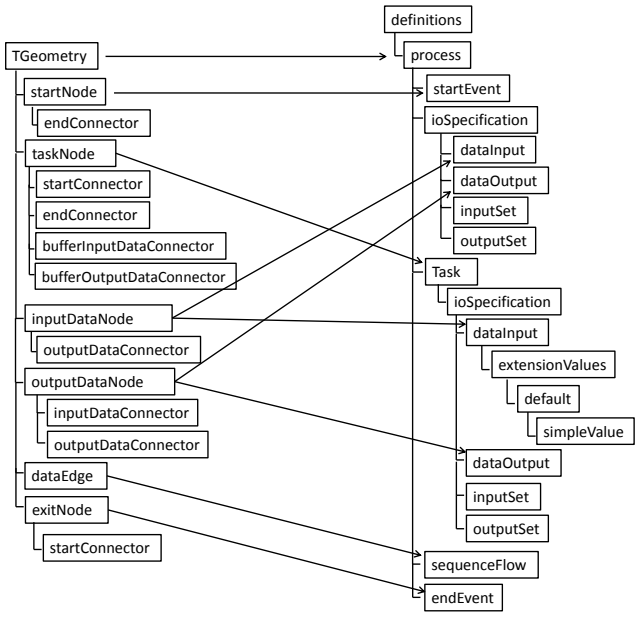

Figure 7. Correspondence between the XML elements during a transformation by considering a single activity from the workflows defined in Figures 1 and 2.

extensionValues element is generated. The two new elements contained in the *extensionValues* element are *default* and *simpleValue*.

Each data output of the activity node is captured as an *outputDataNode* object, which is in turn transformed into a *dataOutput* of BPMN. This transformation has been presented in the definition of the relation *getDataOutputTask* introduced before. Note that an *InputOutputSpecification* must define at least one *InputSet* element and at least one *OutputSet* element. Once the data input and output have been generated, the *inputSet* and *outputSet* are in turn generated. The corresponding QVT generation code can be found in the relations *createInputSetsTask* and *createOutputSetsTask* respectively.

VIII. DISCUSSION

The paper has proposed the use of a standard model-to-model transformation technology in order to convert scientific and engineering workflows into a business process standard format. The main contributions of the proposal are the following:

- **Technical feasibility**: the paper has shown that QVT provides an effective and standard method to transform scientific and engineering workflows into a standard business process format. It has shown that concepts coming from model driven architecture (MDA) can be applied in the domain of science and engineering design. Being QVT part of the OMG standards, these concepts can be useful as the basis for the development of domain-specific Model Driven Engineering tools [27].
- **Incentive to support standards in scientific and engineering community**: companies that use a proprietary workflow format that is properly defined with a model schema, can use a similar transformation process to export their workflows into a standard format. There are no restrictions on the use of QVT for this purpose, since it is an open standard defined by the OMG with many alternative implementations available.
- **Transformation example with a real workflow format widely used in industry**: the legacy workflow model is a widely used format in engineering all around the world, definitely not a model defined just for this paper evaluation. ESTECO is a world-wide leader in the domain of multi-objective optimization applied to engineering design, which is currently pursuing strong efforts to increase support for standards in the multi-objective optimization domain in the context of engineering processes, as it can be seen in [5].

Note that the example presented in this paper is intentionally small, in order to effectively demonstrate the approach, without introducing the reader into extra complexity generated by a larger example. Due to this successful results, the company plan to extended it to support the full specifications of the original legacy workflows,

becoming a part of the tool sets provided in a new BPMN compatible workflow environment.

IX. CONCLUSION

The paper has proposed the use of QVT-based transformation technology in order to transform engineering workflows defined in a legacy proprietary format to a well-defined business process standard. An example involving only data related components has been presented. The approach has been validated experimentally in an engineering environment supported by a company specialized in multi-objective optimization. It is important to stress that this transformation allows the conversion of most ESTECO industrial workflows to BPMN, consenting their execution in BPMN workflow engines with adequate extensions support.

The objective of this work has been to apply important concepts of business processes to the industrial field. Furthermore, it intended to show the importance of the use of standards in industrial fields in order to guarantee portability between tools that support BPMN. As a more general objective, it is expected that the use of a standard for scientific and engineering workflows will facilitate the collaboration between scientists and industrial designers, enhance the interaction between different engineering and scientific fields, providing also a common vocabulary in scientific and engineering publications [5].

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GUI Failures of In-Vehicle Infotainment: Analysis, Classification, Challenges, and Capabilities

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***Abstract*—With the growth of complexity in modern automotive infotainment systems, graphical user interfaces become more and more sophisticated, and this leads to various challenges in software testing. Due to the enormous amount of possible interactions, test engineers have to decide, which test aspects to focus on. In this paper, we examine what types of failures can be found in graphical user interfaces of automotive infotainment systems, and how frequently they occur. In total, we have analyzed more than 3,000 failures, found and fixed during the development of automotive infotainment systems at Audi, Bosch, and Mercedes-Benz. We applied the Orthogonal Defect Classification for categorizing these failures. The difficulties we faced when applying this classification led us to formulating requirements for an own classification scheme. On this basis, we have developed a hierarchical classification scheme for failures grounded on common concepts in software engineering, such as Model-View-Controller and Screens. The results of the application of our classification show that 62% of the reports describe failures related to behavior, 25% of the reports describe failures related to contents, 6% of the reports describe failures related to design, and 7% of the reports describe failures to be categorized. An outlined capability of the results is the support for fault seeding approaches which leads to the challenge of tracing the found failures to the correspondent faults.**

Keywords-domain specific failures; GUI based software; in-vehicle infotainment system; failure classification; fault seeding.

I. Introduction

This article focuses on classifying failures found and fixed during the development of automotive infotainment systems. As the research was conducted as part of a funded research project, we had the unique chance to analyze failure data collected by both car manufacturers and suppliers. The developed classification was awarded as best paper on the Fourth International Conference on Advances in System Testing and Validation Lifecycle [1] and invited for an additional journal publication.

In modern automotive infotainment systems ("Infotainment" is a combination of "information" and "entertainment"), the graphical user interface (GUI) is an essential part of the software. The so-called human machine interfaces (HMI) enable the user to interact with the system functionality, such as the radio system, the navigation, or the tire pressure monitoring system. According to Robinson and Brooks [2], a GUI "is essential to customers, who must use it whenever they need to interact with the system". Additionally, they "found that the majority of customer-reported GUI defects had a major impact on day-to-day operations, but were not fixed until the next major release" [2].

GUI-based software, especially in the automotive domain, is becoming more and more complex [3] - often, documents with more than 2,000 pages are written to describe all the functionality [4]. The reasons are (a) the growing number of functions, which form more and more complex systems, as well as (b) increasing variability due to more adaptive and customizable interaction behavior.

When testing GUIs, sequences of system interactions are performed and the system reaction is compared to the specified reaction in each step. It is obvious that not all possible combinations of user inputs can be tested. Thus, it is necessary to focus testing activities on certain failure types. To be able to (a) choose strategies accordingly, (b) adjust test case development or (c) guide failure recognition, the following questions need to be answered: What types of failures are to be expected in GUI based software today? Is it possible to build a classification of these types? What

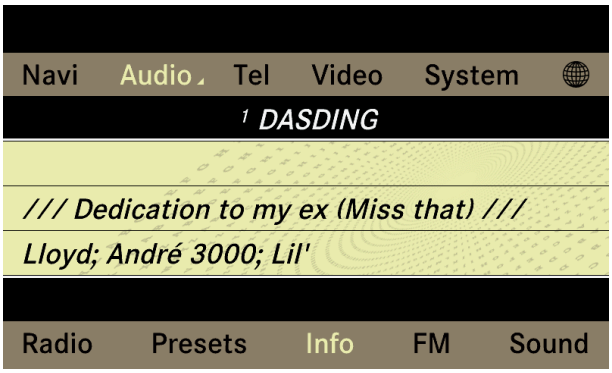


Figure 1. Example of a graphical user interface of the Mercedes-Benz infotainment system COMAND.

Figure 2. Example of a graphical user interface of the AUDI infotainment system MMI [6].

Figure 3. Example of a graphical user interface of the Bosch Multimedia Reference System (MRS).

are frequent failures in current GUI software? Which are common, which are rare?

Our context is the quality assurance of GUIs for automotive infotainment systems. As these are built into a car, the situation is different from that of desktop software. There is no convenient possibility to upgrade the system or to buy a new release, which means that manufacturers need to assure quality in the first release. Additionally, when the system does not work correctly, drivers may get distracted from driving. Therefore, special attention has to be paid to find and fix defects during development. The interaction with the system is different from that of desktop GUIs [5]. A common interaction device is the central control element (CCE).

Based on typical examples, the structure and the interaction concept of automotive infotainment systems are described in the following. In the Mercedes-Benz COMAND system shown in Figure 1, the GUI consists of a menu at the top of the screen, where all available applications, e.g., navigation or audio, can be accessed. Each application consists of an application area in the middle of the screen, where the actual content is displayed (here: information about the radio station and the song being played) and a sub-menu for content-specific options at the bottom (here: “Radio”, “Presets”, “Info”, etc.). The GUI is operated via the CCE, allowing the user to set the selection focus by rotating or pushing the CCE in one direction, and to activate options by pressing it.

Another well-known in-vehicle infotainment system is the “MMI” (Multi Media Interface) developed by Audi. Figure 2 shows a GUI of the MMI with an example of a navigation program. In contrast to COMAND, the main menu options of the Audi infotainment system are located in the four corners of the screen. In the middle area of the screen, the information and the menu options of the navigation program are displayed. To operate the GUI, a physical interactive component called MMI-Terminal is used, which consists of a central button allowing rotary and push operations, as well as four push buttons around the central button. Analogous to COMAND, the MMI enables the focus selection and the operation confirmation of the GUI.

Besides the above described ones, Bosch has introduced another in-vehicle infotainment system called “Multimedia Reference System” (MRS), which is based on an open source platform. Compared with infotainment systems of Mercedes-Benz and Audi, the MRS focuses on a full touch solution. Figure 3 exemplifies the MRS with a view of the main menu and with a view of the albums. The top of the screen is the area displaying the status of applications, such as E-mail, phone and weather report. The left border and right border are used for hot keys related to several frequently used functionality.

This article is structured as follows. In Section II, we discuss related work and stress the need to create a new classification scheme. In Section III, we describe how we applied the scheme that has been identified as most appropriate in an empirical study. In Section IV, we present our approach to develop the classification. The scheme itself is detailed in Section V. Section VI discusses the results based on the defined requirements. Section VII presents concluding remarks and future research directions.

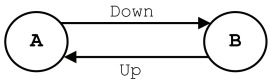
II. Related Work

In the literature, various types of defect classifications can be found. However, many of them lack practical usage and empirical data in the form of distributions of defects into the scheme, and thus it is hard to tell whether they are a valuable addition. Other schemes for classification are used frequently, or at least once. For our study, we concentrate on those latter ones, and discuss why they are not fully suited for our means. As described above, our context is black-box testing of a GUI for automotive infotainment systems.

A. Definitions

First, we have to clarify the distinction between different terms for “defects”. The IEEE [7] released a standard for defect classification, which also includes a scheme for

1) Specification



2) Implementation

```
if (cState.equals(state.A) || cEvent.equals(event.DOWN)) {
   showStateScreen(state.B);
}
```

Fault

3) User Input

The user starts in `A` and presses `Up`.

4) Execution

```
if (cState.equals(state.A) || cEvent.equals(event.DOWN)) {
➡ showStateScreen(state.B);
}
```

Error

5) Expected HMI Output

No reaction.

6) Actual HMI Output

After pressing `Up` in state `A` the user reaches the screen of state `B`. Failure

(This behavior does not comply with the specification.)

Figure 4. Example of the distinction of a fault, an error and a failure.

distinguishing between defects and failures. A defect is "an imperfection or deficiency in a work product that does not meet its requirements or specifications", while a failure is "an event, in which a system or system component does not perform a required function within specified limits" [7]. Therefore, when a defect is present, and we perform GUI testing, we can observe failures. They are caused by defects in the code, but since we test by using the GUI, and not the code (i.e., black-box), what we can observe is the behavior. This is why we do not create a defect but a failure classification scheme. The missing consistency of precise terms within the related work is complicating its conflation. According to [7], e.g., the terms anomaly, error, fault, failure, incident, flaw, problem, gripe, glitch, defect, and bug are often used synonymously. There is no need for our work to define all related terms. Here, "defect" is used as a collective noun. In accordance with IEEE [7], the usage of the terms fault, error and failure is based on Jean-Claude Laprie [8]: "A system failure occurs when the delivered service deviates from fulfilling the system function, the latter being what the system is aimed at. An error is that part of the system state, which is liable to lead to subsequent failure: an error affecting the service is an indication that a failure occurs or has occurred. The adjudged or hypothesized cause of an error is a fault." Figure 4 shows a concise example in the HMI context for clarifying the distinction between the terms.

According to [9], faults cause errors and errors cause failures. However, not every fault is the reason for an error and not every error is the reason for a failure. Hence black-box testing can lead to a sophisticated task because some faults cause failures only in very particular situations. In addition, failures that are caused by faults and lead to errors can cause other faults – resulting in a propagation of faults. Additionally, no one-to-one correspondence of failure and faults can be assumed. One failure can be symptom for more than one fault, one fault can cause more than one failure. The analyzed reports are based on the results of black-box testing. Thus, only failures were detected and documented within these reports. They contain no information about the faults – the root of the failures.

B. Defect Classification Schemes

IBM created the so-called Orthogonal Defect Classification (ODC) [10] in the early nineties. Since then, many companies have applied this approach. It consists of several attributes, such as *triggers*, *defect types*, *impact*, and others. A GUI section is included in the ODC extension V5.11 [10]. It contains *triggers*, such as *design conformance*, *navigation*, and *widget / GUI behavior*.

Another scheme, which contains several categories for GUI-related issues, was proposed by Li et al. [11]. It consists of 300 categories and is based on the ODC, but adapted for black-box testing. It contains, e.g., categories for a *GUI in general*, and for *GUI control* [11]. However, this scheme contains many categories that refer to highly specific GUI elements and therefore lacks in abstraction levels. For example, there are categories for a *Textbox*, *Dropdown list*, or a *Title bar* that are not applicable to systems that do not contain those. The scheme also contains categories for *interaction of various menus* or *display styles* [11]. There is no further differentiation, e.g., there may be an unexpected reaction of the system, or there may be no reaction when using a menu. This scheme is created for regular desktop software, as it also classifies keyboard- or mouse-related faults. In order to adapt this schema, a large number of categories would have to be exchanged. As there are no further abstraction levels, only few common aspects remain which limits the potential of general conclusions.

Børretzen and Dyre-Hansen [12] created a scheme that is also based on the ODC. They target industrial projects. A single GUI fault category is included, but not further segmented. The rationale for this is that, although "function and GUI faults are the most common fault types", they are most often not severe, and thus, not as critical as other categories [12]. This seems to be a contradiction to what was stated in the introduction, but the criticalities of certain types of defects are subject to the application domain. In the beginning, in our application domain they are very critical, and therefore, we focus on them to assure software quality.

Hewlett-Packard created a scheme based on three categories: *origin*, *type*, and *mode* [13]. *Origin* refers to where the defect was introduced; the *type* can, e.g., be

logic, *computation*, or *user interface*. The *mode* refers to why something has been entered: *missing*, *unclear*, *wrong*, *changed*, or *better way*. This last category, *mode*, is an interesting detail for classifications, as it not only allows a deeper hierarchical structure, but also allows distinguishing different kinds of defects of one type. However, the scheme created by Hewlett-Packard does not distinguish the various types of GUI-related failures, and, thus, does not enable us to categorize our defects.

Another well-known scheme was developed by Beizer [14]. The main categories are "requirements, features and functionality, structure, data, implementation and coding, integration, system and software architecture, and testing" ([14], p. 33), each having three levels of subcategories. The scheme is very detailed, but does not contain GUI-related categories. An adaptation of this scheme for GUI contexts was created by Brooks, Robinson and Memon [15]. The authors emphasize that "defining a GUI-fault classification scheme remains an open area for research" [15]. They simplified Beizer's scheme to create a two-level classification and added a subcategory for GUI-related issues, "to categorize defects that exist either in the graphical elements of the GUI or in the interaction between the GUI and the underlying application" [15]. However, since there is only one category specifically for GUIs and since we focus on GUIs, it is not possible to use this scheme for our purposes. Adapting it would result in the same effort as creating a separate one.

There also exists a fault classification scheme for automotive infotainment systems [16]; however, this scheme is based on network communication and can thus not be used for classifying software based GUI failures. This scheme differentiates between hardware and software, but does not differentiate further. It also has many categories not usable in our context, and does not include different GUI-related categories. Ploski et al. [17] studied several schemes for classification, including approaches not presented here. Since there were no matching schemes, we do not present them here.

Another approach was created by the IEEE [7]. However, this approach lists a number of attributes to be filled out for each defect and is not expedient for reaching our goals. This is due to the purpose of the standard to "define a common vocabulary with which different people and organizations can communicate [...] and to establish a common set of attributes that support industry techniques for analyzing software defect and failure data" [7]. This is much broader than what we want to achieve. However, the examples of defect attribute values in the standard contain a *mode* section with the values *wrong*, *missing*, and *extra* [7]. We adapted this *mode* section, and expanded it where necessary. The results will be presented in Section V.

The classification schemes available do not meet our requirements. Since we employ black-box testing of GUIs, we cannot use any code-related categories or schemes. We focus only on GUI-related failures. The schemes presented in [13][14] and [16] do not have GUI-related categories and because of this, they cannot be used by us. Others ([12][15]) have GUI-related categories, but still do not match very well to our purposes. The scheme presented in [11] has many GUI-related categories, but for desktop software. Due to the differences between desktop and automotive infotainment GUIs, we did not adapt it because we would then have had to either delete or change most of the categories.

As the trigger aspect listed in the ODC ([10]) was identified as the most appropriate existing scheme we found, an experimental application of the ODC was conducted, and the results are presented in Section III. For now, we just state that the ODC in the current state cannot be employed for our purposes perfectly. Since using or adapting other schemes does not lead to savings in effort (no differentiated GUI categories to use, most categories not applicable), we created our own failure classification scheme. After describing the approach we used, the categories of our scheme are explained in Section V.

III. Empirical Pre-Study

As stated in Section II, the ODC [18] [10] seems to be the most appropriate scheme to classify failures in GUIs for automotive infotainment systems. It provides eight attributes, such as *triggers*, *defect types*, *impact*, and others, describing pieces of information concerning a defect from different points of view. The ODC is intended to facilitate the entire bug tracking process including reproducibility (opener section) and fixing (closer section). The information of the ODC describing how the defect has been produced can be specified in the opener section using so called "trigger" categories. According to [18], a trigger is "the environment or condition that had to exist for the defect to surface". As this paper focuses on classifying failure types, this trigger section is most relevant for our purposes. Originally, the ODC included not primarily GUI related categories, such as "Logic/Flow" or "Concurrency". With the extension v5.11, these have been extended for graphical user interfaces introducing the values *design conformance*, *widget / icon appearance*, *screen text / characters*, *input devices*, *navigation*, and *widget / GUI behavior* [18]. See Table I below for an explanation for the trigger values.

A. Design

For this research, we analyzed databases of existing failure reports. The data was collected during the development of state-of-the-art automotive infotainment systems. The testers executed the System Under Test (SUT) manually, based on specification documents, and used failure reporting tools to keep records of anomalies. The reports were handed over to the developers, who then rechecked and fixed the software. In this context, failures are defined as mismatch

between the SUT and an explicit GUI specification, which can be observed while operating the system. Any implicit requirements, such as general standards or guidelines, are not subject of the study. Only reports that were accepted as failures by both testers and developers were considered. Failures not referring to the GUI were sorted out. Examples for such failures are hardware errors or display flickering.

As a threat to the validity of this application of the ODC has to be mentioned, that we want to use the classification for dynamic testing purposes. However, in this section, we also selected entries for the *design conformance* value. One can argue that reviewing the design documents is not a dynamic testing activity. However, the ODC is not meant solely for testing, and a real application has to be done for the whole life cycle. When we simulate the usage of the ODC, we have to account for this, even when we do this in the aftermath of quality assurance activities. Additionally, a deviation between the design documents and the realization in a system cannot be found until the application is implemented and the implemented design can be reviewed and compared to the design documents.

B. Execution

For this study, Audi, Bosch, and Mercedes-Benz provided failure data. Hence, the analyzed reports represent a broad variety of contexts, as they stand for different infotainment systems (Audi MMI, Mercedes-Benz COMAND, and several projects developed at Bosch), different steps in the development process involved (e.g., module, system, and acceptance test), as well as different test strategies, test personnel, and test environments. As preparation to the analysis, the reports were exported to an Excel document. Testers sometimes recognize several anomalies at once but register those only in a single report. Therefore, reports that describe more than one failure have been split up in one line for each failure. Redundant reports that describe exactly the same failure as already considered ones were removed. After that, more than 3,000 reports remained to be analyzed. One third of the reports were used as training data to construct the failure classification, which was then fine-tuned using the remaining reports as test data. The following information per report was relevant for the analysis:

Table I
TRIGGER VALUES OF THE ODC EXTENSIONS V5.11.

Value for the attribute "trigger"	Description
Widget / GUI Behavior	Concerned with the system reaction related to widget / GUI elements.
Navigation	Concerned with the system reaction related to navigating between screens.
Widget / Icon Appearance	Concerned with the layout / design of widget or icon elements.
Design Conformance	Concerned with the conformance of the design of the developed application with the design documents.
Screen Text / Characters	Concerned with the correctness of labels or other text elements.
Input Devices	Concerned with the system reaction related to using various input devices.

Table II
EXAMPLES OF THE ANALYZED FAILURE REPORTS.

ID	Title	Problem description
4711	Inserted music CDs are not played automatically	*Setup*: Any state *Actions*: Insert music CD *Observed result*: Nothing happens *Expected result*: System should display CD play screen *Reference*: R0026679 *Workaround*: Navigate to CD play screen manually
4712	Cell phone icon on call screen obsolete	*Setup*: Connect cell phone *Actions*: Navigate to Call screen *Observed result*: Placeholder icon for cell phones is displayed *Expected result*: Correct icon is displayed *Reference*: R0026672 *Workaround*: —

A *Report ID* provides unique identification for each report. In the *Title*, the testers describe the essence of the report. The *Problem description* is a detailed statement about (a) the required setup of the system under test, (b) the actions that lead to the failure, (c) the behavior or result that has been observed, (d) a description of what should have been displayed instead, and (e) how this failure could be bypassed. If failures were ambiguous or hard to describe, screen shots were added. Table II shows simple examples of reports.

C. Results & Discussion

In Table III, the percentages of the pre-study results are presented. As shown, of the more than 3,000 failure reports, we could classify more than 90% into the values suggested by the ODC extension. However, as we focus exclusively on HMI software testing, it was not possible to classify any reports to the *input devices* value. Input device reliability had been ensured in previous testing phases. We examined the failure reports manually to categorize them according to the trigger values mentioned above. During this process, we had the impression that the values in the ODC are not as disjunctive as expected: [18] states that an example of *widget / GUI behavior* is "help button doesn't work". However, when this button is pressed, one could argue that an attempt to navigate has been made. Thus, such a failure could also be categorized with the *navigation* value for the *trigger*. To be able to categorize such failures, we decided to use screens as a criterion; if the screen does change although it should not, or if the wrong screen is presented, or no new screen appears although it should, then we classified this as *navigation*, otherwise as *widget / GUI behavior*. More than 50% of all reports fall into these two values: we classified 18% as *navigation* failures, and 38% as wrong *widget / GUI*

Table III
RESULTS OF THE ODC APPLICATION.

Value for the attribute "trigger"	Distribution
Widget / GUI Behavior	38.0%
Navigation	18.0%
Widget / Icon Appearance	17.0%
Design Conformance	9.6%
Screen Text / Characters	9.2%
Input Devices	0%
—	—
Remaining reports not classified	8.2%

behavior.

We could classify 9.6% as *design conformance* and 9.2% as *screen text / characters*. Differentiation between these two values was not clear either. In this case, we had to use an additional criterion for separation: If a text is "wrong" and the text itself is known only at run time, then it is a *screen text / characters* failure. If a text is "wrong" and is known already at design time, then it can be found in design documents, and thus it is categorized under *design conformance*. This separation does not comply with the examples given in [18]. However, we did not consider the examples given for these values sufficient, as the example for *screen text / characters* is limited to the description "button mislabeled". Such a label is known at design time, and thus, the label has to be defined in the design documents. If the label is correct in the documents and wrong in the implemented system, the application does not conform to its design. This is a problem with *design conformance*, but it is listed under *screen text / characters*. Now, we could also differentiate whether the label is already wrong in the design documents or not and then had the possibility to categorize it. Nevertheless, this discussion shows that the values are not detailed enough as necessary for our purposes.

The last remaining value in the *trigger* section, *widget / icon appearance*, was used to classify about 17% of all reports. One additional problem we faced was that we also had to classify failures in relation to animations. Here, we decided to use the same criterion as with the *design conformance* and the *screen text / characters* values: Is the problem already known at design time or only at run time? The former are categorized as being a problem with *design conformance*, the latter were tagged with the *widget / icon appearance* value.

In summary, we state that the categorization following the ODC extension v5.11 was not satisfactory. Besides the difficulties with the values not being disjunctive enough for our purposes, which led to the usage of additional criteria, the distribution across the trigger values is rather imbalanced. Not a single entry could be categorized into *input devices*, because this is not in the focus of the testing activities we examined, so this cannot be counted as a weakness in the ODC. But for the remaining values, we have two categories with more than 9%, two categories with nearly 18%, and one category with more than 38%.

IV. APPROACH

The experiences described in Section II led us to the conclusion that it is more appropriate to create our own classification scheme, which would be more suitable for our needs. Following the lessons we had learned, we tried to include the additional categories we invented for using the ODC, and we posed requirements, for example to prevent categories growing as large as the *widget / GUI behavior* value. It should also be possible to use the ODC in combination with our taxonomy.

Therefore, a classification is needed that both gives a good overview and allows extension for comprehensiveness. Guidance is necessary to avoid universal categories with little information. In order to achieve those objectives, a hierarchical structure seems adequate: the lowest levels represent the actual failure class. Higher levels should summarize similar categories on the following level. By doing so, the impact of adding additional classes in the future should be mitigated, and different versions of the classification should be comparable at least at higher abstraction levels, such as "logic" or "design". Developing failure classes on lower levels has to be conducted thoroughly: On the one hand, classes have to be sufficiently abstract to satisfy the various analyzed contexts; on the other hand, they still have to be meaningful. As an indication of how many hierarchy levels have to be applied and whether one category could be subdivided reasonably or whether several categories should be combined, we defined the following requirements for the failure classes:

- To scale the scope of each classification level, an initial analysis of the data indicates the necessity to limit the percentage of the lowest level to 10% of the total numbers of failures.
- To develop a clear and easy-to-use structure, the number of categories on every level has to be a minimum of 2 and a maximum of 5.
- To ensure reproducibility, the assignment of failure reports should allow no ambiguity. Each failure class on the lowest level has to be disjunctive and well-defined.

The development of the classification was influenced by the Bug Tracking Systems (BTS) in use, as they already allow to roughly categorize reports. However, as this classification is intended (a) to focus on GUI-related failures and (b) to be applicable not only to one system, we combined several report databases that use different failure categories with varying levels of abstraction. During the development stage analyzing one third of the reports, the classification had to be conducted manually. Once the basic structures had been established, the newly developed categories could be compared and systematically reviewed to match the existing ones. Unclear reports were reviewed and information required for classification was added. In the future, BTS

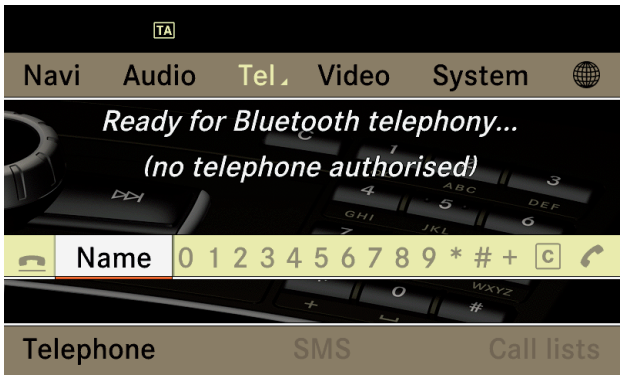


Figure 5. Screen example: Telephone application.

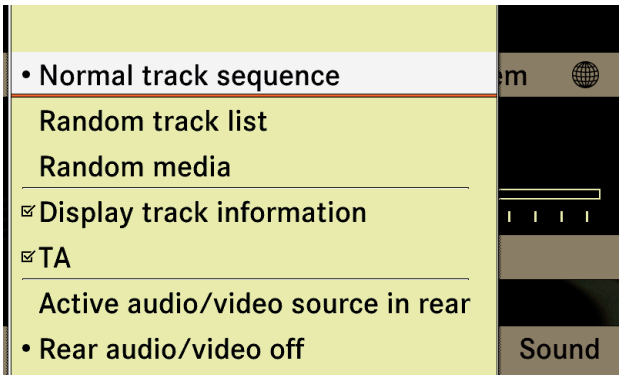


Figure 6. Screen example: Overlaying submenu.

might be able to provide these more detailed classes to make the classification during the GUI testing process more meaningful. Manual categorization would then no longer be necessary.

To determine the similarity of failures, the classification is based on concepts and patterns used in software engineering. For example, the top-level failure classes are *behavior*, *contents*, and *design*, according to the well-established Model-View-Controller [19] design pattern. The structure of the classification and the related separation criteria are presented in Section V.

V. Failure Classification

In this section, the GUI failure report classification is described. Table IV gives an overview of the entire classification, including the failure distribution. In Figure 7, the distribution of the most frequent classes is illustrated. As mentioned above, the top level follows the Model-View-Controller concept [19], proved to be an adequate abstraction for GUI-based software. This choice was made due to the authors' background as software developers. *Controllers* (here: *behavior*) abstract the observable behavior, indicating how input is processed. *Models* (here: *contents*) define all contents that are displayed by the system. *Views* (here: *design*) describe the layout and appearance of the contents to be displayed. As the SUT was tested as a blackbox, the MVC pattern is not intended to represent the actual software structure or to relate any failures to implemented software modules.

In order to avoid enforced classifications of reports to existing classes, a category "to be categorized" (TBC) was created. As for other categories, on the lowest level the TBC failure class is limited to 10% of the total number of failures. Classifying more failures than that limit as TBC would indicate that the definition of an additional failure class is necessary.

A. Behavior

The top-level failure class *behavior* contains all failure reports describing that stimuli to the SUT do not result in the specified output. In order to subdivide this failure class, common abstractions in GUI development were applied:

Screens [20][21] represent the current state of the GUI displayed. This state defines the options available to the user. Figure 1 shows the radio screen, where the current radio station and the song playing are displayed. The options provided allow users to change the waveband (FM option) or adjust the sound setting (Sound option).

The scope of screens is often a matter of system design. For example, in the COMAND infotainment system, similar to desktop applications, some of the options shown in the first place are general topics. Upon activation, a submenu is displayed on top of the remaining screen content (Figure 6). As the context of use remains unchanged, those menus are considered as part of the original screen, although they are not displayed all the time.

Screens are structured based on elementary GUI elements, so-called *widgets*. Widgets are either primitive (label, rectangle, etc.) or complex, meaning that they are compositions of primitive or again complex widgets. An example of widgets in Figure 5 would be the horizontal list in the top part. This list contains button widgets for all available applications, such as "Navi", "Audio", or "Tel" (i.e., phone). In terms of interaction logic, lists primarily manage the focus. Lists determine how their content can be iterated and what option is focused on (re)entering. If many options are available, e.g., when entering alphanumeric characters, the middle of the available options has to be focused on start. In cases of touch screens as input modality, lists would calculate the touch points of their containing entries depending on their visibility. Buttons consist of labels and/or symbols representing their function to the user. Additionally, buttons might define what actions have to be executed on pressing them and provide their visibility status on demand.

In this classification, the concepts of screens and widgets are used to differentiate micro behavior, which affects single elements on the display (e.g., iterating list entries), and macro behavior, which changes the entire context of use.

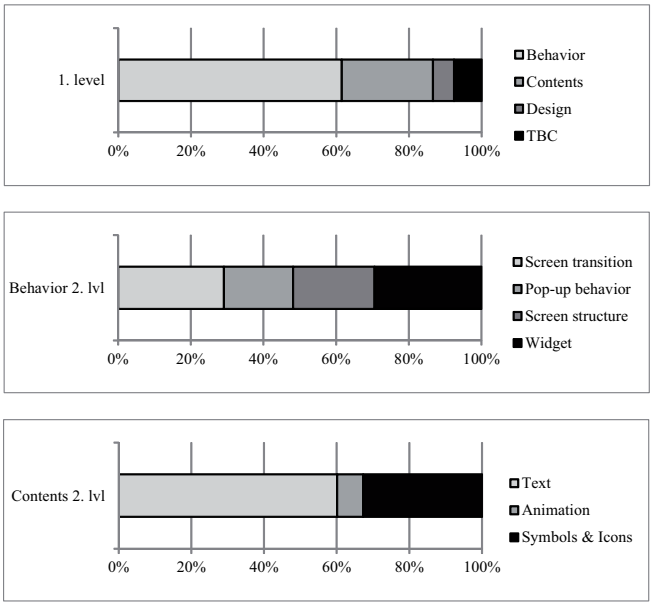


Figure 7. Failure distribution overview.

1) Widget Failures: The GUIs of the automotive infotainment systems analyzed mainly use various types of lists to present options to the user. To activate an option, those lists set a focus by having the user turn or push the CCE and press it once the desired option is focused. Potential failures might be that the wrong option is focused on start or that the focus does not change as specified. An example would be that every time the main menu is entered, the element in the middle should be focused automatically. A failure would exist if the first element would be focused instead. Those failures are considered as deficient *widgets focus* logic. The subcategories are:

- *initial*: the wrong option is focused when a list is (re-) entered.
- *implicit*: the focus has to be reset due to changing system conditions.
- *explicit*: the user resets the focus by turning or pushing the CCE.

For widgets, additional behavior is often specified. One example might be alphabetic scrolling to allow the user to jump to a subgroup of list entries starting with one specific letter. Those failures are considered as deficient *widget behavior*. Subcategories are:

- *missing*: specified behavior is not implemented.
- *wrong*: instead of the specified behavior, not specified behavior is implemented.
- *extra*: behavior is implemented but is not specified.

2) Screen Structure Failures: In this failure class, reports are clustered describing the logic for determining the widget objects the screens contain and what data they hold. In automotive infotainment systems, the availability of options depends on numerous conditions, such as available devices (e.g., radio tuner available, connected mobile phones, etc.), the current environmental conditions (e.g., car is moving faster than 6 km/h), or even previous interactions (e.g., activating route guidance). These conditions affect whether options are displayed but cannot be selected (gray-out mechanism) or whether options are even listed at all. Therefore, two subcategories refer to option provision behavior. The first subclass is *option offer* which summarizes failures that refer to occurrence or order of options. The class is further

Table IV
THE DISTRIBUTION OF FAILURES.

1. level	2. level	3. level	4. level	distr.
TBC	-	-	-	*7.6 %*
Behavior (Σ: 61.5%)	Screen Transition (Σ: 17.9%)	missing	-	*5.8 %*
		extra	-	*2.9 %*
		wrong	-	*9.2 %*
	Pop-up Behavior (Σ: 11.7%)	missing	-	*3.6 %*
		extra	-	*3.2 %*
		priority	-	*0.5 %*
		wrong	-	*4.4 %*
	Screen Structure (Σ: 13.8%)	screen composition (Σ: 5.4%)	missing	*2.4 %*
			extra	*0.9 %*
			wrong	*2.1 %*
		options offer (Σ: 5.4%)	missing	*2.2 %*
			extra	*1.3 %*
			wrong	*1.0 %*
			order	*0.9 %*
		option gray-out (Σ: 3.0%)	missing	*1.6 %*
			extra	*1.0 %*
			wrong	*0.4 %*
	Widget (Σ: 18.1%)	Behavior (Σ: 14.7%)	missing	*5.1 %*
			extra	*0.9 %*
			wrong	*8.7 %*
		focus (Σ: 3.4%)	initial	*0.9 %*
			implicit	*1.5 %*
			explicit	*1.0 %*
Contents (Σ: 25.1%)	Text (Σ: 15.1%)	design time (Σ: 5.9%)	missing	*1.2 %*
			incomplete	*0.3 %*
			extra	*0.5 %*
			wrong	*3.9 %*
		run time (Σ: 9.2%)	missing	*2.2 %*
			incomplete	*1.1 %*
			extra	*1.0 %*
			wrong	*4.9 %*
	Animation (Σ: 1.8%)	design time (Σ: 0.8%)	missing	*0.4 %*
			extra	*0.1 %*
			wrong	*0.2 %*
			others	*0.1 %*
		run time (Σ: 1.0%)	missing	*0.4 %*
			extra	*0.1 %*
			wrong	*0.3 %*
			others	*0.1 %*
	Symbols & Icons (Σ: 8.2%)	design time (Σ: 2.9%)	missing	*1.5 %*
			extra	*0.2 %*
			wrong	*1.2 %*
		run time (Σ: 5.3%)	missing	*2.2 %*
			extra	*1.0 %*
			wrong	*2.1 %*
Design (Σ: 5.8%)	color	-	-	*1.0 %*
	font	-	-	*0.4 %*
	dimension	-	-	*0.7 %*
	shape	-	-	*0.4 %*
	position	-	-	*2.7 %*
	other	-	-	*0.6 %*

differentiated as follows:

- *missing*: an option that should be displayed is not visible.
- *wrong*: an option A is displayed instead of option B.
- *extra*: an option is displayed but should not be visible.
- *order*: an option B is listed before option A but should be listed after.

The second option specific failure class contains failures that refer to their *gray-out behavior*, which again is further detailed as follows:

- *missing*: an option should be grayed-out but is available.
- *wrong*: instead of an option A an option B is grayed-out.
- *extra*: an option A is grayed-out but should be available.

The subclass *screen composition* clusters failures related to deficient setup of widgets on screen. Subclasses of this category are:

- *missing*: widgets that are specified are absent.
- *wrong*: the wrong widget is displayed.
- *extra*: an unspecified widget is displayed.

Screen structure failures are distinguished from the *widget behavior* category as follows: the former represents erroneous selection of widgets such as horizontal or vertical lists, whereas the latter clusters failures of widget behavior itself, such as the scrolling logic or widget state change.

3) Screen Transition Failures: As described above, screens represent one special usage context. The failure class *screen transition* clusters failures occurring when those usage contexts change, such as radio, players, or system setup. One indication of a screen transition is that the widget composition and the displayed options are replaced. With Figure 1 and Figure 5, a screen transition is demonstrated: First, the Radio screen is shown; by activating the option "Tel", the context changes to the telephone screen of the infotainment system. Subclasses of this category are

- *missing*: a screen transition that is specified does not take place.
- *wrong*: instead of screen A, screen B is displayed.
- *extra*: a screen transition that is not specified takes place.

4) Pop-up Behavior Failures: In automotive infotainment systems, messages are often overlaid over the regular screen (Pop-up mechanism). Those messages inform users about relevant events or changes of conditions. For example, those messages might state that the car has reached the destination of an active route guidance or that hardware has heated up critically. These messages might be confused with overlaying submenus described above as part of screens. The difference is that pop-up messages do not depend on the current system state and may occur any time, triggered by system conditions or events. Overlaying submenus are only displayed on particular screens and are triggered explicitly by user input. Pop-up behavior subcategories are

- *missing*: the pop-up is not displayed although the respective conditions are active.
- *wrong*: instead of pop-up A, pop-up B is displayed.
- *extra*: pop-up appears although the respective conditions are not active.

Additionally, with the pop-up mechanism the priority system is important: A pop-up with higher priority always has to be displayed on top of pop-ups with lower priority. Those failures are clustered in the subclass *priority*.

B. Contents Failures

The next top-level category is related to contents. The separation criterion is the type of the content: *symbols & icons*, *animations*, or *text*. In Figure 1, a text failure would be if the button for the "Audio" application was labeled incorrectly with "Adio". If the globe symbol in the upper right corner of the screen were a simple square as placeholder, this would be considered a symbol failure. Examples of erroneous animations might be if the focus highlight transition is faster than specified (wrong) or if the overlay menus are not faded in (missing). In this classification, we additionally distinguish content that is known at *design time* (e.g., the labels of available applications) and content that cannot be defined until *runtime* (e.g., displaying the names of available Bluetooth devices). Design time does include localization failures. Although this content depends on the language setting, the particular data is already defined and stored in a database. Characteristic for failures at runtime are patterns that define what data is needed for the content (e.g., title and artist of music on connected media) and how it is displayed (e.g., order, format, etc.). This explicitly includes how content might have to be shortened or reduced. Therefore, content runtime failures are close to the behavior category. As they are strongly related to the respective data to be displayed, we considered this a content category. For each of those content types, the following subclasses are defined:

- *missing*: Content that is specified is not displayed.
- *wrong*: Instead of the content that is specified other content is displayed.
- *extra*: Content that is not specified is displayed.

This category might be confused with the screen structure failure class in the behavior sub-tree. For example, a failure report describing that the second button in the main menu is "Blind Text" instead of "Audio" could be categorized as either a *contents* or an *option provision* failure. If pressing the button still leads to a screen transition to the Audio context, the report is considered as deficient contents. If another context is displayed, for example the Telephone screen, it would be a deficient option provision.

C. Design Failures

The last top-level category clusters reports that describe design failures. This includes

- *color*: e.g., focus color is red instead of orange.
- *font*: e.g., text font is Courier instead of Arial.
- *dimension*: e.g., a button is higher or broader than specified.
- *shape*: e.g., a button should be displayed with rounded instead of sharp edges.
- *position*: e.g., a label of a button is centered instead of left-aligned.

As design failures were often described vaguely, a subcategory for *other* design failures was defined. Ambiguous descriptions were, for example, that wrong arrows, wrong Cyrillic letters, or a wrong clock were observed. As it became obvious early that a low percentage of reports were categorized as design failures, no additional work was done to clarify this category.

VI. Discussion

The requirements defined in Section IV were fulfilled for most failure classes. We intended to cover at least 90% of all defect reports analyzed. Only 7.6% of the reported failures had to be classified as "to be categorized". Furthermore, we intended to limit the percentage of the classes on the lowest level of the hierarchy to 10%. This could be achieved as well: with 9.2%, the largest category was *behavior - screen transition - wrong*. We intended to allow only 2-5 categories on each hierarchy level. This could not be realized for the design category (6 sub classes). However, due to a very small number of failures classified as design-related (5.8%), we did not consider it necessary to restructure this category.

The requirements further stated that the failure classes have to be disjunctive. Most of the distinction was clear during the classification process. In the available reports, there was no interference between logic and design failures. However, failures regarding design, which is determined by algorithms were not analyzed. For those cases, a new class within the logic sub-tree has to be defined. No ambiguity was noticed in terms of differences between content and design failures.

Most challenges were experienced in differentiating content and logic failures, especially in cases where several failures occurred at once. This was due to the fact that the systems had to be tested as a black-box and only the information displayed on the screen could be accessed. The following scenario exemplifies the key issues: let us assume all 5 buttons in the main menu line illustrated in Figure 1 are labeled as "Blind Text". This is definitely a content text failure. However, it has to be checked whether there are additional failure symptoms such as wrong, missing, or extra options provided, or a failure regarding the order of menu entries. Those additional failures have to be revealed by analyzing other button properties. In this case, it would have been checked which screen transition they trigger. However, several alternatives have to be considered:

- If pressing the second button in the menu line – which should be the Audio button – triggers the transition to the Audio context, no additional failure has to be reported.
- If pressing not the second but the third button triggers the transition to the Audio screen, an additional option provision (order or extra) failure has been revealed.
- If pressing a button labeled Telephone triggers the Audio screen, this could be a screen transition failure or a content text failure.

In the analyzed reports, this distinction was possible due to the given descriptions. However, problems might occur when applying the classification in the future. This is not only an issue with failure classifications, but an issue with reporting failures in general. We recommend bearing the ambiguity of symptoms in mind while testing and reporting. It is essential to provide the information that is needed to differentiate failure symptoms. A detailed classification, such as the one presented in this paper, might help to clarify the exact circumstances even in early phases.

Further, we answered the question raised in this paper what types of failures are frequent in current information systems. The results show that the majority (61.5%) are failures related to behavior. This demonstrates the complex macro and micro behavior in modern infotainment systems. Most of the failure reports are related to missing or wrong individual widget behavior (13.8%) as well as missing or wrong screen transitions (15.0%). The content category is the second largest top-level failure class (25.1%), with erroneous text being the biggest subcategory (15.1%). The majority (9.2%) is not known until runtime. Explanations are (a) that in most infotainment systems, information is mainly displayed textually and (b) that testing texts is easier for human testers than comparing symbols or animations in detail. Very few failures (5.8%) describe erroneous design. One explanation might be that design is hard to test manually. For example, it is a problem to differentiate shades of colors visually. In addition, most design errors are less critical and even might not be recognized by users. Therefore, testing design might not be of high priority to test planners. Hence, this data cannot be seen as definite evidence showing that design failures are indeed this rare. However, we addressed this limitation by analyzing failure reports representing a broad variety of contexts such as testing goals, test personnel, or test environments.

VII. Conclusion and Future Work

In this paper, we answered the question of what types of failures can be found in GUI-based software in the automotive domain today. A failure classification was developed and applied to more than 3,000 failure reports. Ultimately, each related fault concerning the reported failures was fixed during the development process. The reports were created during the development of modern automotive infotainment

systems at AUDI, Bosch, and Mercedes-Benz. 61.5% of the reports describe failures related to high- and low-level behavior, 25.1% of the reports describe failures related to contents, and 5.8% of the reports describe failures related to design. We support not only the testers in creating detailed and clear reports, but also the entire GUI development process by pointing out pitfalls leading to gaps between the specification and the implementation. The classification indicates, which aspects need special attention in specification documents and might need to be described more explicitly than is common today. For roles responsible for the implementation of GUI concepts, this work points out aspects that might be ambiguous and require clarification.

Requirements were defined in order to guide the classification process and to avoid categories that are too general or too specific. These requirements proved to be effective for guiding the classes development process. General sections such as those suggested by the ODC extension v5.11 [18] could be avoided. However, as there are classes with less than 1%, the presented classification seems to be over detailed. In most cases, classes follow the missing/extra/wrong pattern suggested by the IEEE classification [7], which was applied with ease. In future applications, those minor classes might be ignored.

In future research, the suggested classification might be scaled by reducing the maximum percentages of lowest-level categories. Thus, some categories have to be differentiated further and additional failure classes have to be defined. Moreover, additional parameters such as "failure criticality", "predicted number of affected users", or "costs for testing" could be added to the classification. Those aspects are not in focus at the current stage and might influence the choice of test strategies significantly. Future failure reports should include information about those aspects. Extension of the failure reports would require intensive collaboration between testers, programmers, requirement engineers, and other participants in the development process. Extended reports together with the failure distribution might enable the derivation of prioritization factors. The usage of existing prioritization approaches, such as the techniques for selecting cost-effective test cases shown by Elbaum [22], is conceivable. One could then focus or prioritize testing on those types of failures that are most critical based on their frequency and these additional parameters. For this purpose, coverage criteria and prioritization techniques are currently being examined to check which of them, if any, can be used for our purposes. This classification could be applied to future automotive infotainment systems to analyze changes of the failure focus.

Another part of future work will be to analyze whether our defined classification scheme and the ascertained distribution of failures could be combined with fault seeding approaches, which are used to measure and predict reliability. One of the most popular fault seeding models is the hypergeometric model by Harlan D. Mills [23]. According to [24] and [25], fault seeding is based on seeding a known number of faults in a software program whose total number of faults is unknown. After testing the software, the comparison of the number of "found seeded faults" and "found indigenous faults" allows estimating the number of remaining faults. In the case of [23], estimation is realized by using the hypergeometric distribution. Related work like [26], [27] and [28] focus on the described principle "with the purpose of simulating the occurrence of real software faults" [29]. Andrews [30] shows that generated mutants are similar to real faults and consequently claims that mutation operators yield trustworthy results. Based on Andrews, the work of [31] is about adding numerous faults for each module by selecting mutation operators simultaneously applied to the source code. This results in a single high-order mutant that represents the faulty version of the system. The approach performs a "1/10 sampling" to limit the number of seeded faults. This means that 10% of the maximum number of the calculated faults – e.g., faults regarding the logical operators or any constants – are seeded into the system.

The knowledge of the classified distribution of faults could improve fault seeding approaches by considering the known fault rates during the seeding process. However, the analyzed reports in our work contain the description of failures and not faults. Due to the fact that the origin of a failure is always a fault and that fault seeding is based on faults and not failures, traceability between faults and failures (through errors) is necessary to obtain the benefits of a known classified distribution of failures. An enabler for these benefits could be failure proximity approaches, which identify failing traces and group traces to the same fault together. [32] regards "two failing traces as similar if they suggest roughly the same fault location" and assumes that collecting failing traces can support developers, respectively testers, in prioritizing and diagnosing faults. In conclusion, our classified distribution of failures could support the effectiveness of fault seeding approaches. Applications will follow.

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Linear Constraints and Guarded Predicates as a Modeling Language for Discrete Time Hybrid Systems

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***Abstract*—Model based design is particularly appealing in *software based control systems* (e.g., *embedded software*) design, since in such a case system level specifications are much easier to define than the control software behavior itself. In turn, model based design of embedded systems requires modeling both continuous subsystems (typically, the plant) as well as discrete subsystems (the controller). This is typically done using *hybrid systems*. Mixed Integer Linear Programming (MILP) based abstraction techniques have been successfully applied to automatically synthesize correct-by-construction control software for *discrete time linear hybrid systems*, where plant dynamics is modeled as a linear predicate over state, input, and next state variables. Unfortunately, MILP solvers require such linear predicates to be conjunctions of linear constraints, which is not a natural way of modeling hybrid systems. In this paper we show that, under the hypothesis that each variable ranges over a bounded interval, any linear predicate built upon conjunction and disjunction of linear constraints can be automatically translated into an equivalent conjunctive predicate. Since variable bounds play a key role in this translation, our algorithm includes a procedure to compute all implicit variable bounds of the given linear predicate. Furthermore, we show that a particular form of linear predicates, namely *guarded predicates*, are a natural and powerful language to succinctly model discrete time linear hybrid systems dynamics. Finally, we experimentally show the feasibility of our approach on an important and challenging case study taken from the literature, namely the multi-input Buck DC-DC Converter. As an example, the guarded predicate that models (with 57 constraints) a 6-inputs Buck DC-DC Converter is translated in a conjunctive predicate (with 102 linear constraints) in about 40 minutes.**

***Keywords*-Model-based software design; Linear predicates; Hybrid systems**

I. Introduction

Many embedded systems are *Software Based Control Systems* (SBCS). An SBCS consists of two main subsystems: the *controller* and the *plant*. Typically, the plant is a physical system consisting, for example, of mechanical or electrical devices, while the controller consists of control software running on a microcontroller. In an endless loop, each T seconds (*sampling time*), the controller, after an *Analog-to-Digital* (AD) conversion (*quantization*), reads sensor outputs from the plant and, possibly after a *Digital-to-Analog* (DA) conversion, sends commands to plant actuators. The controller selects commands in order to guarantee that the *closed loop system* (that is, the system consisting of both plant and controller) meets given safety and liveness specifications (*system level specifications*).

This paper is an extension of the ICSEA 2012 paper [1], and contributes to *model based design* of embedded software [2]. Software generation from models and formal specifications forms the core of model based design of embedded software. This approach is particularly interesting for SBCSs, since in such a case system level specifications are much easier to define than the control software behavior itself. In this setting, correct-by-construction software generation from (as well as formal verification of) system level specifications for SBCSs requires modeling both the continuous subsystem (the plant) and discrete systems (the controller). This is typically done using *hybrid systems* (e.g., see [3][4]). Here we focus on *Discrete Time Linear Hybrid Systems* (DTLHS) [5][6] which provide an expressive model for closed loop systems. A DTLHS is a discrete time hybrid system whose dynamics is defined as a linear predicate (i.e., a boolean combination of linear constraints) on its continuous as well as discrete (modes) variables. A large class of hybrid systems, including mixed-mode analog circuits, can be modeled using DTLHSs. System level safety as well as liveness specifications are modeled as set of states defined, in turn, as linear predicates. Moreover, discrete time non-linear hybrid systems may be properly overapproximated with DTLHSs [7] in such a way that a controller for the overapproximated system is guaranteed to work also for the original non-linear system.

In our previous work [8][9], stemming from a constructive sufficient condition for the existence of a quantized sampling controller for an SBCS modelled as a DTLHS (which is an undecidable problem [10]), we presented an algorithm that, given a DTLHS model $\mathcal{H}$ for the plant, a quantization schema (i.e., how many bits we use for AD conversion) and system level specifications, returns the C code [11] of a correct-by-construction quantized feedback *control software* (if any) meeting the given system level specifications. The synthesis algorithm rests on the fact that, because of the quantization process, the plant P is seen by the controller as a *Nondeterministic Finite State Automaton* (NFSA) $\hat{P}$, that

is an abstraction of P. The NFSA $\hat{P}$ is computed by solving *Mixed Integer Linear Programming* (MILP) problems which contains the definition of the DTLHS dynamics as a sub-problem. Since available MILP solvers (e.g., GLPK [12] and CPLEX [13]) require conjunctive predicates (i.e., a conjunction of linear constraints) as input, we have that the DTLHS dynamics must be given as a conjunctive predicate.

While this is not a limitation for DTLHSs with a not too complex dynamics, this may turn in an obstruction for more complex systems. As an example, the dynamics of the 6-inputs Buck DC-DC Converter of Section VII-A is described by the conjunction of 102 linear constraints. However, by allowing disjunction, the same dynamics may be written as a linear predicate consisting of 45 linear constraints. Moreover, constants occurring in such a linear constraint are directly linked to the system physical (known) parameters, while the ones in the conjunctive predicate must be suitably computed. This results in a practical limitation for the effective application of the method in [8][9].

This paper is motivated by circumventing such a limitation, by showing that, under the hypothesis that each variable ranges over a bounded interval, any linear predicate can be automatically translated into an equivalent conjunctive predicate.

Note that it is a reasonable hypothesis to assume variables describing a DTLHS behavior to be bounded. In fact, control software drives the plant towards a goal, while keeping it inside a given desired bounded admissible region. Namely, bounds on present state variables essentially model the *sensing region*, that is the range of values observable by the sensors. Such a region is usually a bounded rectangular region (i.e., the Cartesian product of bounded intervals). Bounds on controllable input variables model the *actuation region*, that is the range of values of commands that the actuators may send to the plant and it is also typically a bounded rectangular region. Other variables may model both non-observable plant state variables and uncontrollable inputs (i.e., disturbances). Therefore, bounds on such variables are usually derived from reasonable assumptions or DTLHS knowledge. On the other hand, *next state* variable bounds are typically not explicitly given. However, they may be derived from all other above mentioned variable bounds (as it will be shown in Example 4 of Section V).

Finally, note that the application of the methods outlined here is not limited to the scenario shown above, but may be applied to nearly all possible usages of MILP solvers in any field.

A. Our Main Contributions

In this paper, we give an algorithm to translate any *linear predicate* into an equivalent (as for solving MILP problems, as it will be shown in Proposition 1 of Section II-B) *conjunctive predicate*, i.e., a conjunction of linear constraints. This allows us to circumvent the limitation mentioned above, i.e., that conjunctive predicates must be used to describe DTLHSs dynamics.

We consider predicates built upon conjunctions and disjunctions of linear constraints (i.e., inequalities of the shape $\sum_{i=1}^{n} a_i x_i \leq b$, Section II). In order to translate them into a conjunctive predicate, we employ a two-stage approach. First, we show that, at the price of introducing fresh boolean variables, a predicate can be translated into an equivalent *guarded predicate* (Section IV-A), i.e., a conjunction of *guarded constraints* of the shape $y \rightarrow (\sum_{i=1}^{n} a_i x_i \leq b)$. Guarded predicates themselves are shown to be a powerful means of modeling DTLHSs dynamics in Section VI. Second, once a guarded predicate has been obtained (or a guarded predicate has been directly provided as the input DTLHS model), we show that it can be in turn translated into a conjunctive predicate (Section IV-B). This latter translation needs, as a further input, the (finite) upper and lower bounds for each variable in the predicate. To this end, in Section V we give an algorithm that computes bounds for a variable x in a given guarded predicate $G(X)$, i.e., either it returns two values $m_x, M_x \in \mathbb{R}$ such that if $G(X)$ holds, then $m_x \leq x \leq M_x$, or it concludes that such values do not exist.

An experimental evaluation of the translation algorithm presented in this paper is in Section VII. As an example, we show that the linear predicate that models a 4-inputs Buck DC-DC Converter with 39 linear constraints is translated into a conjunctive predicate of 82 linear constraints in slightly more than 3 hours.

Note that there are two available inputs for our translation algorithm: i) a linear predicate or ii) a guarded predicate. Namely, if a guarded predicate is provided as input, only the second stage mentioned above is performed. Our experimental evaluation also shows that it is more convenient to use guarded predicates instead of linear predicates when modeling DTLHSs dynamics. As an example, the guarded predicate that models a 6-inputs Buck DC-DC Converter with 57 constraints (including 12 different guards), is translated into a conjunctive predicate of 102 linear constraints in about 40 minutes.

B. Paper Outline

The paper is organized as follows. Section II provides the basic definitions to understand our approach. In Section III, we formally define DTLHSs. In Section IV, our two-steps approach (from linear predicates to guarded predicates and then to conjunctive predicates) is outlined, assuming variables bounds to be known. In Section V, we show how we automatically compute bounds for all variables in a guarded predicate, thus completing the description of our approach. Section VI shows that guarded predicates are a powerful and natural modeling language for DTLHSs. Section VII shows experimental results on a meaningful case study,

namely the multi-input Buck DC-DC Converter. Finally, Sections VIII and IX conclude the paper, by comparing the approach presented here with previous work and by providing concluding remarks and future work.

II. Basic Definitions

An initial segment $\{1, \ldots, n\}$ of $\mathbb{N}$ is denoted by $[n]$. We denote with $X = [x_1, \ldots, x_n]$ a finite sequence of distinct variables, that we may regard, when convenient, as a set. Each variable x ranges on a known (bounded or unbounded) interval $\mathcal{D}_x$ either of the reals (continuous variables) or of the integers (discrete variables). The set $\prod_{x \in X} \mathcal{D}_x$ is denoted by $\mathcal{D}_X$. Boolean variables are discrete variables ranging on the set $\mathbb{B} = \{0, 1\}$. If x is a boolean variable we write $\bar{x}$ for $(1 - x)$. The sequence of continuous (discrete, boolean) variables in X is denoted by X^r (X^d, X^b).

The set of sequences of n boolean values is denoted by $\mathbb{B}^n$. The set $\mathbb{B}^n_k \subseteq \mathbb{B}^n$ denotes sequences that contains exactly k elements equal to 1. Given $a, b \in \mathbb{B}^n$, we say that $a \leq b$ if a is point-wise less or equal to b, i.e., if for all $i \in [n]$ we have that $a_i \leq b_i$. Given a set $B \subseteq \mathbb{B}^n$ and $a \in \mathbb{B}^n$ we write $a \leq B$ if there exists $b \in B$ such that $a \leq b$ and $a \geq B$ if there exists $b \in B$ such that $a \geq b$. We denote with $\mathrm{Ones}(b)$ be the set of indexes such that $b_j = 1$, i.e., $\mathrm{Ones}(b) = \{j \in [n] \mid b_j = 1\}$.

A. Predicates

A *linear expression* $L(X) = \sum_{i=1}^{n} a_i x_i$ is a linear combination of variables in X with rational coefficients. A *constraint* is an expression of the form $L(X) \leq b$, where b is a rational constant. We write $L(X) \geq b$ for $-L(X) \leq -b$, $L(X) = b$ for $(L(X) \leq b) \wedge (-L(X) \leq -b)$, and $a \leq L(X) \leq b$ for $(L(X) \leq b) \wedge (L(X) \geq a)$.

(Linear) predicates are inductively defined as follows. A constraint $C(X)$ is a predicate over X. If $A(X)$ and $B(X)$ are predicates, then $(A(X) \wedge B(X))$ and $(A(X) \vee B(X))$ are predicates over X. Parentheses may be omitted, assuming usual associativity and precedence rules of logical operators. A *conjunctive predicate* is a conjunction of constraints.

A *valuation* over X is a function v that maps each variable $x \in X$ to a value $v(x)$ in $\mathcal{D}_x$. We denote with $X^* \in \mathcal{D}_X$ the sequence of values $v(x_1), \ldots, v(x_n)$. We call valuation also the sequence of values X^*. Given a valuation X^*, the value for variable x is $X^*(x)$. Given a predicate $P(Y, X)$, $P(Y, X^*)$ denotes the predicate obtained by replacing each occurrence of x with $X^*(x)$. A *satisfying assignment* to a predicate $P(X)$ is a valuation X^* such that $P(X^*)$ holds. A predicate is said to be *satisfiable* if there exists at least one satisfying assignment. Abusing notation, we denote with P also the set of satisfying assignments to the predicate P. $P(X)$ and $Q(X)$ are *equivalent*, notation $P \equiv Q$, if they have the same set of satisfying assignments. $P(X)$ and $Q(Z)$ are *equisatisfiable*, notation $P \simeq Q$, if P is satisfiable if and only if Q is satisfiable. Finally, two predicates $P(X)$ and $Q(X, Z)$ are X-*equivalent*, notation $P \equiv_X Q$, if the following holds for all valuations X^*, Z^*:

1) if $P(X^*)$ holds, then $Q(X^*, Z)$ is satisfiable;
2) if $Q(X^*, Z^*)$ holds, then $P(X^*)$ holds.

B. Mixed Integer Linear Programming

A *Mixed Integer Linear Programming* (MILP) problem with *decision variables* X is a tuple $(\max, J(X), A(X))$ where X is a list of variables, $J(X)$ (*objective function*) is a linear expression over X, and $A(X)$ (*constraints*) is a predicate over X. A *solution* to $(\max, J(X), A(X))$ is a valuation X^* such that $A(X^*)$ and $\forall Z\,(A(Z) \rightarrow (J(Z) \leq J(X^*)))$. $J(X^*)$ is the *optimal value* of the MILP problem. A *feasibility* problem is a MILP problem of the form $(\max, 0, A(X))$. We write also $A(X)$ for $(\max, 0, A(X))$. In algorithm outlines, MILP solver invocations are denoted by function *feasible*$(A(X))$ that returns 1 if $A(X)$ is satisfiable and 0 otherwise, and by function *optimalValue*$(\max, J(X), A(X))$ that returns either the optimal value of the MILP problem $(\max, J(X), A(X))$ or ∞ if such MILP problem is unbounded. We write $(\min, J(X), A(X))$ for $(\max, -J(X), A(X))$.

Note that available MILP solvers (e.g., GLPK [12] or CPLEX [13]) require $A(X)$ to be a conjunctive predicate. However, as explained in Section I, MILP problems arising in methods like [8][9] are more easily represented as linear predicates. Thus, we need a translation algorithm from a linear predicate A to a conjunctive predicate A' such that a solution to $(\max, J, A')$ (which may be computed by a MILP solver) is also a solution to $(\max, J, A)$ (which may not be computed by a MILP solver). To this end, Proposition 1 clarifies that X-equivalence between predicates must be sought.

Proposition 1: Let $(\max, J(X), A(X))$ be a MILP problem, let $B(X, Z)$ be a conjunctive predicate which is X-equivalent to $A(X)$ and let $\tilde{J}(X, Z) = J(X) + \sum_{z \in Z} 0z$. Then for all solutions X^*, Z^* of $(\max, \tilde{J}(X, Z), B(X, Z))$, X^* is a solution of $(\max, J(X), A(X))$. Moreover, for all solutions X^* of $(\max, J(X), A(X))$, there exists Z^* such that X^*, Z^* is a solution of $(\max, \tilde{J}(X, Z), B(X, Z))$. Finally, *optimalValue*$(\max, J(X), A(X))$ = *optimalValue*$(\max, \tilde{J}(X, Z), B(X, Z))$.

Proof: Let X^*, Z^* be a solution of $(\max, \tilde{J}(X, Z), B(X, Z))$. This entails that $B(X^*, Z^*)$ holds, and that $\forall X^+, Z^+$ such that $B(X^+, Z^+)$ holds, $\tilde{J}(X^*, Z^*) \geq \tilde{J}(X^+, Z^+)$. Suppose by absurd that X^* is not a solution for $(\max, J(X), A(X))$. Then, either i) $A(X^*)$ does not hold or ii) there exist $\tilde{X}$ such that $A(\tilde{X})$ holds and $J(X^*) < J(\tilde{X})$. Case i) is not possible, since $B(X^*, Z^*)$ holds and $B(X, Z)$ is X-equivalent to $A(X)$. Case ii) is not possible since, by X-equivalence of $B(X, Z)$ and $A(X)$ and by definition of $\tilde{J}(X, Z)$, there would exist $\tilde{Z}$ such that $B(\tilde{X}, \tilde{Z})$ holds and $\tilde{J}(\tilde{X}, \tilde{Z}) = J(\tilde{X}) > J(X^*) = \tilde{J}(X^*, Z^*)$.

With a similar reasoning, it is possible to prove the other implication. Finally, equality of optimal values immediately follows from solutions equivalence and definition of $\tilde{J}$.

■

As a consequence of Proposition 1, the translation algorithm we need must take as input a linear predicate $P(X)$ and return as output an X-equivalent conjunctive predicate $Q(X, Z)$. In the following sections, we will show how we achieve this goal.

III. Discrete Time Linear Hybrid Systems

Discrete Time Linear Hybrid Systems (DTLHS) provide a suitable model for many SBCS (including embedded control systems) since they can effectively model linear algebraic constraints involving both continuous as well as discrete variables. This is shown, e.g., in Example 1, that presents a DTLHS model of a buck DC-DC converter, i.e., a mixed-mode analog circuit that converts the *Direct Current* (DC) input voltage to a desired DC output voltage.

Definition 1: A *Discrete Time Linear Hybrid System* is a tuple $\mathcal{H} = (X, U, Y, N)$ where:

- $X = X^r \cup X^d$ is a finite sequence of real and discrete *present state* variables. X' denotes the sequence of *next state* variables obtained by decorating with $'$ variables in X.
- $U = U^r \cup U^d$ is a finite sequence of *input* variables.
- $Y = Y^r \cup Y^d$ is a finite sequence of *auxiliary* variables. Auxiliary variables typically models *modes* (switching elements) or *uncontrollable inputs* (e.g., disturbances).
- $N(X, U, Y, X')$ is a predicate over $X \cup U \cup Y \cup X'$ defining the *transition relation* (*next state*) of the system.

Example 1: The buck DC-DC converter [15] is a mixed-mode analog circuit (Figure 1) converting the DC input voltage (V_i in Figure 1) to a desired DC output voltage (v_O in Figure 1). Buck DC-DC converters are used off-chip to scale down the typical laptop battery voltage (12-24) to the just few volts needed by the laptop processor (e.g., see [15]) as well as on-chip to support *Dynamic Voltage and Frequency Scaling* (DVFS) in multi-core processors. (e.g., see [14]). Because of its widespread use, control schemes for buck DC-DC converters have been widely studied (e.g., see [14][15][16]). The typical software based approach (e.g., see [15]) is to control the switch u in Figure 1 (typically implemented with a MOSFET, i.e., a *Metal-Oxide-Semiconductor Field-Effect Transistor*) with a microcontroller.

The circuit in Figure 1 can be modeled as a DTLHS $\mathcal{H} = (X, U, Y, N)$ as follows. The circuit state variables are i_L and v_C. However we can also use the pair i_L, v_O as state variables in $\mathcal{H}$ model since there is a linear relationship between i_L, v_C and v_O, namely: $v_O = \frac{r_C R}{r_C+R} i_L + \frac{R}{r_C+R} v_C$. Such considerations lead us to the following DTLHS model

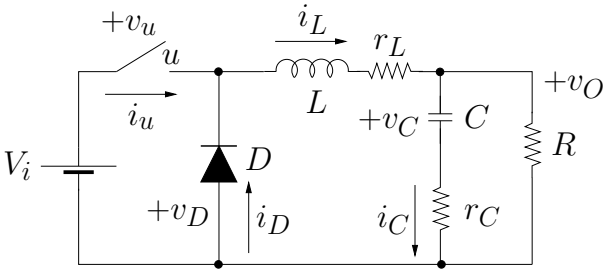

Figure 1. Buck DC-DC converter

$\mathcal{H}$: $X = X^r = [i_L, v_O]$, $U = U^d = [u]$, $Y = Y^r \cup Y^d$ where $Y^r = [i_u, v_u, i_D, v_D]$ and $Y^d = [q]$. Note how $\mathcal{H}$ auxiliary variables Y stem from the constitutive equations of the switching elements (i.e., the switch u and the diode D in Figure 1). From a simple circuit analysis (e.g., see [17]) we have the following equations:

$$\dot{i_L} = a_{1,1} i_L + a_{1,2} v_O + a_{1,3} v_D \quad (1)$$

$$\dot{v_O} = a_{2,1} i_L + a_{2,2} v_O + a_{2,3} v_D \quad (2)$$

where the coefficients $a_{i,j}$ depend on the circuit parameters R, r_L, r_C, L and C as follows: $a_{1,1} = -\frac{r_L}{L}$, $a_{1,2} = -\frac{1}{L}$, $a_{1,3} = -\frac{1}{L}$, $a_{2,1} = \frac{R}{r_c+R}[-\frac{r_c r_L}{L} + \frac{1}{C}]$, $a_{2,2} = \frac{-1}{r_c+R}[\frac{r_c R}{L} + \frac{1}{C}]$, $a_{2,3} = -\frac{1}{L}\frac{r_c R}{r_c+R}$. Using a discrete time model with sampling time T and writing x' for $x(t+1)$, we have:

$$i'_L = (1 + T a_{1,1}) i_L + T a_{1,2} v_O + T a_{1,3} v_D \quad (3)$$

$$v'_O = T a_{2,1} i_L + (1 + T a_{2,2}) v_O + T a_{2,3} v_D. \quad (4)$$

The algebraic constraints stemming from the constitutive equations of the switching elements are the following:

$$v_D = v_u - V_i \quad (5) \qquad (u = 1) \vee (v_u = R_{\text{off}} i_u) \quad (7)$$

$$i_D = i_L - i_u \quad (6) \qquad (u = 0) \vee (v_u = 0) \quad (8)$$

$$((i_D \geq 0) \wedge (v_D = 0)) \vee ((i_D \leq 0) \wedge (v_D = R_{\text{off}} i_D)) \quad (9)$$

The transition relation N of $\mathcal{H}$ is given by the conjunction of the linear predicates (3)–(9).

IV. From Linear to Conjunctive Predicates

As shown in [8][9], MILP solvers can be used to build a suitable discrete abstraction of a DTLHS. As shown in Sections I and II-B (especially in Proposition 1), in order to do this we need a translation algorithm from linear predicates to X-equivalent conjunctive predicates. In this section, we show how we achieve this goal, by designing a two-steps algorithm. First, in Section IV-A, we introduce *guarded predicates* and we show that each predicate $P(X)$ can be translated into an X-equivalent guarded predicate $Q(X, Z)$ at the price of introducing new auxiliary boolean variables Z. Then, in Section IV-B, we show that, under the hypothesis that each variable ranges over a bounded interval, each guarded predicate can be in turn translated into an equivalent conjunctive predicate.

A. Guarded Predicates

As formalized in Definition 2, a *guarded predicate* is an implication between a boolean variable (*guard*) and a predicate.

Definition 2: Given a predicate $P(X)$ and a fresh boolean variable $z \notin X$, the predicate $z \rightarrow P(X)$ (resp. $\bar{z} \rightarrow P(X)$) denotes the predicate $(z = 0) \vee P(X)$ (resp. $(z = 1) \vee P(X)$). We call z the *guard variable* and both z and $\bar{z}$ *guard literals*. Let $C(X)$ be a constraint. A predicate of the form $z \rightarrow C(X)$ or $\bar{z} \rightarrow C(X)$ is called *guarded constraint*. A predicate of the form $z \rightarrow C(X)$ is called *positive guarded constraint*, whilst a predicate of the form $\bar{z} \rightarrow C(X)$ is called *negative guarded constraint*. A *generalized guarded constraint* is a predicate of the form $z_1 \rightarrow (z_2 \rightarrow \ldots \rightarrow (z_n \rightarrow C(X))\ldots)$ A *guarded predicate* (resp. *generalized* guarded predicate, *positive* guarded predicate) is a conjunction of either constraints or guarded constraints (resp. generalized guarded constraints, positive guarded constraints).

To simplify proofs and notations, without loss of generality, we always assume guard literals to be distinct: a conjunction $z \rightarrow C_1(X) \wedge z \rightarrow C_2(X)$ is X-equivalent to the guarded predicate $z_1 \rightarrow C_1(X) \wedge z_2 \rightarrow C_2(X) \wedge z_1 = z \wedge z_2 = z$, being z_1, z_2 fresh boolean variables. Moreover, in algorithm outlines, conjunctive (resp., guarded) predicates will be sometimes regarded as sets of linear (resp., guarded) constraints.

By applying standard propositional equivalences, we have the following facts.

Fact 2: A predicate of the form $z \rightarrow \bigwedge_{i\in[n]} P_i(X)$ is equivalent to the predicate $\bigwedge_{i\in[n]}(z \rightarrow P_i(X))$.

Fact 3: A generalized guarded constraint $z_1 \rightarrow (z_2 \rightarrow \ldots \rightarrow (z_n \rightarrow C(X))\ldots)$ is X-equivalent to the positive guarded predicate $(z - \sum_{i\in[n]} z_i \geq 1 - n) \wedge (z \rightarrow C(X))$, where z is a fresh boolean variable.

Proof: Let z be a fresh boolean variable. We have:

$$
\begin{aligned}
& z_1 \rightarrow (z_2 \rightarrow \ldots \rightarrow (z_n \rightarrow C(X))\ldots) \\
& \equiv z_1 \wedge z_2 \wedge \ldots \wedge z_n \rightarrow C(X) \\
& \equiv_X ((z_1 \wedge z_2 \wedge \ldots \wedge z_n) \rightarrow z) \wedge (z \rightarrow C(X)) \\
& \equiv (\bar{z}_1 \vee \bar{z}_2 \vee \ldots \vee \bar{z}_n \vee z) \wedge (z \rightarrow C(X)) \\
& \equiv z + \textstyle\sum_{i\in[n]}(1 - z_i) \geq 1 \wedge (z \rightarrow C(X)) \\
& \equiv (z - \textstyle\sum_{i\in[n]} z_i \geq 1 - n) \wedge (z \rightarrow C(X))
\end{aligned}
$$

■

Lemma 4 and its constructive proof allow us to translate any predicate $P(X)$ to an X-equivalent generalized guarded predicate $Q(X, Z)$.

Lemma 4: For all predicates $P(X)$, there exists a predicate $Q(X, Z) = G(X, Z) \wedge D(Z)$ such that:

1) $P(X)$ is X-equivalent to $Q(X, Z)$;
2) $G(X, Z)$ and $D(Z)$ (and hence $Q(X, Z)$) are generalized guarded predicates;
3) each generalized guarded constraint in $G(X, Z)$ is of the form $z_1 \rightarrow z_2 \rightarrow \ldots \rightarrow z_m \rightarrow C(X)$, with $z_i \in Z$ and $z_i \notin X$ for all $i \in [m]$.

Proof: The proof is by induction on the structure of the predicate $P(X)$.

- Case $P(X) = C(X)$ for some linear constraint $C(X)$ (base of the induction). Then the thesis holds with $G(X, Z) = P(X)$, $D(Z) = 1$ and $Z = \varnothing$.
- Case $P(X) = P_1(X) \wedge P_2(X)$ for some predicates $P_1(X), P_2(X)$. By inductive hypothesis there exist $Z_1, Z_2, G_1(X, Z_1), D_1(X, Z_1), G_2(X, Z_2), D_2(X, Z_2)$ such that P_i is X-equivalent to $G_i(X, Z_i) \wedge D_i(Z_i)$ for all $i \in \{1, 2\}$. This entails that $P(X)$ is X-equivalent to $G_1(X, Z_1) \wedge G_2(X, Z_1) \wedge D_1(Z_1) \wedge D_2(Z_1)$. By taking $Z = Z_1 \cup Z_2$, $G(X, Z) = G_1(X, Z_1) \wedge G_2(X, Z_2)$ and $D(X, Z) = D_1(Z_1) \wedge D_2(Z_2)$, and recalling that by inductive hypothesis G_i, D_i are generalized guarded predicates and Z_i is the set of boolean variables that occur positively as guards in G_i (for all $i \in \{1, 2\}$), the thesis follows.
- Case $P(X) = P_1(X) \vee P_2(X)$ for some predicates $P_1(X), P_2(X)$. By inductive hypothesis there exist $Z_1, Z_2, G_1(X, Z_1), D_1(X, Z_1), G_2(X, Z_2), D_2(X, Z_2)$ such that P_i is X-equivalent to $Q_i(X, Z_i) = G_i(X, Z_i) \wedge D_i(Z_i)$ for all $i \in \{1, 2\}$. We can always choose auxiliary boolean variables in such a way that $Z_1 \cap Z_2 = \varnothing$.
  Taken two fresh boolean variables $y_1, y_2 \notin Z_1 \cup Z_2$, the predicate $y_1 \rightarrow Q_1(X, Z_1) \wedge y_2 \rightarrow Q_2(X, Z_2) \wedge y_1 + y_2 \geq 1$ is X-equivalent to $P(X)$. For all $i \in \{1, 2\}$, the predicate $\tilde{Q}_i(X, Z_i, y_i) = y_i \rightarrow Q_i(X, Z_i) = y_i \rightarrow (G_i(X, Z_i) \wedge D_i(Z_i))$ is not a generalized guarded predicate. Since $G_i(X, Z_i)$ and $D_i(Z_i)$ are generalized guarded predicates by inductive hypothesis, we have that $G_i(X, Z_i) = \bigwedge_{j\in[n]} \tilde{G}_{i,j}(X, Z_i)$ and $D_i(Z_i) = \bigwedge_{j\in[p]} \tilde{D}_{i,j}(Z_i)$, being $\tilde{G}_{i,j}(X, Z_i), \tilde{D}_{i,j}(Z_i)$ generalized guarded constraints. This allows us to apply Fact 2 to $\tilde{Q}_i(X, Z_i, y_i)$, obtaining an equivalent predicate $R_i(X, Z_i, y_i) = (\bigwedge_{j\in[n]} y_i \rightarrow \tilde{G}_{i,j}(X, Z_i)) \wedge (\bigwedge_{j\in[p]} y_i \rightarrow \tilde{D}_{i,j}(Z_i))$. The thesis follows by taking $Z = Z_1 \cup Z_2 \cup \{y_1, y_2\}$, $G(X, Z) = \bigwedge_{i\in\{1,2\}}(\bigwedge_{j\in[n]} y_i \rightarrow \tilde{G}_{i,j}(X, Z_i))$, and $D(Z) = \bigwedge_{i\in\{1,2\}}(\bigwedge_{j\in[p]} y_i \rightarrow \tilde{D}_{i,j}(Z_i)) \wedge (y_1 + y_2 \geq 1)$. As for point 3, note that this is the only case in which generalized guarded constraints in $G(X, Z)$ are generated, and that the generation takes place by adding boolean fresh guards only. Being the starting predicate only dependent on X, also point 3 is proved.

■

Lemma 4 and its constructive proof are exploited in Algorithm 1, which takes as input a linear predicate $P(X)$ and outputs the generalized guarded predicates $G(X, Z)$ and $D(Z)$. The function *fresh*( ) returns at each invocation a

(globally) fresh variable. Correctness of Algorithm 1 is given as a corollary of Lemma 4.

Corollary 5: For all predicates $P(X)$, Algorithm 1 returns $\langle G, D, Z\rangle$ such that $G(X,Z) \wedge D(Z)$ is X-equivalent to P and fulfills all properties of Lemma 4.

Proposition 6 and its constructive proof allow us to translate any predicate $P(X)$ in an X-equivalent positive guarded predicate $Q(X,Z)$. Moreover, predicate $Q(X,Z)$ has a special form, i.e., it is the conjunction of two positive guarded predicates $G(X,\tilde{Z})$ and $D(Z)$, with $\tilde{Z} \subseteq Z$. This is accomplished by first translating $P(X)$ in an X-equivalent generalized guarded predicate $\tilde{Q}(X,\tilde{Z})$ by using Lemma 4.

Proposition 6: For all predicates $P(X)$, there exists an X-equivalent positive guarded predicate $Q(X,Z) = G(X,\tilde{Z}) \wedge D(Z)$, where G and D are positive guarded predicates and $\tilde{Z} \subseteq Z$.

Proof: Let $\tilde{Q}(X,Z_1) = \tilde{G}(X,Z_1) \wedge \tilde{D}(Z_1)$ be the generalized guarded predicate obtained by applying the proof of Lemma 4 (i.e., by applying Algorithm 1 to $P(X)$). Let $\tilde{G}(X,Z_1) = G_1(X,Z_1) \wedge \bigwedge_{i\in[n]}(z_{i,1} \rightarrow z_{i,2} \rightarrow \ldots z_{i,q_i} \rightarrow C_{i,1}(X)))$, being G_1 a positive guarded predicate. By Fact 3, $\tilde{G}(X,Z_1)$ is $(X \cup Z_1)$-equivalent to the positive guarded predicate $G_1(X,Z_1) \wedge \bigwedge_{i\in[n]}\left(\tilde{z}_i \rightarrow C_{i,1}(X) \wedge \tilde{z}_i - \sum_{j\in[q_i]} z_{i,j} \geq 1 - q_i\right)$, where $\tilde{z}_i \notin Z_1$ for all $i \in [n]$. Analogously, by Fact 3 $\tilde{D}(Z_1)$ is Z_1-equivalent to the positive guarded predicate $D_1(Z_1) \wedge \bigwedge_{i\in[p]}\left(\hat{z}_i \rightarrow C_{i,2}(Z_1) \wedge \hat{z}_i - \sum_{j\in[r_i]} z_{i,j} \geq 1 - r_i\right)$, where $\hat{z}_i \notin Z_1 \cup \{\tilde{z}_j \mid j \in [n]\}$ for all $i \in [p]$. Thus the thesis follows by taking:

- $\tilde{Z} = Z_1 \cup \{\tilde{z}_j \mid j \in [n]\}$
- $Z = \tilde{Z} \cup \{\hat{z}_j \mid j \in [p]\}$
- $G(X,\tilde{Z}) = G_1(X,Z_1) \wedge \bigwedge_{i\in[n]} \tilde{z}_i \rightarrow C_{i,1}(X)$
- $D(Z) = D_1(Z_1) \wedge \left(\bigwedge_{i\in[n]} \tilde{z}_i - \sum_{j\in[q_i]} z_{i,j} \geq 1 - q_i\right) \wedge \left(\bigwedge_{i\in[p]} \hat{z}_i \rightarrow C_{i,2}(Z_1) \wedge \hat{z}_i - \sum_{j\in[r_i]} z_{i,j} \geq 1 - r_i\right)$

■

Proposition 6 and its constructive proof are exploited in Algorithm 2, which takes as input a linear predicate $P(X)$ and outputs the positive guarded predicates $G(X,\tilde{Z})$ and $D(Z)$. To this aim, Algorithm 1 is used as an auxiliary procedure. Correctness of Algorithm 2 is given as a corollary of Proposition 6.

Corollary 7: For all predicates $P(X)$, Algorithm 2 returns $\langle G, D, \tilde{Z}, Z\rangle$ such that $G(X,\tilde{Z}) \wedge D(Z)$ is X-equivalent to P and $\tilde{Z} \subseteq Z$.

Example 2: Let $\mathcal{H}$ be DTLHS in Example 1. Given the predicate $N(X,U,Y,X')$ that defines the transition relation of $\mathcal{H}$, function *PtoG* computes the guarded predicate $N^{gp}(X,U,Y,X')$ which is $(X \cup U \cup Y \cup X')$-equivalent to N as follows.

Constraints (3)–(6) remain unchanged, as they are linear constraints in a top-level conjunction. The disjunction (9) is first replaced by the conjunction of linear predicates (10)–(12) as follows.

$$z_1 \rightarrow (i_D \geq 0 \wedge v_D = 0) \quad (10) \qquad z_2 \rightarrow (i_D \leq 0 \wedge v_D = R_{\text{off}} i_D) \quad (11)$$

$$z_1 + z_2 \geq 1 \quad (12)$$

Then, predicates (10)–(11) are replaced by guarded constraints (17)–(20) below, obtained by moving arrows inside the conjunctions, as shown by Fact 2. Similarly, disjunctions (7) and (8) are replaced by guarded linear constraints (21)–(24) and (26)–(27). Summing up, $N^{gp}(X,U,Y,X')$ is given by the conjunction of the following (guarded) constraints:

$$i'_L = (1 + Ta_{1,1}) i_L + Ta_{1,2} v_O + Ta_{1,3} v_D \quad (13)$$

$$v'_O = Ta_{2,1} i_L + (1 + Ta_{2,2}) v_O + Ta_{2,3} v_D. \quad (14)$$

$$v_D = v_u - V_i \quad (15) \qquad i_D = i_L - i_u \quad (16)$$

$$z_1 \rightarrow (i_D \geq 0) \quad (17) \qquad z_3 \rightarrow (u = 1) \quad (21)$$

$$z_1 \rightarrow (v_D = 0) \quad (18) \qquad z_4 \rightarrow (v_u = R_{\text{off}} i_u) \quad (22)$$

$$z_2 \rightarrow (i_D \leq 0) \quad (19) \qquad z_5 \rightarrow (u = 0) \quad (23)$$

$$z_2 \rightarrow (v_D = R_{\text{off}} i_D) \quad (20) \qquad z_6 \rightarrow (v_u = 0) \quad (24)$$

$$z_1 + z_2 \geq 1 \quad (25) \qquad z_3 + z_4 \geq 1 \quad (26) \qquad z_5 + z_6 \geq 1 \quad (27)$$

With respect to the statement of Proposition 6, we have that $Z = \tilde{Z} = \{z_1, z_2, z_3, z_4, z_5, z_6\}$, $G(X,Z')$ is the conjunction of guarded constraints (13)–(24) and $D(Z)$ is the conjunction of constraints (25)–(27).

Algorithm 1 From predicates to generalized guarded predicates (auxiliary for Algorithm 5)

Input: P predicate over X

Output: $\langle G, D, Z\rangle$ where $G(X,Z) \wedge D(Z)$ is a generalized guarded predicate X-equivalent to $P(X)$ (see Lemma 4)

function *PtoGG*(P, X)

1. **if** P is a constraint $C(X)$ **then return** $\langle C(X), \varnothing, \varnothing\rangle$
2. **let** $P = P_1 \diamond P_2 \quad (\diamond \in \{\wedge, \vee\})$
3. $\langle G_1, D_1, Z_1\rangle \leftarrow$ *PtoGG*(P_1)
4. $\langle G_2, D_2, Z_2\rangle \leftarrow$ *PtoGG*(P_2)
5. **if** $P = P_1 \wedge P_2$ **then return** $\langle G_1 \cup G_2, D_1 \cup D_2, Z_1 \cup Z_2\rangle$
6. **if** $P = P_1 \vee P_2$ **then**
7. $\quad y_1 \leftarrow$ *fresh*( ), $y_2 \leftarrow$ *fresh*( ), $\tilde{Z} \leftarrow Z_1 \cup Z_2 \cup \{y_1, y_2\}$
8. $\quad \tilde{D} = \{y_1 \rightarrow \gamma \mid \gamma \in D_1\} \cup \{y_2 \rightarrow \gamma \mid \gamma \in D_2\} \cup \{y_1 + y_2 \geq 1\}$
9. $\quad \tilde{G} = \{y_1 \rightarrow \gamma \mid \gamma \in G_1\} \cup \{y_2 \rightarrow \gamma \mid \gamma \in G_2\}$
10. $\quad$ **return** $\langle \tilde{G}, \tilde{D}, \tilde{Z}\rangle$

B. From Guarded Predicates to Conjunctive Predicates

Guarded predicates may be translated into equivalent conjunctive predicates (our final target for Proposition 1) once bounds for all variables occurring in them are known. In this section, we will show how this translation is performed, assuming bounds to be known. In Section V, we will show

Algorithm 2 From predicates to positive guarded predicates (auxiliary for Algorithm 5)

Input: P predicate over X

Output: $\langle G, D, Z, \tilde{Z}\rangle$ where $G(X, \tilde{Z}) \wedge D(Z)$ is a positive guarded predicate X-equivalent to $P(X)$ (see Proposition 6)

function *PtoG*(P, X)

1. $\langle G, D, Z\rangle \leftarrow$*PtoGG*$(P,\ X)$
2. $\tilde{G} \leftarrow \varnothing$, $\tilde{D} \leftarrow \varnothing$, $\tilde{Z} = Z$
3. **for all** $\gamma \in G \cup D$ **do**
4. **if** $\gamma \equiv z_1 \rightarrow (\ldots \rightarrow (z_n \rightarrow C(W))\ldots)$ **then**
5. $w \leftarrow$*fresh*$(\,)$, $Z \leftarrow Z \cup \{w\}$
6. **if** $W \subseteq X$ **then**
7. $\tilde{G} \leftarrow \tilde{G} \cup \{w \rightarrow C(W)\}$, $\tilde{Z} \leftarrow \tilde{Z} \cup \{w\}$
8. **else**
9. $\tilde{D} \leftarrow \tilde{D} \cup \{w \rightarrow C(W)\}$
10. $\tilde{D} \leftarrow \tilde{D} \cup \{w - \sum_{i\in[n]} z_i \geq 1 - n\}$
11. **else if** *vars*$(\gamma) \subseteq X$ **then**
12. $\tilde{G} \leftarrow \tilde{G} \cup \{\gamma\}$
13. **else**
14. $\tilde{D} \leftarrow \tilde{D} \cup \{\gamma\}$
15. **return** $\langle \tilde{G}, \tilde{D}, Z, \tilde{Z}\rangle$

how bounds for variables may be computed if some bounds are already known.

Definition 3: Let $P(X)$ be a predicate. A variable $x \in X$ is said to be *bounded* in P if there exist $a, b \in \mathcal{D}_x$ such that $P(X)$ implies $a \leq x \leq b$. A predicate P is bounded if all its variables are bounded. We write $\sup(P, x)$ and $\inf(P, x)$ for the minimum and maximum value that the variable x may assume in a satisfying assignment for P. When P is clear from the context, we will write simply $\sup(x)$ and $\inf(x)$.

Given a real number a and a variable $x \in X$ over a bounded interval, we write $\sup(ax)$ for $a\sup(x)$ if $a \geq 0$ and for $a\inf(x)$ if $a < 0$. We write $\inf(ax)$ for $a\inf(x)$ if $a \geq 0$ and for $a\sup(x)$ if $a < 0$. Given a linear expression $L(X) = \sum_{i=1}^{n} a_i x_i$ over a set of bounded variables, we write $\sup(L(X))$ for $\sum_{i=1}^{n} \sup(a_i x_i)$ and $\inf(L(X))$ for $\sum_{i=1}^{n} \inf(a_i x_i)$.

Proposition 8: For each bounded guarded predicate $P(X)$ there exists an equivalent conjunctive predicate $Q(X)$.

Proof: The conjunctive predicate $Q(X)$ is obtained from the guarded predicate $P(X)$ by replacing each guarded constraint $C(X)$ of the shape $z \rightarrow (L(X) \leq b)$ in $P(X)$ with the constraint $\tilde{C}(X) = (\sup(L(X)) - b)z + L(X) \leq \sup(L(X))$. If $z = 0$ we have $C(X) \equiv \tilde{C}(X)$ since $C(X)$ holds trivially and $\tilde{C}(X)$ reduces to $L(X) \leq \sup(L(X))$ that holds by construction. If $z = 1$ both $C(X)$ and $\tilde{C}(X)$ reduce to $L(X) \leq b$. Along the same line of reasoning, if $C(X)$ has the form $\bar{z} \rightarrow (L(X) \leq b)$ we set $\tilde{C}(X)$ to $(b - \sup(L(X)))z + L(X) \leq b$. ■

Together with Proposition 6, Proposition 8 implies that any bounded predicate $P(X)$ can be translated into an X-equivalent conjunctive predicate, at the cost of adding new auxiliary boolean variables, as stated in the following proposition.

Proposition 9: For each bounded predicate $P(X)$, there exists an X-equivalent conjunctive predicate $Q(X, Z)$.

Example 3: Let $\mathcal{H}$ be the DTLHS in Example 2. We set the parameters of $\mathcal{H}$ as follows:

$$\begin{array}{llll} r_L = 0.1\Omega & R = 5\Omega & V_i = 15V & L = 2\cdot 10^{-4}H \\ r_C = 0.1\Omega & R_{\text{off}} = 10^4 & T = 10^{-6}\text{secs} & C = 5\cdot 10^{-5}F \end{array}$$

and we assume variables bounds as follows:

$$\begin{array}{llll} -2{\cdot}10^4 \leq v_u \leq 15 & -4 \leq i_L \leq 4 & -1 \leq v_O \leq 7 & -4 \leq i'_L \leq 96 \\ -2{\cdot}10^4 \leq v_D \leq 0 & -1.1 \leq v'_O \leq 17 & -4 \leq i_u \leq 4 & -2 \leq i_D \leq 4 \end{array}$$

By first decomposing equations of the shape $L(X) = b$ in the conjunctive predicate $L(X) \leq b \wedge -L(X) \leq -b$ and then by applying the transformation given in the proof of Proposition 8, guarded constraints (17)–(24) are replaced by the following linear constraints:

$$2z_1 - i_D \leq 2 \quad (28)$$
$$4\cdot 10^4 z_4 + v_u - 10^4 i_u \leq 4\cdot 10^4 \quad (29)$$
$$6\cdot 10^4 z_4 - v_u + 10^4 i_u \leq 6\cdot 10^4 \quad (30)$$
$$-2.10^4 z_1 - v_D \leq 2\cdot 10^4 \quad (31)$$
$$2.10^4 z_2 + v_D - 10^4 i_D \leq 2.10^4 \quad (32)$$
$$6.10^4 z_2 - v_D + 10^4 i_D \leq 6.10^4 \quad (33)$$
$$2\cdot 10^4 z_6 + v_u \leq 15 \quad (34)$$
$$2\cdot 10^4 z_4 - v_u \leq 2\cdot 10^4 \quad (35)$$
$$v_D \leq 0 \quad (36)$$
$$4z_2 + i_D \leq 4 \quad (37)$$
$$z_5 + u \leq 1 \quad (38)$$
$$-u \leq 0 \quad (39)$$
$$15z_6 + v_u \leq 15 \quad (40)$$
$$z_3 - u \leq 1 \quad (41)$$
$$u \leq 1 \quad (42)$$

V. Computing Variable Bounds

In this section, we present two algorithms that check if a variable x is bounded in a guarded predicate $G(X, Z)$, where Z is the set of guard variables. If this is the case, both algorithms return BND (for *bounded*) and compute $a, b \in \mathcal{D}_X$ such that $G(X, Z)$ implies $a \leq x \leq b$. If this is not the case, then INFEAS (for *infeasible*) is returned if $G(X, Z)$ is unfeasible, and UNB (for *unbounded*) is returned otherwise.

The first algorithm, described in function *exhComputeBounds* of Algorithm 3, works for all guarded predicates $G(X, Z)$, where Z is the set of (boolean) variables occurring as guards in $G(X, Z)$. Namely, it is the naïve algorithm which, for all valuations Z^* of $\mathbb{B}^{|Z|}$ (line 5), builds the conjunctive predicate $Q(X) = G(X, Z^*)$. This implies that, for all guarded constraints $\tilde{G}(X, Z) = z \rightarrow C(X, Z)$ inside G, if $Z^*(z)$ is false then Q will not contain $\tilde{G}$, and will contain only $C(X, Z^*)$ otherwise (line 6). Then, if $G(X, Z^*)$ is feasible, the upper and lower bounds for x under $G(X, Z^*)$ are computed (lines 9 and 10). The overall maximum upper bound and minimum lower bound are finally returned in line 15. Unfortunately, this exhaustive procedure requires to solve $2^{|Z|}$ MILP problems.

The second algorithm, described in function *computeBounds* of Algorithm 4, refines Algorithm 3 in order to

Algorithm 3 Computing variable bounds in a guarded predicate (auxiliary for Algorithm 5 and 6)

Input: Guarded predicate $G(X, Z)$ and variable $x \in X$.
Output: $\langle \mu, \inf, \sup \rangle$ with $\mu \in \{\text{BND}, \text{UNBND}, \text{INFEAS}\}$, $\inf, \sup \in \mathcal{D}_x \cup \bot$.
function *exhComputeBounds*(G, X, Z, x)

1. **let** $G(X, Z) = \bigwedge_{i \in [n]} G_i(X, Z)$, being each $G_i(X, Z)$ either a constraint $C_i(X, Z)$ or a guarded constraint $z_i \to C_i(X, Z)$, $\bar{z}_i \to C_i(X, Z)$
2. **let** $g(i)$, for $i \in [n]$, be the guard of G_i, if any , or 1 otherwise
3. **let** $c(i, Z^*)$, for $i \in [n]$, be true iff $(g(i) = z_i \wedge Z^*(z_i) = 1) \vee (g(i) = \bar{z}_i \wedge Z^*(z_i) = 0) \vee g(i) = 1$
4. $\inf \leftarrow +\infty$, $\sup \leftarrow -\infty$, $f \leftarrow 0$
5. **for** $Z^* \in \mathbb{B}^{|Z|}$ **do**
6. $\quad Q(X, Z^*) \leftarrow \bigwedge_{i \in [n] \wedge c(i, Z^*)} C_i(X, Z^*)$
7. $\quad$ **if** *feasible*$(Q(X, Z^*))$ **then**
8. $\quad\quad f \leftarrow 1$
9. $\quad\quad M \leftarrow$ *optimalValue*$(\max, x, Q(X, Z^*))$
10. $\quad\quad m \leftarrow$ *optimalValue*$(\min, x, Q(X, Z^*))$
11. $\quad\quad$ **if** $M = \infty \vee m = \infty$ **then**
12. $\quad\quad\quad$ **return** $\langle \text{UNBND}, \bot, \bot \rangle$
13. $\quad\quad \sup \leftarrow \max(\sup, M)$, $\inf \leftarrow \min(\inf, m)$
14. **if** f **then**
15. $\quad$ **return** $\langle \text{BND}, \inf, \sup \rangle$
16. **else**
17. $\quad$ **return** $\langle \text{INFEAS}, \bot, \bot \rangle$

save unnecessary MILP invocations. Differently from Algorithm 3, Algorithm 4 works only in the case that the input is a positive guarded predicate of form $G(X, \tilde{Z}) \wedge D(Z)$, where $G(X, \tilde{Z})$ is a positive guarded predicate, $D(Z)$ is a conjunctive predicate, and $\tilde{Z} \subseteq Z$ is the set of (boolean) variables occurring as guards in $G(X, \tilde{Z})$. However, such form may be derived from the one output by Algorithm 2 (see Algorithm 5), thus we still have a method to translate any predicate into a conjunctive predicate.

Algorithm 4 is based on the observation that, if an assignment Z_1^* makes true more guards than an assignment Z_2^*, then the conjunctive predicate $G(X, Z_1^*)$ has more constraints than $G(X, Z_2^*)$. Therefore, if x is bounded in $G(X, Z_2^*)$, then it is also bounded in $G(X, Z_1^*)$, and if $G(X, Z_2^*)$ is unfeasible, then also $G(X, Z_1^*)$ is unfeasible (Proposition 10). In the following, we establish the correctness of function *computeBounds*. We begin with a proposition on fixing boolean values in a positive guarded predicate.

Proposition 10: Let $Z = [z_1, \ldots, z_n]$ and let $G(X, Z) = \bigwedge_{i \in [n]} (z_i \to C_i(X))$ be a conjunction of positive guarded constraints. Then:

1) For any $Z^* \in \mathbb{B}^n$, $G(X, Z^*)$ is equivalent to the conjunctive predicate $\bigwedge_{j \in \text{Ones}(Z^*)} C_j(X)$.
2) If $Z_1^* \leq Z_2^*$, then $G(X, Z_2^*) \Rightarrow G(X, Z_1^*)$.

Proof: Statement 1 easily follows by observing that a guarded constraint $z \to C(X)$ is trivially satisfied if z is assigned to 0 and it is equivalent to $C(X)$ if z is assigned to 1. Statement 2 follows from the observation that $a \leq b$ implies $\text{Ones}(a) \subseteq \text{Ones}(b)$ and hence $G(X, b)$ has more constraints than $G(X, a)$. ■

Algorithm 4 is based on the capability of operating *cuts* on the boolean space. Definition 4 formalizes this concept.

Definition 4: We say that a set $C \subseteq \mathbb{B}^n$ is a *cut* if for all $b \in \mathbb{B}^n$ we have $b \leq C$ or $b \geq C$. Let $D(Z)$ be a predicate over a set boolean variables $Z = Z_1 \cup Z_2$. A cut $C \subseteq \mathbb{B}^{|Z_2|}$ is (D, Z_2)-minimal if

- for all $c \in C$, $D(Z_1, c)$, is satisfiable
- for all $b < C$, $D(Z_1, b)$ is not satisfiable.

Proposition 11 shows how cuts are exploited by Algorithm 4. Namely, to verify that a variable x is bounded in the positive guarded predicate $G(X, \tilde{Z}) \wedge D(Z)$, where $D(Z)$ is a conjunctive predicate, it suffices to check if it is bounded in the conjunctive predicate $G(X, c)$, for all c that are $(D, \tilde{Z})$-minimal cuts.

Algorithm 4 Computing variable bounds in a positive guarded predicate (auxiliary for Algorithms 5 and 6)

Input: Positive guarded predicate $G(X, \tilde{Z})$, conjunctive predicate $D(Z)$ with $\tilde{Z} \subseteq Z$ set of guards in $G(X, \tilde{Z})$, and variable $x \in X$.
Output: $\langle \mu, \inf, \sup \rangle$ with $\mu \in \{\text{BND}, \text{UNBND}, \text{INFEAS}\}$, $\inf, \sup \in \mathcal{D}_x \cup \bot$.
function *computeBounds*$(G, D, X, Z, \tilde{Z}, x)$

1. $C \leftarrow \varnothing$, $r \leftarrow |\tilde{Z}|$, $\inf \leftarrow +\infty$, $\sup \leftarrow -\infty$, $f \leftarrow 0$
2. $r' \leftarrow$ *optimalValue*$(\min, \sum_{i \in [r]} z_i, D(Z))$
3. $r'' \leftarrow$ *optimalValue*$(\max, \sum_{i \in [r]} z_i, D(Z))$
4. **for** $k = r'$ **to** r'' **do**
5. $\quad end \leftarrow 1$
6. $\quad$ **for all** $b \in \mathbb{B}_k^r$ **do**
7. $\quad\quad$ **if** $C \not\leq b$ **then**
8. $\quad\quad\quad end \leftarrow 0$
9. $\quad\quad\quad$ **if** *feasible*$(D(Z, c))$ **then**
10. $\quad\quad\quad\quad C \leftarrow C \cup \{b\}$
11. $\quad\quad\quad\quad$ **if** *feasible*$(G(X, b))$ **then**
12. $\quad\quad\quad\quad\quad f \leftarrow 0$
13. $\quad\quad\quad\quad\quad M \leftarrow$ *optimalValue*$(\max, x, G(X, b))$
14. $\quad\quad\quad\quad\quad m \leftarrow$ *optimalValue*$(\min, x, G(X, b))$
15. $\quad\quad\quad\quad\quad$ **if** $M = \infty$ **or** $m = \infty$ **then**
16. $\quad\quad\quad\quad\quad\quad$ **return** $\langle \text{UNBND}, \bot, \bot \rangle$
17. $\quad\quad\quad\quad\quad \sup \leftarrow \max(\sup, M)$, $\inf \leftarrow \min(\inf, m)$
18. $\quad$ **if** end **then break**
19. **if** f **then**
20. $\quad$ **return** $\langle \text{BND}, \inf, \sup \rangle$
21. **else**
22. $\quad$ **return** $\langle \text{INFEAS}, \bot, \bot \rangle$

Proposition 11: Let $Q(X,Z) = G(X,\tilde{Z}) \wedge D(Z)$, where $G(X,\tilde{Z})$ is a positive guarded predicate, $D(Z)$ is a conjunctive predicate, and $\tilde{Z} \subseteq Z$ is the set of (boolean) variables occurring as guards in $G(X,\tilde{Z})$. Let C be a $(D,\tilde{Z})$-minimal cut and $x \in X$. If, for all $c \in C$, x is bounded in $G(X,c)$, then x is bounded in $Q(X,Z)$.

Proof: Since C is a $(D,\tilde{Z})$-minimal cut, any satisfying assignment (X^*,Z^*) to Q is such that $C \leq \tilde{Z}^*$. As a consequence, there exists $c \in C$ such that $c \leq \tilde{Z}^*$. Proposition 10 (point 2) implies that, for all $Z^* \geq C$, $\max\{x \mid G(X,Z^*)\} \leq \max\{x \mid G(X,c)\}$ and $\min\{x \mid G(X,Z^*)\} \geq \min\{x \mid G(X,c)\}$. Therefore, if x is bounded in $Q(X,c)$ for any $c \in C$, then it is bounded in $Q(X,Z)$. ■

Stemming from Proposition 11, function *computeBounds* (Algorithm 4) checks if a variable x is bounded in a guarded predicate by finding a minimal cut. To limit the search space, in line 2 (resp. line 3) it is computed the minimum (resp. maximum) number of 1 that a satisfying assignment to the predicate $D(Z)$ must have. The loop in lines 4–18 examines possible assignments to guard variables in Z, keeping the invariant $\forall b < C[\neg \mathit{feasibleG}(X,b)] \wedge \forall b \geq C[\max\{x \mid G(X,Z)\} \leq \max\{x \mid G(X,b)\} \wedge \min\{x \mid G(X,Z^*)\} \geq \min\{x \mid G(X,b)\}]$. In the loop in lines 6–17, if the assignment c under consideration is greater than an assignment in C, no further investigation are needed (by Proposition 11 x is bounded in $Q(X,c)$). If $D(Z \setminus \tilde{Z}, b)$ is unfeasible, the assignment c is not relevant, because $c \leq C$, for any $(D,\tilde{Z})$-minimal cut C. Otherwise, c is a relevant assignment and it is added to C (line 10). If x is unbounded in $Q(X,c)$ (lines 13 and 16) we can immediately conclude that x is unbounded in $Q(X,Z)$. Otherwise, we update the approximations computed for $\inf(x)$ and $\sup(x)$ (line 17). If for all assignments in $c \in \mathbb{B}^n_k$ we have $c \geq C$ ($\mathbb{B}^n_k$ is a cut) we are done, C is a $(D,\tilde{Z})$-minimal cut, and $\inf$ and $\sup$ computed so far are over-approximation of x bounds in $Q(X,Z)$ (line 18).

The above reasoning gives the proof of correctness for function *computeBounds* of Algorithm 4.

Proposition 12: Let $G(X,\tilde{Z})$ be a positive guarded predicate, $D(Z)$ be a conjunctive predicate, where $\tilde{Z}$ is the set of guards in $G(X,\tilde{Z})$ and $\tilde{Z} \subseteq Z$, and let $x \in X$. Then function *computeBounds* of Algorithm 4 returns:

- $\langle \textsc{UnBnd}, \bot, \bot \rangle$ if $G(X,\tilde{Z}) \wedge D(Z)$ is unbounded in x;
- $\langle \textsc{Infeas}, \bot, \bot \rangle$ if $G(X,\tilde{Z}) \wedge D(Z)$ is unfeasible;
- $\langle \textsc{Bnd}, a, b \rangle$ if $G(X,\tilde{Z}) \wedge D(Z)$ is bounded, where a, b are such that $G(X,\tilde{Z}) \wedge D(Z)$ implies $a \leq x \leq b$.

Example 4: In Example 3 we assumed bounds for each variable in the DTLHS $\mathcal{H}$ introduced in Example 1. Such bounds has been obtained by fixing bounds for state variables i_L and v_O and for auxiliary variables i_u, v_u, v_D and i_D, and then by computing bounds for variables i'_L, v'_O using Algorithm 4.

Algorithm 5 From predicates to conjunctive predicates

Input: P predicate over X and modality $\nu \in \{\textsc{Exh}, \textsc{Cut}\}$
Output: result μ and conjunctive predicate $C(X,Z)$ such that $C(X,Z)$ is X-equivalent to $P(X)$ if $P(X)$ is bounded.

function *PtoC*(P, X, ν)
1. $\langle G, D, Z, \tilde{Z} \rangle \leftarrow$*PtoG*$(P, X)$
2. $\tilde{D} \leftarrow$*GtoC*$(D, Z, \mathbf{0}, \mathbf{1})$
3. **for all** $x \in X$ **do**
4. **if** $\nu = \textsc{Cut}$ **then**
5. $\langle \mu, m_x, M_x \rangle \leftarrow$*computeBounds*$(G, \tilde{D}, X, Z, \tilde{Z}, x)$
6. **else**
7. $\langle \mu, m_x, M_x \rangle \leftarrow$*exhComputeBounds*$(G(X,\tilde{Z}) \wedge \tilde{D}(Z), X \cup Z, x)$
8. **if** $\mu \neq \textsc{Bnd}$ **then**
9. **return** $\langle \mu, \bot \rangle$
10. **return** $\langle \textsc{Bnd}, \mathit{GtoC}(G, X \cup Z, m, M) \rangle$

Function *PtoC* of Algorithm 5 presents the overall procedure that translates a bounded predicate $P(X)$ into an X-equivalent conjunctive predicate $C(X,Z)$. Function *PtoC* calls functions in Algorithms 1–4 and function *GtoC*(A, W, m, M), which translates a bounded guarded predicate $A(W)$ with known lower bounds m and upper bounds M for variables in W in a conjunctive predicate, as shown in the proof of Proposition 8. As a first step, Algorithm 5 translates the input predicate $P(X)$ into an X-equivalent guarded predicate $G(X,\tilde{Z}) \wedge D(Z)$ by calling the function *PtoG* (line 1). Since boolean variables are trivially bounded (bounds are vectors $\mathbf{0} = \langle 0, \ldots, 0 \rangle$ and $\mathbf{1} = \langle 1, \ldots, 1 \rangle$), the guarded predicate D can be translated into a conjunctive predicate $\tilde{D}$ by calling the function *GtoC* on D (line 2). To apply function *GtoC* on $G(X,\tilde{Z})$, we need bounds for each variable in X. These bounds are computed by calling $|X|$ times the function *computeBounds* and are stored in the two arrays m, M (lines 3 and 5). If the function *computeBounds* finds that $\tilde{G}$ is unfeasible or some x is not bounded in $\tilde{G}$ (line 8), the empty constraint is returned together with the failure explanation (line 9). Otherwise, the desired conjunctive predicate is returned in line 10.

Correctness of function *PtoC* of Algorithm 5 is stated in Proposition 13.

Proposition 13: Let $P(X)$ be a predicate. Then function *PtoC* of Algorithm 5 returns:

- $\langle \textsc{Unb}, \bot \rangle$ if $P(X)$ is unbounded for some $x \in X$;
- $\langle \textsc{Infeas}, \bot \rangle$ if $P(X)$ is unfeasible;
- $\langle \textsc{Bnd}, C(X,Z) \rangle$ if $P(X)$ is bounded, being $C(X,Z)$ a conjunctive predicate which is X-equivalent to $P(X)$.

Proof: The proof easily follows Propositions 5, 7, 8 and 12. ■

We end this section by proposing a syntactic check, that most of the time may be used to compute variable bounds

avoiding to use the function *computeBounds*.

Definition 5: A variable x is *explicitly bounded* in a predicate $P(X)$, if $P(X) = B(x) \wedge \tilde{P}(X)$, where $B(x) = x \leq b \wedge x \geq a$, for some constants a and b.

Proposition 14: Let $\mathcal{H} = (X, U, Y, N)$ be a DTLHS such that each variable $v \in X \cup U \cup Y$ is explicitly bounded in N, and for all $x' \in X'$ there are in N at least two constraints of the form $x' \geq L_1(X, U, Y)$ and $x' \leq L_2(X, U, Y)$. Then N is bounded.

Proof: Since all variables in X, U, and Y are explicitly bounded in N, they are also bounded in N. Therefore $\inf(L_1(X, U, Y))$ and $\sup(L_2(X, U, Y))$ are finite. Since N is guarded, it is a conjunction of guarded constraints and for all $x' \in X'$ it can be written as $x' \geq L_1(X, U, Y) \wedge x' \leq L_2(X, U, Y) \wedge \tilde{N}(X, U, Y, X')$ for a suitable guarded predicate $\tilde{N}$. This implies $\inf(L_1(X, U, Y)) \leq x' \leq \sup(L_2(X, U, Y))$, which in turn implies that x' is bounded in N. ■

Example 5: Let $\mathcal{H}_1$ be the DTLHS $(\{x\}, \{u\}, \varnothing, N_1)$, where $N_1(x, u, x') = (0 \leq x \leq 3) \wedge (0 \leq u \leq 1) \wedge (x' = x + 3u)$. By Proposition 14, $\mathcal{H}_1$ is bounded with $\inf(x') = 0$ and $\sup(x') = 6$. All other variables are explicitly bounded in N. Explicit bounds on present state and input variables do not imply that next state variables are bounded. As an example, let us consider the DTLHS $\mathcal{H}_2 = (\{x\}, \{u\}, \varnothing, N_2)$, where $N_2(x, u, x') = (0 \leq x \leq 3) \wedge (0 \leq u \leq 1) \wedge (x' \geq x + 3u)$. Since, for any value of x and u, x' can assume arbitrary large values, we have that N_2 is not bounded.

VI. Guarded Predicates as Modeling Language

The disjunction elimination procedure given in Algorithm 5 returns a guarded predicate that may contain a large number of fresh auxiliary boolean variables and this may heavily impact on the effectiveness of control software synthesis or verification (as well as the complexity of Algorithm 5 itself, since the auxiliary Algorithm 4 depends on the number of guard variables). On the other hand, guarded predicates, which are used as an intermediate step in Algorithm 5, are themselves a natural language to describe DTLHS behavior: assignments to guard variables play a role similar to modes in hybrid systems and, by using negative literals as guards, we can naturally model different kinds of plant behavior according to different commands sent by actuators.

Example 6: By directly using guarded predicates as modeling language, the DTLHS of Example 1 may be modeled by the conjunction of guarded constraints (43)–(52).

$$i'_L = (1 + Ta_{1,1})i_L + Ta_{1,2}v_O + Ta_{1,3}v_D \quad (43)$$
$$v'_O = Ta_{2,1}i_L + (1 + Ta_{2,2})v_O + Ta_{2,3}v_D. \quad (44)$$

$$v_D = v_u - V_i \quad (45) \qquad q \rightarrow v_D = 0 \quad (49)$$
$$i_D = i_L - i_u \quad (46) \qquad q \rightarrow i_D \geq 0 \quad (50)$$
$$u \rightarrow v_u = 0 \quad (47) \qquad \bar{q} \rightarrow v_D = R_{\text{off}} i_D \quad (51)$$
$$\bar{u} \rightarrow v_u = R_{\text{off}} i_u \quad (48) \qquad \bar{q} \rightarrow v_D \leq 0 \quad (52)$$

Algorithm 6 From guarded predicates to conjunctive predicates

Input: $G(X, Z)$ guarded predicate over X with guards in Z and modality $\nu \in \{\text{EXH}, \text{CUT}\}$.

Output: result μ and conjunctive predicate $C(X, Z)$ such that $C(X, Z)$ is X-equivalent to $G(X, Z)$ if $G(X, Z)$ is bounded.

function *GPtoC*(G, X, Z, ν)

1. **let** G and g be as in lines 1–2 of Algorithm 3
2. **if** $\nu = \text{CUT}$ **then**
3. $\quad \hat{Z} \leftarrow \{z \in Z \mid \exists i : g(i) = \bar{z} \vee g(i) = z\} \cup \{\tilde{z} \in Z \mid \exists i : g(i) = \bar{z}\}$
4. $\quad Z \leftarrow Z \cup \{\tilde{z} \in Z \mid \exists i : g(i) = \bar{z}\}$
5. $\quad G(X, \hat{Z}) \leftarrow \bigwedge_{i \in [n] \wedge g(i) = z_i} g(i) \rightarrow C_i(X, Z) \wedge \bigwedge_{i \in [n] \wedge g(i) = \bar{z}_i} \tilde{z}_i \rightarrow C_i(X, Z)$
6. $\quad D(Z) \leftarrow \bigwedge_{i \in [n] \wedge g(i) = 1} C_i(X, Z) \wedge \bigwedge_{z \in Z \wedge \exists i : g(i) = \bar{z}} \tilde{z} + z = 1$
7. **for all** $x \in X$ **do**
8. $\quad$ **if** $\nu = \text{CUT}$ **then**
9. $\quad\quad \langle \mu, m_x, M_x \rangle \leftarrow$ *computeBnds*$(G, D, X, Z, \hat{Z}, x)$
10. $\quad$ **else**
11. $\quad\quad \langle \mu, m_x, M_x \rangle \leftarrow$ *exhComputeBounds*(G, X, Z, x)
12. $\quad$ **if** $\mu \neq \text{BND}$ **then**
13. $\quad\quad$ **return** $\langle \mu, \bot \rangle$
14. **return** $\langle \text{BND}, \textit{GtoC}(G, X \cup Z, m, M) \rangle$

Note that disjunctions (7)–(9) in Example 1 have been replaced by guarded constraints (47)–(52). The resulting model for the buck DC-DC converter is much more succinct than the guarded model in Example 2 and it has 2 guard variables only, rather than 6 as in Example 2 (and 10 guarded constraints rather than 15).

Algorithm 4 cannot be directly applied to guarded predicates with both positive and negative guard literals. This obstruction can be easily bypassed, by observing that a guarded constraint $\bar{z} \rightarrow C(X)$ is $(X \cup \{z\})$-equivalent to the positive guarded predicate $(\tilde{z} \rightarrow C(X)) \wedge (\tilde{z} + z = 1)$. On the other hand, guarded predicates with both positive and negative guard literals may be directly translated in a conjunctive predicate by using the exhaustive procedure in Algorithm 3 to compute variable bounds. Both such translations are outlined in function *GPtoC* of Algorithm 6. Namely, if $\nu = \text{CUT}$ then the input guarded predicate is translated in a positive guarded predicate and then Algorithm 4 is used. Otherwise, i.e., if $\nu = \text{EXH}$ then the exhaustive Algorithm 3 is used directly on the original guarded predicate. Note that the above described method to obtain a positive guarded predicate from a guarded predicate (lines 3–6 in Algorithm 6) doubles the number of variables originally used as negative guards. Thus, it turns out that it is more convenient to call function *GPtoC* with $\nu = \text{EXH}$ (see experimental results in Section VII).

Summing up, guarded predicates turn out to be a powerful and natural modeling language for describing DTLHS transition relations.

VII. Experimental Results on a Case Study

In this section, we evaluate the effectiveness of our predicate translation functions, i.e., function *PtoC* of Algorithm 5 and function *GPtoC* of Algorithm 6. To this end, we implemented such functions in C programming language, using GLPK to solve MILP problems. We name the resulting tools PtoC (*Predicates to Conjunctive predicates translator*) and GPtoC (*Guarded Predicates to Conjunctive predicates translator*). We will write calls to functions *PtoC* (resp. *GPtoC*) with $\nu = \tilde{\nu}$ as PtoC($\tilde{\nu}$) (resp., GPtoC($\tilde{\nu}$)). PtoC and GPtoC are part of a more general tool named *Quantized feedback Kontrol Synthesizer* (QKS) [8][9].

We present the experimental results obtained by using PtoC and GPtoC on a n-inputs buck DC-DC converter (described in Section VII-A), that we model with two DTLHSs $\mathcal{H}_i = (X_i, U_i, Y_i, N_i)$, with $i \in [2]$, such that $X_1 = X_2$, $U_1 = U_2$, $Y_1 \subset Y_2$, $N_1(X_1, U_1, Y_1, X_1')$ is a predicate, and $N_2(X_2, U_2, Y_2, X_2')$ is a guarded predicate $(X_1 \cup U_1 \cup Y_1 \cup X_1')$-equivalent to N_1. All experiments have been carried out on a 3.00GHz Intel Xeon hyperthreaded Quad Core Linux PC with 8GB of RAM.

We run PtoC on N_1 and GPtoC on N_2 for increasing values of n (which entails that the number of guards increases), in order to show effectiveness of PtoC and GPtoC. To this end, both values for parameter ν will be used, which means that, for each n, 4 experiments are run. In Section VII-B we show experimental results PtoC. Furthermore, in Section VII-C we show that results obtained with GPtoC(Exh) are better than those obtained with both GPtoC(Cut) and PtoC. That is, the best results are obtained by exploiting knowledge of the system and modeling it with guarded predicates, and then using the exhaustive algorithm.

A. Multi-Input Buck DC-DC Converter

A Multi-Input Buck DC-DC Converter [18] (Figure 2), consists of n power supplies with voltage values $V_1 < \ldots < V_n$, n switches with voltage values $v_1^u, \ldots, v_n^u$ and current values $I_1^u, \ldots, I_n^u$, and n input diodes $D_0, \ldots, D_{n-1}$ with voltage values $v_0^D, \ldots, v_{n-1}^D$ and current values $i_0^D, \ldots, i_{n-1}^D$ (in the following, we will also write v_D for v_0^D and i_D for i_0^D). As for the converter in Example 1, the state variables are i_L and v_O, whereas action variables are $u_1, \ldots, u_n$, thus a control software for the n-input buck DC-DC converter has to properly actuate the switches $u_1, \ldots, u_n$. Constant values are the same given in Example 3.

B. Multi-Input Buck as a Predicate

We model the n-input buck DC-DC converter with the DTLHS $\mathcal{H}_1 = (X_1, U_1, Y_1, N_1)$, where $X_1 = [i_L, v_O]$, $U_1 = [u_1, \ldots, u_n]$, and

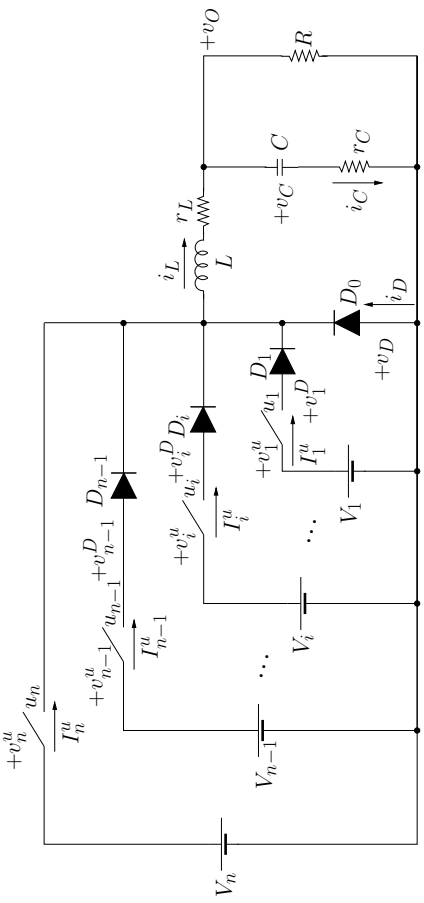

Figure 2. Multi-input Buck DC-DC converter

$Y_1 = [v_D, v_1^D, \ldots, v_{n-1}^D, i_D, I_1^u, \ldots, I_n^u, v_1^u, \ldots, v_n^u]$. From a simple circuit analysis (e.g., see [17]), we have that N_1 is the conjunction of linear predicates (53)–(61).

$$i_L' = (1 + Ta_{1,1})i_L + Ta_{1,2}v_O + Ta_{1,3}v_D \quad (53)$$

$$v_O' = Ta_{2,1}i_L + (1 + Ta_{2,2})v_O + Ta_{2,3}v_D. \quad (54)$$

$$((i_D \geq 0) \wedge (v_D = 0)) \vee ((i_D \leq 0) \wedge (v_D = R_{\text{off}} i_D)) \quad (55)$$

$$\bigwedge_{i \in [n]} (u_i = 0) \vee (v_i^u = 0) \quad (56)$$

$$\bigwedge_{i \in [n]} (u_i = 1) \vee (v_i^u = R_{\text{off}} I_i^u) \quad (57)$$

$$\bigwedge_{i \in [n-1]} ((I_i^u \geq 0) \wedge (v_i^D = 0)) \vee ((I_i^u \leq 0) \wedge (v_i^D = R_{\text{off}} I_i^u)) \quad (58)$$

$$i_L = i_D + \sum_{i=1}^{n} I_i^u \quad (59)$$

$$\bigwedge_{i \in [n-1]} v_D = v_i^u + v_i^D - V_i \quad (60)$$

$$v_D = v_n^u - V_n \quad (61)$$

N_1 also contains the following explicit bounds: $-4 \leq i_L \leq 4 \wedge -1 \leq v_O \leq 7 \wedge -10^3 \leq i_D \leq 10^3 \wedge \bigwedge_{i=1}^{n} -10^3 \leq I_i^u \leq 10^3 \wedge \bigwedge_{i=1}^{n} -10^7 \leq v_i^u \leq 10^7 \wedge \bigwedge_{i=0}^{n-1} -10^7 \leq v_i^D \leq 10^7$.

Table I
PTOC PERFORMANCE (PREDICATES)

n	r	r'	r''	k	$\|cut\|$	CPU_c	Mem_c	CPU_e	Mem_e	$\|In\|$	$\|Out\|$
2	12	6	12	11	64	1.07e+00	5.14e+07	3.07e+01	5.14e+07	21	44
3	18	9	18	17	512	9.63e+01	5.15e+07	2.92e+03	5.14e+07	30	63
4	24	12	24	23	4096	1.15e+04	5.15e+07	>1.38e+06	N/A	39	82

We run PTOC(CUT) with parameters $N_1, X_1 \cup U_1 \cup Y_1 \cup X_1'$ for increasing values of n, and we compare its computation time with that of PTOC(EXH) with the same input parameters. Table I shows our experimental results. In Table I, columns meaning are as follows:

- column n shows the number of buck inputs;
- column r shows the number of guards (see line 1 of Algorithm 4);
- columns r', r'' have the meaning given in lines 2 and 3 of Algorithm 4;
- column k gives the value of k at the end of the outer for loop of Algorithm 4;
- column $|cut|$ gives the size of cut at the end of the for loop of Algorithm 4;
- columns CPU_c and Mem_c (resp. CPU_e and Mem_e) show the computation time in seconds and memory usage in bytes of PTOC(CUT) (resp., of PTOC(EXH))
- column $|In|$ shows the size of the input predicate, as the number of linear constraints (i.e., of the linear predicate atoms) in the input linear predicate N_1;
- column $|Out|$ shows the size of the output conjunctive predicate, as the resulting number of linear constraints in the output conjunctive predicate.

C. Multi-Input Buck as a Guarded Predicate

We modify the DTLHS $\mathcal{H}_1$ of Section VII-B by defining $\mathcal{H}_2 = (X_2, U_2, Y_2, N_2)$, where $X_2 = X_1$, $U_2 = U_1$, $Y_2 = Y_1 \cup Y_2' = Y_1 \cup \{q_0, \ldots, q_{n-1}\}$ and N_2 is obtained from N_1 by replacing disjunctions (55)–(58) with guarded constraints. Thus, N_1 is given by the conjunction of guarded constraints (62)–(76).

$$i_L' = (1 + Ta_{1,1}) i_L + Ta_{1,2} v_O + Ta_{1,3} v_D \quad (62)$$

$$v_O' = Ta_{2,1} i_L + (1 + Ta_{2,2}) v_O + Ta_{2,3} v_D. \quad (63)$$

$$q \rightarrow v_D = 0 \quad (64) \qquad \bar{q} \rightarrow v_D = R_{\mathrm{off}} i_D \quad (66)$$

$$q \rightarrow i_D \geq 0 \quad (65) \qquad \bar{q} \rightarrow v_D \leq 0 \quad (67)$$

$$\bigwedge_{i \in [n-1]} q_i \rightarrow v_i^D = 0 \quad (68) \qquad \bigwedge_{i \in [n-1]} \bar{q}_i \rightarrow v_i^D \leq 0 \quad (71)$$

$$\bigwedge_{i \in [n-1]} q_i \rightarrow I_i^u \geq 0 \quad (69) \qquad \bigwedge_{i \in [n-1]} \bar{q}_i \rightarrow v_i^D = R_{\mathrm{off}} I_i^u \quad (72)$$

$$\bigwedge_{i \in [n]} u_i \rightarrow v_i^u = 0 \quad (70) \qquad \bigwedge_{i \in [n]} \bar{u}_i \rightarrow v_i^u = R_{\mathrm{off}} I_i^u \quad (73)$$

$$i_L = i_D + \sum_{i=1}^{n} I_i^u \quad (74)$$

$$\bigwedge_{i \in [n-1]} v_D = v_i^u + v_i^D - V_i \quad (75)$$

$$v_D = v_n^u - V_n \quad (76)$$

We call both GPTOC(CUT) and GPTOC(EXH) with parameters $N_2, X_2 \cup U_2 \cup Y_2 \cup X_2'$ for increasing values of n, and we compare their computation times.

Table II shows our experimental results. Columns meaning in Table II are the same as of Table I. An additional column $|Y_2|$ shows the number of guard variables in N_2.

D. Evaluation

Results in Table I show that heuristics implemented in function *computeBounds* are indeed effective w.r.t. executing function *exhComputeBounds*. In fact, by comparing columns CPU_c and CPU_e (and recalling that the only difference between PTOC(CUT) shown in CPU_c and PTOC(CUT) shown in CPU_e is that the former calls function *computeBounds* whilst the latter calls function *exhComputeBounds*), we see that such heuristics provide at least a one-order-of-magnitude speed-up in variable bounds computation. Such speed-up rapidly grows with the size of the input. In fact, for the 4-bits buck DC-DC converter, PTOC(EXH) requires more than 2 weeks, whilst PTOC(CUT) terminates in about 3 hours. Moreover, we also note that the resulting number of linear constraints output by PTOC is at most twice the starting number of linear constraints.

PTOC(CUT) is however not effective on the n-input buck DC-DC converter for $n \geq 5$. In fact, for $n = 5$, there are 30 boolean guards (i.e., $r = 30$), and the heuristics do not provide enough speed-up to obtain termination in a reasonable time. However, if we directly use guarded predicates as input language as in Section VII-C, we are able to generate the conjunctive predicate for both $n = 5$ and $n = 6$. This is due to the smaller number of guard variables used in Section VII-C than that used in Section VII-B. The negative impact of auxiliary boolean variables is clearly showed by the fact that GPTOC(EXH), much slower than GPTOC(CUT) on a model of the same size, performs better than GPTOC(CUT) in this case, because it can work on a model with half of the variables (see columns $|Y_2|$ and r). The same holds if we compare results of GPTOC(EXH) with those of PTOC(EXH) and PTOC(CUT). This phenomenon would be greatly amplified in a verification or control software synthesis procedure. These results strongly support guarded predicates as modeling language.

Table II
GPTOC PERFORMANCE (GUARDED PREDICATES)

n	$\|Y_2\|$	r	r'	r''	k	$\|cut\|$	CPU_c	Mem_c	CPU_e	Mem_e	$\|In\|$	$\|In_{\mathrm{pos}}\|$	$\|Out\|$
2	4	8	4	4	4	16	2.80e-01	5.14e+07	2.50e-01	5.14e+07	17	21	38
3	6	12	6	6	6	64	9.70e-01	5.15e+07	9.70e-01	5.15e+07	24	30	54
4	8	16	8	8	8	256	1.04e+01	5.16e+07	3.41e+00	5.15e+07	31	39	70
5	10	20	10	10	10	1024	1.75e+02	5.17e+07	1.69e+01	5.16e+07	38	48	86
6	12	24	12	12	12	4096	2.55e+03	5.17e+07	8.57e+01	5.17e+07	45	57	102

VIII. RELATED WORK

This paper is an extended version of [1]. With respect to [1], this paper provides more details in the introduction and in the related work description, extends basic definitions and algorithms descriptions, gives more detailed proofs for theorems, and provides a revised and enriched version of the experiments.

MILP problems solving based abstraction techniques have been designed for the verification of *Discrete Time Hybrid Automata* (DHA) [5] and implemented within the symbolic model checker HYSDEL [19]. A MILP based DTLHS abstraction algorithm is the core of automatic control software synthesis from system level specifications in [8][9], and it requires DTLHS dynamics modeled as a conjunctive predicate. The same limitation occurs in abstraction techniques based on the Fourier-Motzkin procedure for existential quantifier elimination [20]. All such approaches may exploit the translation algorithm presented here in order to improve their applicability.

Automatic or automatable translation procedures targeting MILP formulations have been presented in [21] and [22]. Namely, in [22] the authors propose an approach to translate (*reformulate* in their parlance) mixed integer bilinear problems (i.e., problems in which constraints may contain products of a nonnegative integer variable and a nonnegative continuous variable) into MILP problems. This reformulation is obtained by first replacing a general integer variable with its binary expansion and then using McCormick envelopes to linearize the resulting product of continuous and binary variables. In [21], the authors present an automatic conversion from deterministic finite automata to MILP formulations. This allows to efficiently combine supervisory control theory and MILP to automatically generate time-optimal, collision-free and non-blocking working schedules for a flexible manufacturing system. Both these works differ from ours in the starting point of the translation procedure (and of course in the actual algorithms designed): in [21] they are interested in translating deterministic finite automata, whilst in [22] the goal is to translate mixed integer bilinear problems. On the other hand, in this paper we are interested in translating conjunctions and disjunctions of linear constraints (see Section II-A), thus the approaches in [21][22] cannot be used in our context.

Many works in the literature deal with automatic specification of MILP problems in order to solve customized synthesis problem. As an example, in [23] the target is a formal synthesis approach to design of optimal application-specific heterogeneous multiprocessor systems. As a further example, in [24], a topology synthesis method for high performance System-on-Chip design is presented. Finally, in [25] the development of a technique to target fresh water consumption and wastewater generation for systems involving multiple contaminants is presented. In this paper, rather than giving a MILP scheme to be properly customized to solve a problem of a given type, we provide a translation from a general-purpose predicate to an equivalent MILP problem.

Finally, we note that the automatic procedure presented in this paper is reminiscent of Mixed Integer Programming modeling techniques [26] in Operations Research and boolean formula transformations involved in the conversion of a formula into a conjunctive or disjunctive normal form [6][27].

IX. CONCLUSIONS AND FUTURE WORK

The results presented in this paper contribute to *model based design* of SBCS (most notable, of embedded software) by proposing an expressive modeling language for DTLHS. In fact, in our previous work MILP based approaches have been used to synthesize correct-by-construction control software for DTLHSs. However, such approaches require DTLHS dynamics to be modeled as a conjunctive linear predicate over state, input, and next state variables. This may turn out to be not practically feasible for DTLHSs with complex dynamics.

In this paper, we circumvented such a limitation, by giving an automatic procedure that translates any disjunction-conjunction of linear constraints into an equisatisfiable conjunctive predicate, provided that each variable ranges over a bounded interval. This last proviso is automatically enforced by our procedure, since it includes a routine algorithm that, taking a linear predicate P and a variable x, verifies if x is bounded in P, by computing (an over-approximation of) bounds for x.

Finally, our experimental results show the effectiveness of our approach on an important and challenging case study

taken from the literature, namely the multi-input Buck DC-DC Converter. As an example, the linear predicate that models a 4-inputs buck DC-DC converter with 39 linear constraints is translated into a conjunctive predicate of 82 linear constraints in slightly more than 3 hours. Most notably, our experimental results show that guarded predicates, which are used by our translation procedure as an intermediate language, turn out to be a natural language to succinctly describe DTLHS dynamics. In fact, the guarded predicate that models a 6-inputs Buck DC-DC Converter with 57 constraints (including 12 different guards), is translated into a conjunctive predicate of 102 linear constraints in about 40 minutes.

The presented approach has the main drawback to be exponential on the number of boolean guards used in the (initial or intermediate) guarded predicate. As a future work, we aim to counteract such a limitation by recognizing if the input predicate is of some known structure. As an example, if the guarded predicate is composed by k blocks of the same structure, we may translate just one of such blocks and then suitably copy the resulting conjunctive predicate k times.

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ACRONYMS

AD Analog-to-Digital. 1
DA Digital-to-Analog. 1
DC Direct Current. 4
DHA Discrete Time Hybrid Automata. 12
DTLHS Discrete Time Linear Hybrid System. 1, 2, 4, 6, 7, 9–13
DVFS Dynamic Voltage and Frequency Scaling. 4
MILP Mixed Integer Linear Programming. 1–4, 7, 10, 12, 13
NFSA Nondeterministic Finite State Automaton. 1
QKS Quantized feedback Kontrol Synthesizer. 10
SBCS Software Based Control System. 1

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Derivation of Web Service Implementation Artifacts from Service Designs Based on SoaML

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***Abstract*—The increasing complexity of service landscapes requires a detailed planning that considers wide-spread quality attributes, such as loose coupling between services and their autonomy. To support this planning task, the Object Management Group standardized the Service oriented architecture Modeling Language for designing services and entire service-oriented architectures. In order to use the service designs modeled using SoaML within a model-driven development process, the created service designs have to be used to derive web service implementation artifacts. However, mapping rules described nowadays do not consider the SoaML design artifacts or do not consider service designs as a whole. In this article, mapping rules are identified and enhanced to transform service designs into web service implementation artifacts. The transformation rules are exemplarily applied to implement a service-oriented workshop organization system.**

Keywords-service design; SoaML; web service, implementation; derivation.

I. INTRODUCTION

This article is an extension of the work presented in [1]. Due to the increasing number of applications within Information Technology (IT) landscapes, the integration of these applications is an important success factor when realizing new functionality. For that purpose, service-oriented architecture (SOA) evolved as architecture paradigm [2] to create a flexible and maintainable IT. These strategic goals are massively influenced by the design of the building blocks of an SOA, the services. Quality attributes, such as loose coupling and autonomy [3], have been identified that impact flexibility and maintainability as higher-value quality attributes [4]. In order to ensure their fulfillment, a detailed planning is necessary.

For that purpose and for reducing the complexity when designing services, the Object Management Group (OMG) standardized a new language for designing services and entire service-oriented architectures, the Service oriented architecture Modeling Language (SoaML). The standard is vendor- and tool-independent and provides a meta model and a profile for the Unified Modeling Language (UML). As UML profile SoaML adds several stereotypes that focus on the specifics when designing services. Currently, SoaML is released in version 1.0.1 and is already supported by several tool vendors. Also some vendors already replaced their proprietary UML profiles with SoaML, such as IBM [4].

In order to use SoaML as language within a model-driven development process for services in particular web services as introduced by Hoyer et al. [5], a derivation of web service implementation artifacts from service designs based on SoaML is necessary. For that purpose, mapping rules have to be formalized that describe the relation between constructs of the modeled service designs and the generated final implementation. Furthermore, they constitute the basis for automatic transformations that can be embedded into software development tools. The mapping rules have to consider the underlying concepts so that the characteristics of the service designs are reflected by the web services. This is an important aspect for mapping rules, because for example when quality attributes have been considered during the service design phase, such as introduced by Gebhart et al. [1][6][7], the mapping rules are then expected to create web services that again fulfill these quality attributes.

This article analyses proposed mapping rules for creating web service implementation artifacts from service designs based on SoaML. As languages for web service implementation the Web Service Description Language (WSDL) and XML Schema Definition (XSD) are chosen to describe the service interface and included data types. Furthermore, Service Component Architecture (SCA) as component model, and Business Process Execution Language (BPEL) for the implementation of composed services are considered. In a first step, existing rules are analyzed. Since SoaML is available as a UML profile there exist a lot of rules, for instance to create data types based on XSD from UML Classes that can be reused. Afterwards, these rules are extended to support the service designs as a whole. To illustrate the mapping process introduced above, web service designs describing a workshop organization system have been designed using SoaML regarding wide-spread quality attributes.

The article is organized as follows: Section II introduces the concept of service designs and their creation using SoaML. Furthermore, in this section, existing mapping rules and their applicability for service designs are analyzed. In Section III, the scenario of the workshop organization is illustrated and its functioning especially through the created service designs is described. In Section IV, these service designs are mapped onto web services using the prior created mapping rules. Section V concludes this article and introduces future research work.

II. Related Work

This section describes the fundamental terms and existing work in the context of specifying service designs and their mapping onto web service implementation artifacts based on XSD, WSDL, BPEL, and SCA.

A. Service Design

According to Gebhart et al. [7][8] and Erl [9], a service design consists of a service interface as external point of view and a service component fulfilling its functionality. In order to formalize service designs and to enable their transformation into implementation artifacts, Mayer et al. [9] introduce a UML profile for describing behavioral and structural aspects of service interactions. Similarly, within the SENSORIA project [10] a UML profile for the service interaction is specified. Also IBM [11] introduced a UML profile for modeling software services. Even though all of these UML profiles enable the modeling of services they lack in acceptance as they are not standardized. For that reason the OMG decided to work on a standardized UML profile [12] and a meta model to formalize service-oriented architectures and their services. As a result, SoaML has been created [13]. In this article, SoaML in version 1.0.1 is used.

According to Gebhart [14], in SoaML a service interface is described by a stereotyped UML Class that realizes a UML Interface describing the provided operations. A second UML Interface can be used for specifying callback operations the service consumer has to provide. These are necessary to realize asynchronous operation calls as they are for example required to invoke long-running business processes [7].

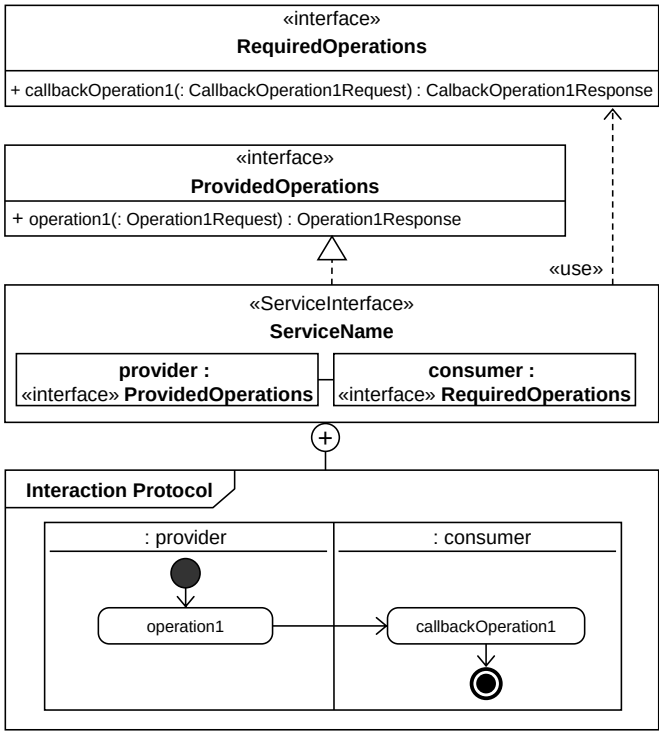


Figure 1. Service interface in SoaML.

An interaction protocol can be added as owned behavior. It is described by means of a UML Activity and determines the valid order of the operation calls. Every call is modeled using a UML Call Operation Action and is assigned to a UML Partition that represents one of the participating roles. Figure 1 shows a service interface in SoaML. In this case, the service interface describes that an operation is provided, namely the operation "operation1". There is one request message expected as input parameter. A response message will be returned as a result of the operation call. Furthermore, one callback operation is expected to be provided by the service consumer. In this case according messages are also included. The service provider is named "provider" and the service consumer is named "consumer". The interaction protocol describes that for a valid result the provided operation has be to be called initially on the part of the provider. Afterwards, the callback operation will be invoked. The messages used as input and output parameters are modeled using UML Classes stereotyped by "MessageType". They can be further refined into more fine-grained data types. Figure 2 shows the modeling of message types.

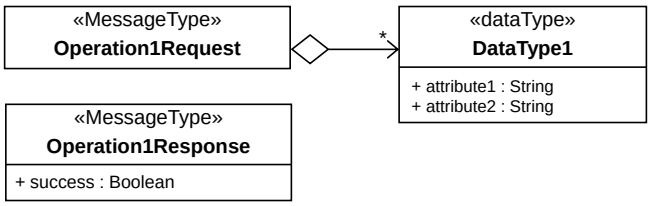


Figure 2. Message types in SoaML.

The service component is represented by a UML Component stereotyped by "Participant". Ports with Service or Request stereotype constitute the access points to the provided or required functionality and are typed by a certain service interface. An Activity as an owned behavior and visualized as UML activity diagram enables the specification of the internal logic.

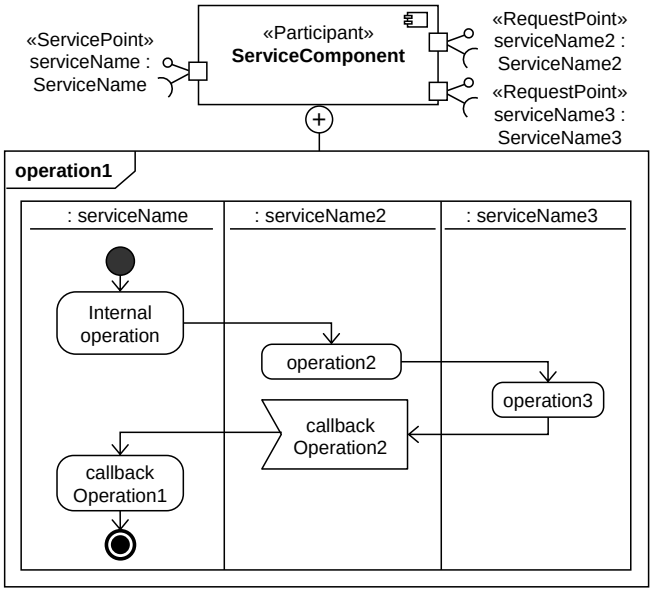


Figure 3. Service component in SoaML.

Figure 3 shows a service component in SoaML. It provides one service specified by the service interface depicted before. In order to fulfill the functionality of the service component, two other services are required. According to the Activity owned by the component, in a first step, an internal operation is performed. This means that this functionality is completely fulfilled by the service component itself. Thus it is modeled using a UML Opaque Action. Afterwards, the operations "operation2" and "operation3", provided by the services "serviceName2" and "serviceName3" respectively, are invoked. These operation calls are modeled using UML Call Operation Actions within according UML Partitions. Next, the service component waits for "callbackOperation2" being invoked. Finally, it invokes the callback operation provided by the initial service consumer.

B. Mapping Rules

In the context of mapping formalized service designs onto web service implementation artifacts based on XSD, WSDL, SCA, and BPEL approaches exist that consider either the derivation from SoaML-based models, UML models with own applied UML profiles, or standard UML models.

For the generation of XSD, IBM [15] and Sparx Systems [16] provide adequate mapping rules that map UML class diagrams onto XSD artifacts and support both the transformation of classes and their relationships like aggregations, compositions, associations, and generalization. Both vendors integrate the mapping rules into their own tools, which enable a model-driven development with a graphical tool support. The transformations are applicable to all UML models without any constraints. The applied rules can be used in our approach to map message types of service designs onto XSD.

Regarding WSDL, Grønmo et al. [17] discuss the advantages and disadvantages between using WSDL-independent and WSDL-dependent models. Their conclusion is that WSDL-dependent models, which are UML models containing WSDL-specific constructs, obscure the behavior and content of modeled services and make service designs incomprehensible. WSDL-independent models in contract simplify building complex web services and integrating existing web services. For that reason, they provide transformations based on UML class diagrams with custom WSDL-independent stereotypes. However, most of the presented transformations are based on standard UML elements and are thus applicable for service designs based on SoaML as it abstracts from WSDL details too. Also IBM [18] introduces mapping rules and an automatic transformation from UML to WSDL in [8]. These rules fully cover the transformation of standard UML elements into WSDL but are not described in detail. Only the relationships between source and target elements can be inferred and used in our work. In contradistinction to the previous related work the transformation generates also needed namespaces not bound to the source models but bound to the project structure used during the transformation. The project structure has the form of a file system containing source models and the relative paths will be used in order to generate namespaces for the target artifacts. This strategy may generate correct namespaces for a simple project. However, when merging the generated artifacts from many projects or changing the project structure during development the resulting namespace changes will make the WSDL files ambiguous.

Hahn et al. [19] present a transformation from a Platform Independent Model (PIM) to a Platform Specific Model (PSM), which converts SoaML to BPEL, WSDL, and XSD artifacts. Compared to our approach requiring a generation of BPEL processes from UML activity diagrams, the authors use BPMN processes as source models for the generation of executable BPEL processes. Even though no detailed mapping rules are provided, a promising and consistent output is generated and the mapping is illustrated using a simple scenario. The approach can be considered as a proof for the possibility of producing web service artifacts from SoaML service designs. The authors restrict that a SoaML service interface is mapped onto one and only one WSDL document containing XSD types that represent the SoaML Messages. A new capability supported by the SoaML to WSDL transformation is the ability to generate Semantic Annotations for WSDL (SAWSDL).

For generating BPEL, Mayer et al. [20] discuss the difficulties when transforming a UML Activity illustrated by means of a UML activity diagram into an executable language, such as BPEL. They introduce two alternatives on generating BPEL constructs. The first alternative is to generate a BPEL process similar to the UML Activity, where control nodes of the UML are replaced with edge and activity guards. The second alternative is to create a BPEL process with constructs in UML converted to their equivalent BPEL constructs. The first alternative is easy to be implemented and results in an unreadable and complex BPEL process, whereas the second one results in a better structured orchestration. The approach presents a robust and promising transformation into BPEL. However, the WSDL artifacts are inferred from elements described by a custom UML profile. Further mapping rules to transform workflows modeled using UML Activity elements onto BPEL artifacts are presented by IBM [21]. The approach handles some constraints of a UML Activity and provides adequate solutions. For example, to specify needed information, as for instance the partner links, the activity diagram should be extended with UML elements, such as input and output pins. Another constraint handled by the authors is how to model loop nodes in an Activity. Here, the authors propose a specific representation in UML to enable an easy and consistent generation of a BPEL loop element. These enhancements among others can be applied to consistently transform a UML Activity as the internal behavior of service components into an executable BPEL process.

SCA is a software technology which provides a model for building and composing applications and systems applying a service-oriented architecture paradigm. Combined with other technologies, such as WSDL and BPEL, SCA provides the underlying component model. In [18], Digre provides mapping rules for SoaML elements and SCA. The transformation is executed manually and the author mentions

that ambiguities in the SoaML model may prevent from producing proper SCA models. This is exactly the reason why a certain self-contained and well-understood design artifact, such as the service design in this article, has to be chosen when describing transformations. Another fully automated and tool-supported mapping of SoaML onto SCA artifacts is proposed by IBM [22]. The tool allows the application of SCA stereotypes to the source models in order to add more details specific to the SCA domain.

III. SCENARIO

In order to illustrate the transformation of service designs based on SoaML into web service implementation artifacts, the scenario of a workshop organization at a university and the involved systems are introduced in this section. The system helps visitors and members of the university in organizing a meeting or a workshop at a room located at the university campus. Additionally, the development steps for creating the required service designs are explained.

A. Business Requirements

In a first step, the business requirements have to be formalized. For that purpose, a domain model, business use cases, and the business processes that are expected to be supported by IT have to be described. These artifacts constitute the basis to create service designs based on SoaML that can be used to derive web service implementation artifacts.

The domain model describes entities and their relation within the considered domain. It is necessary to understand the domain, to unify the terminology, and to avoid misunderstandings. Thus, terms used within business use cases and business processes are expected to follow the domain model. Furthermore, operations and parameters are expected to be named functionally when designing services [1]. This can be only determined when functional terms, such as entities, are documented. To formalize the domain model, there exist several approaches. One alternative is to use UML class diagrams.

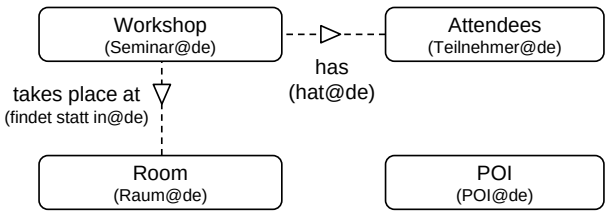


Figure 5. Domain model for workshop organization scenario.

Another alternative that has been chosen in this article is the Web Ontology Language (OWL) [23][24]. One advantage of OWL is that it can be directly referenced by WSDL using the Semantic Annotations language for WSDL (SAWSDL) [25]. By means of labels, OWL allows the description of terms in various languages. This is especially helpful when different languages are used during the requirements, the design, and implementation phases. In this case, the domain model includes the terms in English and German. An excerpt of the domain model for the workshop organization scenario is depicted in Figure 5. The domain model can either be formalized directly using XML or by means of tools, such as Protégé [24].

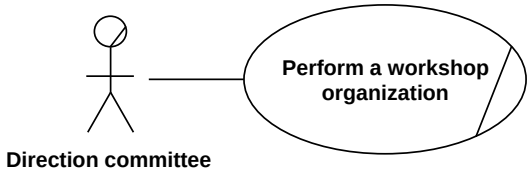


Figure 6. Business use case expected to be supported by IT.

The business use cases are modeled using UML use cases extended by the UML profile for business modeling as introduced by Johnston in [26]. The business use case expected to be supported by IT is illustrated in Figure 6.

Compared to standard UML use cases, a business use case describes the business boundaries instead of system

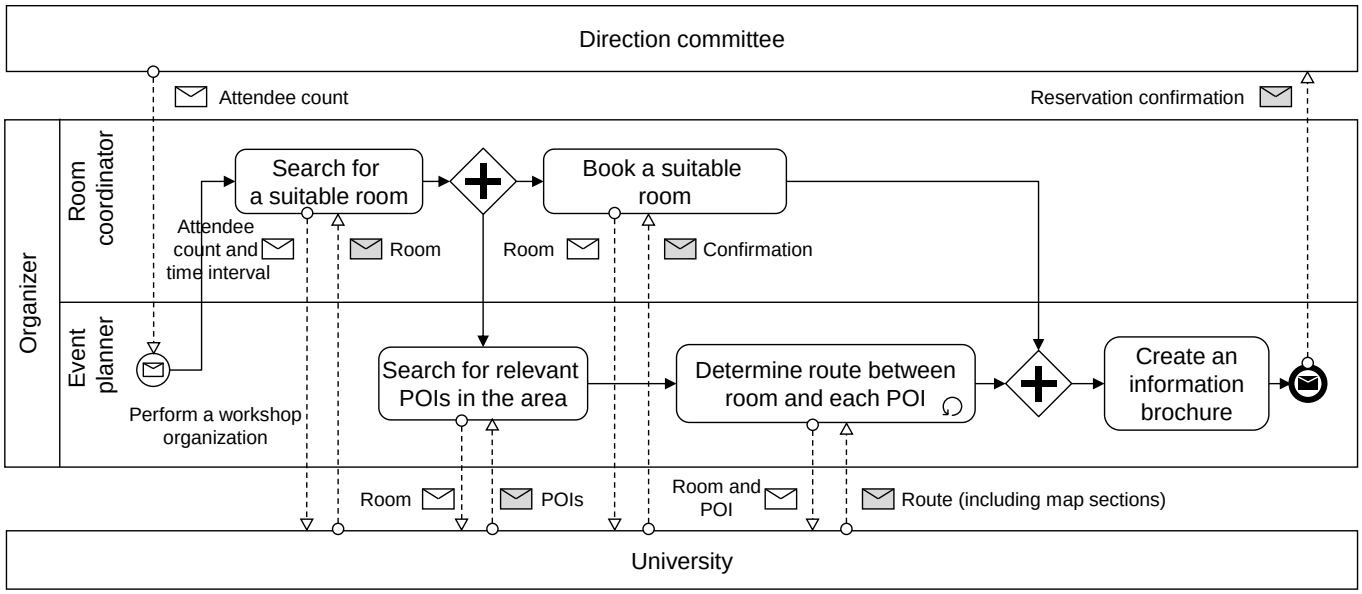


Figure 4. Business process of the workshop organization scenario.

boundaries. This means that the business actor specified by the stereotyped UML Actor is not part of the business represented by the business use case. The business actor, i.e., is an external participant that interacts with the business realizing the business use case. According to the diagram a direction committee is expected to be supported while performing a workshop organization.

A business use case is realized by means of a business process. The business process, i.e., describes the internal behavior of a business use case. Since the business process represents the essential artifact when deriving service designs, the business process for the workshop organization business use case has to be described. For that purpose the Business Process Model and Notation (BPMN) [27] is applied. The process for the considered scenario is illustrated in Figure 4. Two existing systems, provided by the university, are involved in the realization of the business process, namely the KITCampusGuide system and the facility management system. The KITCampusGuide system provides operations to manage Points of Interest (POI) such as the determination of all relevant POIs (Parking, Cafeteria, etc.) in the area surrounding the target and the provision of route guidance to all relevant POIs. The facility management system is concerned with room searches and enables the reservation of a room for a given number of attendees at the desired time interval.

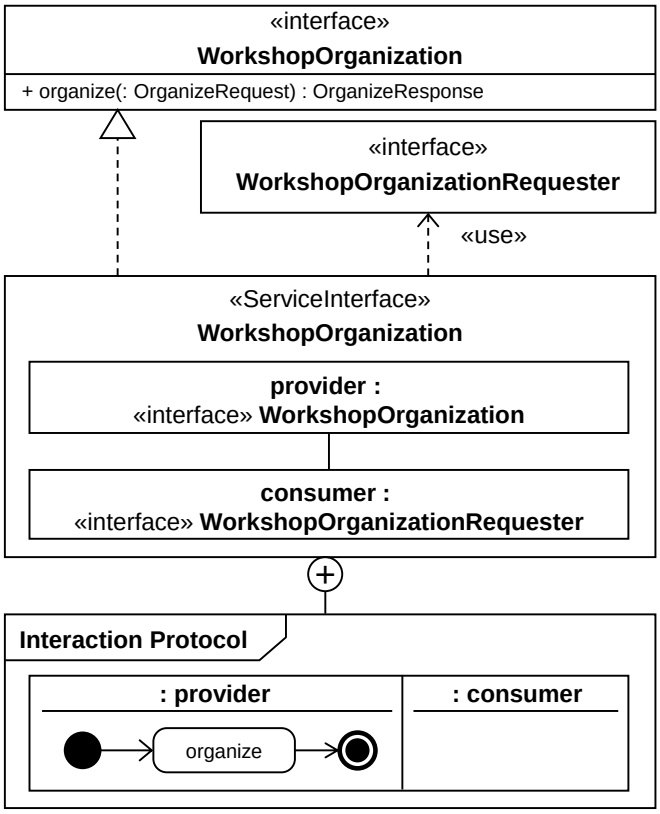


Figure 7. Derived service interface.

B. Service Designs

In the second phase of the development process, the service design phase, a set of service designs have to be designed and modeled using SoaML. Each service design is built according to the understanding introduced in Section II. The service designs can be created systematically as introduced by Gebhart et al. in [28]. In a first step, the service designs are derived from the business requirements. For example, for every pool within the business process, one service interface and one service component is created. All message interactions are used to derive provided and required operations. For example, a message start event in BPMN is transformed into one provided operation. In a next step, the derived service designs are revised regarding quality attributes, such as loose coupling and autonomy, as introduced in [29]. This is important, because these quality attributes influence higher-value ones, such as flexibility and maintainability, which in turn represent essential drivers for service-oriented architectures. For example, in this step naming conventions are considered, operations within service interfaces are split or merged, and it is ensured that long-running operations are provided by means of asynchronous instead of synchronous operations.

The resulting artifact from the design phase which describes the service "WorkshopOrganization" are presented below. This represents the business process and realizes the orchestration of involved services. Figure 7 shows the designed service interface. The UML Interface realized by the ServiceInterface element lists the provided operation "organize" with its input and output parameters. The input and output parameters are defined using the message types "OrganizeRequest" and "OrganizeResponse" described in Figure 9. As the interface associated by means of the usage dependency does not contain any operation, the service consumer does not have to provide callback operations. This corresponds to the interaction protocol. This example also shows the consideration of quality attributes. The operation "organize" represents the "Perform a workshop organization" message start event within the business process modeled in BPMN. However, the quality attribute discoverability describes that operations should be functionally named and should follow naming conventions. Thus, after a systematic derivation of the service interface, the operation is renamed from "Perform a workshop organization" to "organize".

In addition, a service component, representing the component that fulfills the functionality, is specified for this service. The service component and its internal behavior are illustrated in Figure 8. Also in this case, a systematic derivation is first performed. For example, every invoke activity within the business process in BPMN is transformed into a UML Call Operation Action that is assigned to a UML Partition representing a certain system. Flow elements are transformed into equivalents UML constructs. In a next step, quality attributes are considered, i.e., regarding the discoverability, naming conventions are considered and the functional naming is ensured.

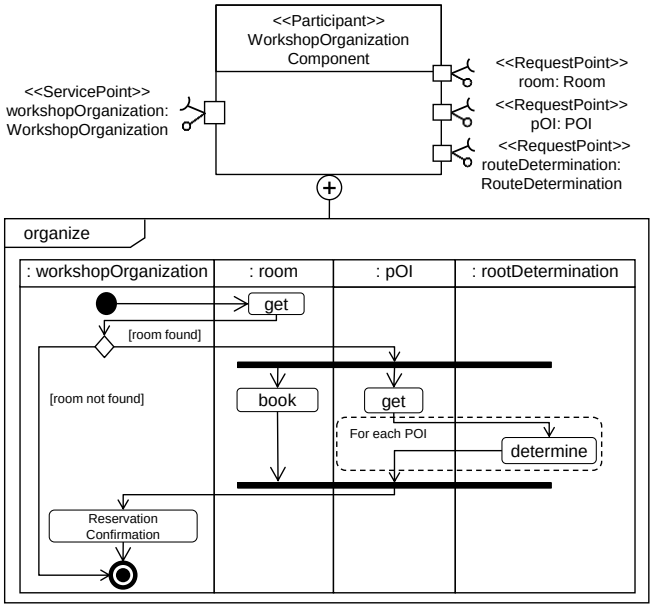


Figure 8. Derived service component.

IV. Derivation of Web Service Implementation Artifacts from Service Designs Based on SoaML

In this section, the steps necessary to derive web service implementation artifacts from service design are illustrated. Divided into four parts, the first subsection targets the derivation of data types and their definitions using XSD. For the provided and required interfaces of the service interface, service interface descriptions based on WSDL with associated message types are generated. For realizing the orchestration of services, BPEL is derived from UML Activity elements and added as the owned behavior of the service component. Finally, a SCA component model describing the structure of the application is derived from the service component. For each step and for each transformation performed existing mapping rules are applied.

A. Derivation of Data Types

Data types contained within the SoaML service designs are expected to be mapped onto XSD to describe request and response messages used within WSDL operations.

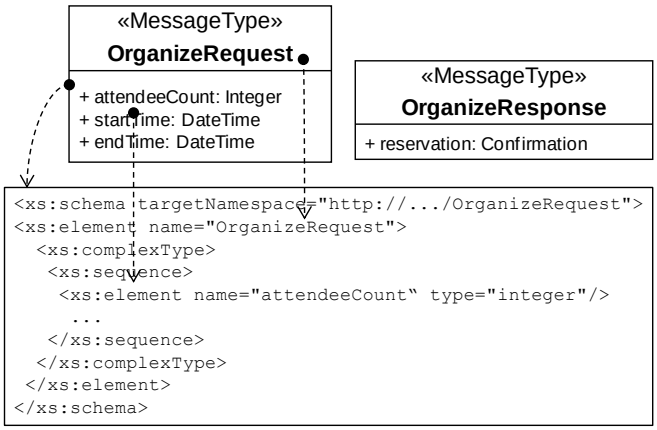


Figure 9. Derived XML Schema Definitions from SoaML messages.

The service interface in Figure 7 provides the operation "organize", which contains input and output messages in the form of UML DataTypes stereotyped by MessageType. They constitute containers for further data types described using attributes or UML Associations to other UML Classes. We follow the mapping rules provided by Sparx Systems [16]. Each input and output parameter is mapped onto an element with a complexType and a sequence of XML elements defining the attributes of the messages as demonstrated in Source Code 1. The XSD descriptions are stored in separate files in order to allow other WSDL documents to reuse the data types.

The separated XSD files are then imported into the WSDL document using an import statement with the corresponding namespace and schema location as shown in Source Code 1.

```
<wsdl:types>
 <xs:import namespace="http://.../OrganizeRequest"
   schemaLocation="http://.../organize.xsd"/>
</wsdl:types>

<wsdl:message name="OrganizeRequestMessage">
 <wsdl:part name="body" element="OrganizeRequest"/>
</wsdl:message>
```

Source Code 1. Derived WSDL message types.

Table I summarizes the transformation, provides more details about the mapping rules, and lists the source and the target elements with necessary attribute configurations.

TABLE I. SoaML artifacts to XML Schema Definition

SoaML Artifact	XML Schema Definition
Package	A schema element with the "targetNamespace" attribute to identify and reference the XSD is generated.
Class (MessageType)	An element as a root element and a complexType definition containing a sequence of child elements are generated. The "name" attribute corresponds to the name of the class.
Attributes (ownedAttributes)	Is mapped onto an element with the "name" and "type" attributes set to the same as in the source.
PrimitiveType, Datatype and MessageType	Are mapped onto the "type" attribute of an element generated while mapping the member attributes of a class. For each referenced data type an import element is used to add the corresponding external schema.
Association	An element is declared for each association owned by a class. The "name" attribute is set to the one of the association role. The "minOccurs" and "maxOccurs" reflect the cardinality of the association.
Generalization (Inheritance)	An extension element is generated for a single inheritance with the "base" attribute set to the base class name. The UML Attributes of the child class are then appended to an "all" group within the extension element.

B. Derivation of Service Interfaces

After generating data types, the operation definitions and their parameters can be derived from the SoaML service interface and its realized interface.

According to IBM [18], a port type acting as container for the operations is generated and each parameter is mapped onto a part element as shown in Source Code 1. The name of the port type is derived from the name of the realized interface in the SoaML service design and enhanced with the suffix "PortType". The WSDL operation element includes the attribute "name", which corresponds to the operation name within the service design. Additionally, the previously derived input and output messages are associated. In case of service inheritance the operations of the parent interface are copied to the same generated port type as stated by Hahn et al. [19]. This allows overcoming the not supported WSDL inheritance limitation.

```
<wsdl:portType name="WorkshopOrganizationPortType">
 <wsdl:operation name="organize">
  <wsdl:input message="OrganizeRequestMessage"/>
  <wsdl:output message="OrganizeResponseMessage"/>
 </wsdl:operation>
</wsdl:portType>
```

Source Code 2. Derived port type in WSDL.

Till now, the abstract part of a WSDL was generated. The concrete part encompasses deployment-specific details about how and where to access a service. A binding definition specifying the communication technology that can be used by the consumer is generated. The binding is named as a combination of the interface name and the suffix "SOAP". Additionally, it is associated with the prior defined port type by setting the attribute "type" to the name of the interface including the suffix "PortType". The messaging protocol binding and the transport protocol binding are set to Simple Object Access Protocol (SOAP) and Hypertext Transfer Protocol (HTTP). In this work, we use SOAP as a default protocol. The final part focuses on the physical endpoint of the service. The endpoint is specified by a URL that has to be specified by the developer.

```
<wsdl:binding name="WorkshopOrganizationSOAP"
              type="WorkshopOrganizationPortType">
 <soap:binding style="document"
 transport="http://schemas.xmlsoap.org/soap/http"/>
 <wsdl:operation name="organize"/>
</wsdl:binding>

<wsdl:service name="WorkshopOrganization">
 <wsdl:port binding="tns:WorkshopOrganizationSOAP"
            name="WorkshopOrganizationSOAP">
  <soap:address location="<server>:<port>"/>
 </wsdl:port>
</wsdl:service>
```

Source Code 3: Derived binding and service definition.

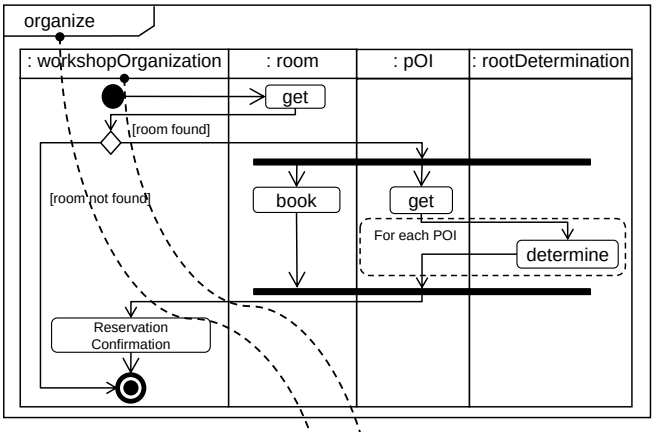
TABLE II. SOAML ARTIFACTS TO WSDL

SoaML Artifact	WSDL
Interface realized by a ServiceInterface	WSDL PortType that will be named according to the interface. It represents provided operations.
Interfaces used by a ServiceInterface	WSDL PortType that will be named according to the interface. It represents callback operations.
Input / Result / Exception parameters in a service interface	WSDL Messages that can be used within the operations.
Parameters	Message Parts that reference the WSDL Messages.
Parameter types	Types, they will be defined in a separate *.xsd document

C. Derivation of Executable Business Logic

The mapping rules provided by IBM [21] cover all UML artifacts of a UML Activity involved in the derivation of control flow elements of a BPEL process. Additionally, new mapping rules to set attribute values were identified in this article and are also mentioned in the following transformation description.

The UML activity diagram in Figure 8 describes the internal behavior of a service operation "organize" and is considered to demonstrate the transformation for most often used control flow elements of a UML activity diagram. The first generated fragment for the BPEL process is the main scope. It exists only once and consists of a sequence of other activities.




```
<bpel:process>
…
<bpel:sequence name="main">
      <bpel:receive name="organize" operation="organize"
       partnerLink="workshopOrganization"
       portType="tns:WorkshopOrganization"
       createInstance="yes" variable="input"/>
…
</bpel:sequence>
…
</bpel:process>
```

Figure 10. Derivation of main scope.

The first partition in the activity diagram contains an initial node which is mapped onto a receive activity with the attribute "partnerLink" set to the label of the partition, namely "workshopOrganization". The attribute "operation" corresponds to the operation name in the interaction protocol. This activity is located at the top of the main scope and waits for an arriving message. The derivation is shown in Figure 10. The mapping rules are not summarized within a table, as according tables are directly available in [21].

The involved web services are specified by separate WSDL definitions containing partnerLink definitions. In order to call these web services, the BPEL process sets a partnerLink for each invoke activity. The partnerLinks are derived from the label of the partitions, such as "room" or "rootDetermination".

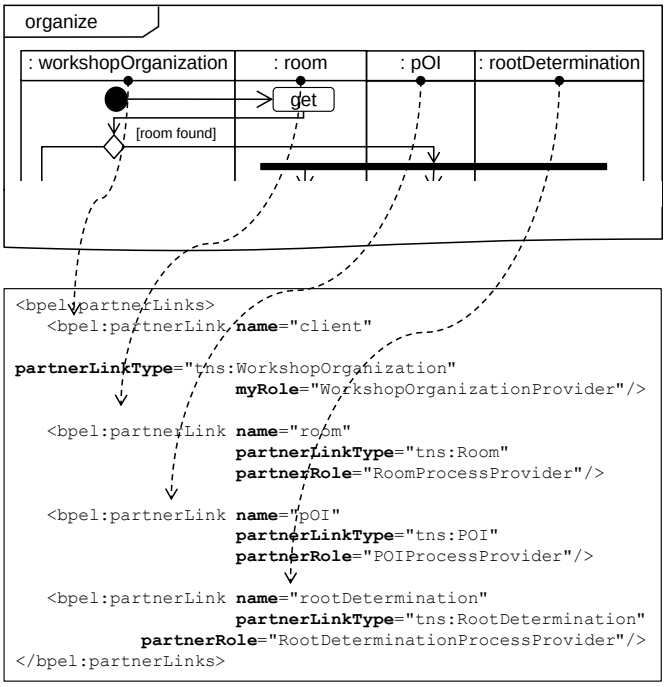


Figure 11. Derivation of partner links.

The partition containing the initial node is mapped onto a partnerLink definition with the attribute "name" set to the value "client" representing the BPEL process itself. For the other partitions, the attribute "name" is equal to the label of the respective partition. Moreover, the partnerLink defining the process itself has the attribute "myRole" whereas other partnerLinks have an attribute "partnerRole" representing the role of an invoked web service. Figure 11 shows the derived partnerLinks for the considered service operation and the invoked service "Room". After defining the partnerLinks, which belong to the abstract part of a BPEL process, the actions within the partitions are mapped onto invoke activities as illustrated in Figure 12.

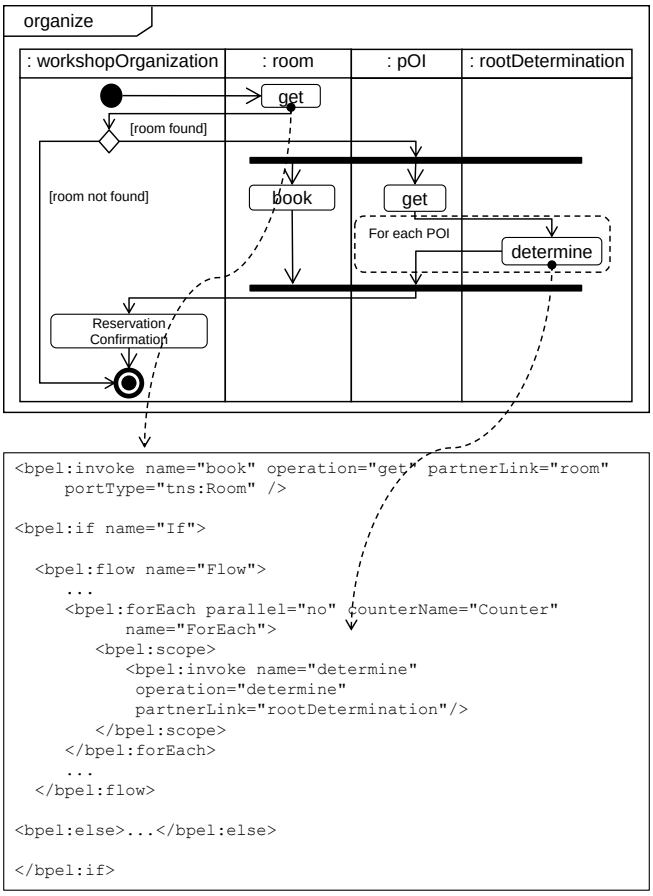


Figure 12. Derivation of activities.

Each activity has the attributes "name" and "operation" set to the name of the action. The attribute "partnerLink" is set to the corresponding partnerLink defined earlier. The activities are located within the corresponding scopes of flow elements mapped later. Compared to the other activities, the action "ReservationConfirmation" in the first partition is an opaque action executed by the BPEL process itself and thus is not mapped onto an invoke activity. After a skeleton for the BPEL process has been created, the control flow elements are derived from corresponding UML elements. The decision node is mapped onto a BPEL if-else construct. The condition of the node has to be added manually by the developer. The black bar representing a fork node and a parallel execution of the contained action is mapped onto a BPEL flow construct. The black bar representing a join node with incoming arrows is implicitly included in the earlier derived BPEL flow construct. The loop node is illustrated using a dashed area and is mapped onto a forEach construct with the attribute "parallel" set to the value "no". If the loop node in UML contains a fork and a join node, the attribute "parallel" is set to "yes". The derivation of flow elements is depicted in Figure 13.

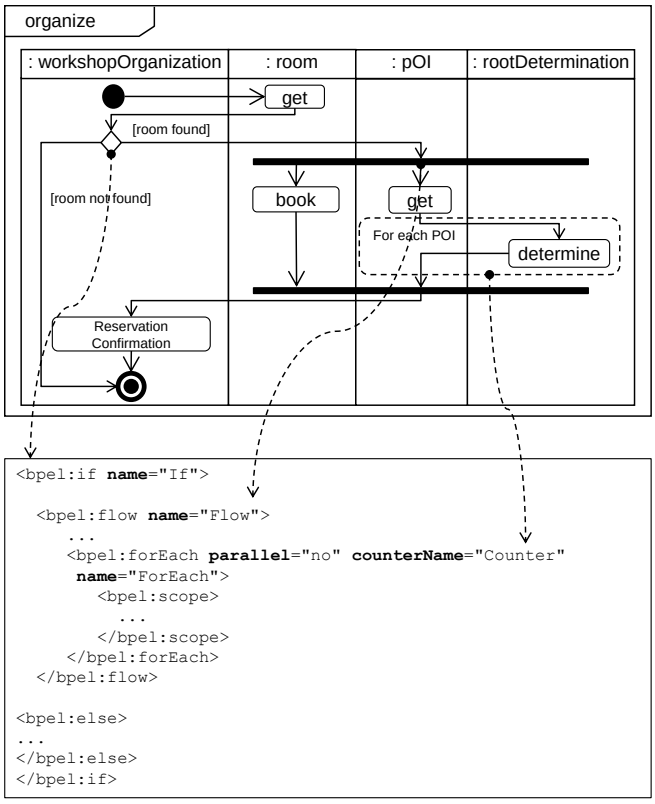


Figure 13. Derivation of flow elements.

D. Derivation of Component Models

In order to embed the already generated artifacts into an entire component model, SCA elements are derived from the service designs. Figure 14 illustrates the mapping between service components described by SoaML Participants and SCA elements, such as SCA Composites, Components, Services, References, and Wires, using mapping rules provided by Digre et al. in [18].

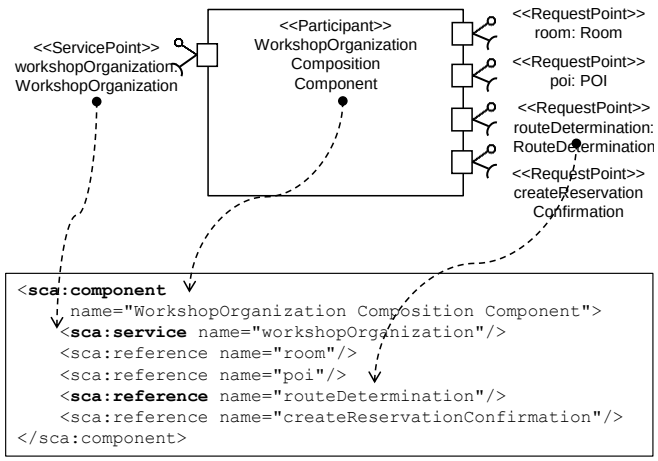


Figure 14. Derivation of SCA component model.

Regard naming conventions, each Participant is mapped onto a SCA component with name set to the label of the Participant. Since each SoaML Participant contains Services and Requests representing provided and required services, SCA Services and SCA References are generated. The names of these elements are set to the names of the ports within the SoaML Participant. The derivation is shown in Figure 14.

The SCA Composite is the basic unit of a composition in a SCA Domain and is an assembly of SCA Components, Services, References, and Wires. The service component presented earlier deals with the orchestration of external services and contains also a reference to an internal component for creating the reservation confirmation. These two components are to be grouped into an SCA Composite, whereas SoaML service channels wiring the Services to Requests are mapped onto SCA Wire elements. Additionally, if two Services or two Requests are wired together to delegate service calls, a promote element is added. Figure 15 illustrates the final SCA Composite in a graphical visualization as introduced by the standard.

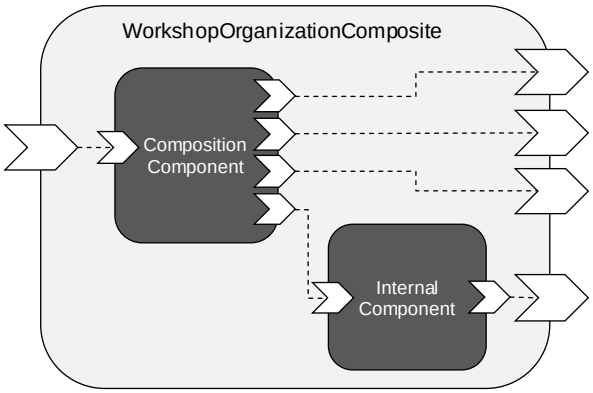


Figure 15. SCA Composite for the workshop organization process.

SCA requires that Service and Reference elements are compatible. The compatibility is assured by means of the assigned interfaces. The interfaces used in this context can be derived from service interfaces in SoaML as illustrated in Section B. The resulting service interface descriptions based on WSDL can be embedded into the SCA Composite. For this purpose, based on the realized and used UML Interfaces representing provided and required interfaces within the service designs, a bidirectional service interface description using WSDL with a base and a callback interface is generated. An “interface.wsdl” element is added to the Service element with the attribute “interface” set to the URL of the WSDL service representing the provided service interface “WorkshopOrganization”. The “callbackInterface” attribute of the Service element is set to the port type representing the “WorkshopOrganizationRequester”. For the corresponding SCA Reference, the assignment is reversed, i.e., the attribute “interface” of the interface element within the SCA Reference is set to the required interface and the attribute “callbackInterface” is set to the provided interface. The systematical derivation is depicted in the following figure.

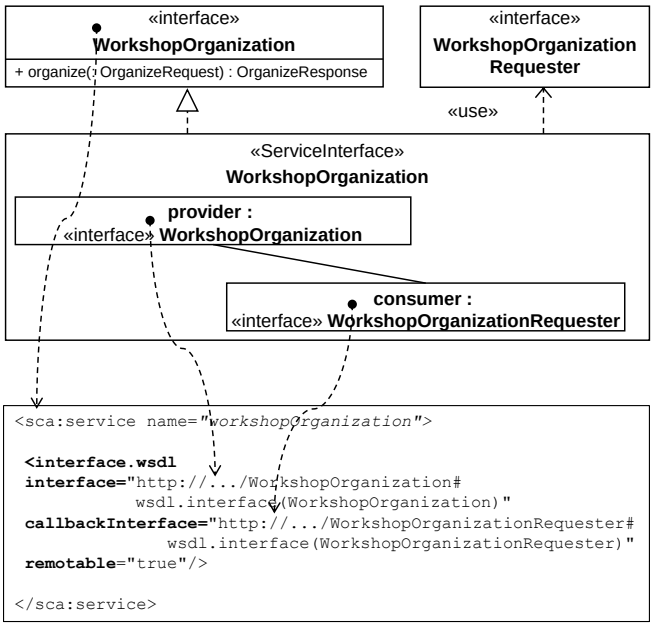


Figure 16. Integration of WSDL into SCA.

When a service component in SoaML consists of further service components, these refinements are also transformed into equivalents in SCA. Figure 17 illustrates the mapping of composite service components.

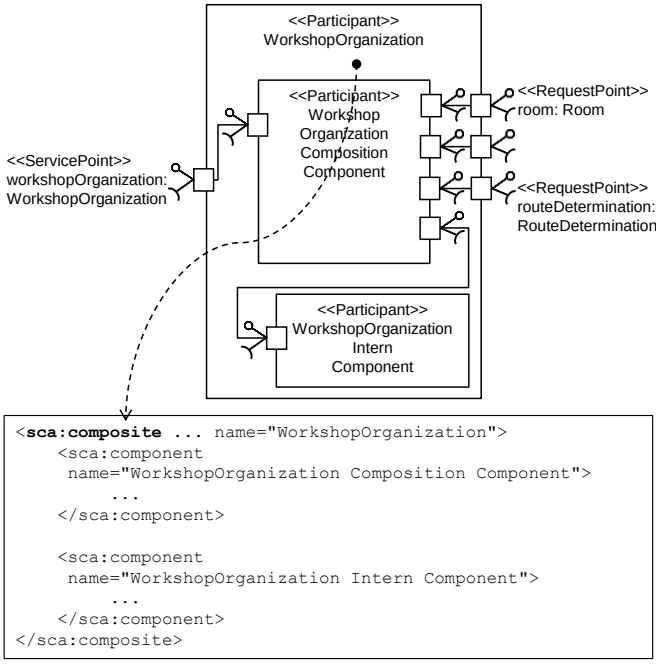


Figure 17. Transformation of composite service components.

As a result, the entire service components including their implementation and refinements into further service components can be mapped into SCA. The following table summarizes the mapping rules.

TABLE III. SOAML ARTIFACTS TO WSDL

SoaML Artifact	SCA
Service Component / Participant	Composite that is named according to the Participant.
Service	Service that is named according to the Service in SoaML. As interface in SCA the mapped service interface the Service is typed by is referenced.
Request	Reference that is named according to the Request in SoaML. Also in this case the Reference has an interface that is derived by the service interface the Request is typed by.
ServiceInterface	The service interface a Service or Request is typed by is transformed into a WSDL according to the rules described before. The service interface is transformed into a interface in SCA that is used to describe Service and References.
OwnedBehavior	An owned behavior that can be transformed into a BPEL process is set as implementation for a certain component in SCA.
Internal Participant	Component within the SCA composite. The component is named according to the internal participant.
Service Channels	Wiring between component within the SCA composite.

V. CONCLUSION AND OUTLOOK

In this article, we illustrated the derivation of web service implementation artifacts from prior created service designs that base on SoaML as standardized modeling language. For that purpose, existing mapping rules that in particular focus on UML as source artifacts have been analyzed and enriched with details that aim at supporting service design specifics. As a result, the mapping rules could be identified to enable the systematic derivation of web services based on XSD, WSDL, BPEL, and SCA as wide-spread technologies.

This systematic derivation is especially necessary in model-driven development approaches for web services. As SoaML is a language standardized by the OMG it is the preferred language when modeling services. Due to the complexity of today's software, a detailed planning and thus modeling before implementation is recommended. During the design phase it is easier to focus on architecture-relevant issues, such as a loose coupling between services. The mapping rules enable a systematic derivation of web services so that prior considered quality attributes are also fulfilled by the implementation artifacts.

The created mapping rules have been exemplified by means of a service-oriented workshop organization system. The system has been created using a model-driven approach. After capturing the requirements, the service designs have been created and aligned with wide-spread quality attributes as introduced by Gebhart et al. [7][29] using the QA82 Analyzer [32]. The methodology has been described in [33]. Afterwards, the service designs have been used to derive web services using the extended mapping rules.

The rules on the one hand help IT architects to understand the relation between service designs, the language SoaML, and web services as implementation, which allows IT architects to reduce the impact of service design changes on the final implementation. On the other hand, the mapping rules constitute the conceptual basis for automatic transformation as they can be realized using languages, such as Query Views Transformation (QVT) [34]. This will increase the significance of SoaML in model-driven development processes as it represents a full-fledged development artifact.

In the past, we especially focused on the creation of quality attributes and metrics for service designs based on SoaML. Also our tool, the QA82 Analyzer that enables automatic quality analyses aimed at the analyses of SoaML models. The conceptual understanding about how characteristics of service designs are reflected within web service implementations enables us to transform our existing SoaML metrics into metrics for web services. Thus, in the future our QA82 Analyzer will also be able to analyze web services regarding wide-spread quality attributes, such as loose coupling and autonomy.

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Incorporating Design Knowledge into the Software Development Process using Normalized Systems Theory

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***Abstract*—The knowledge residing inside a firm is considered to be one of its most important internal assets in obtaining a sustainable competitive advantage. Also in software engineering, a substantial amount of technical know-how is required in order to successfully deploy the organizational adoption of a technology or application. In this paper, we show how knowledge on the development of evolvable software can be managed and incorporated into a knowledge base, to enable the more productive construction of evolvable systems. The Normalized Systems (NS) theory offers well-founded knowledge on the development of highly evolvable software architectures. This knowledge is captured in the form of Normalized Systems elements, which can be regarded as design patterns. In this paper, it is discussed how Normalized Systems elements facilitate the management of state-of-the-art knowledge in four processes: (1) knowledge creation, (2) knowledge storage/retrieval, (3) knowledge application, and (4) knowledge transfer. Based on this discussion, it is shown how lessons can be drawn from the NS approach for the management of software engineering knowledge.**

***Keywords-Normalized Systems*; *Design Patterns*; *Knowledge Management*.**

I. Introduction

As we highlighted in our previous work on which this paper further elaborates [1], an important movement within the strategic management literature, the resource-based view of the firm (RBV) states that internal resources (e.g., money, patents, buildings, geographical location,etc.) are the key elements for organizations in order to obtain a sustainable competitive advantage [2]. More specifically, the *knowledge* residing inside a firm is frequently considered to be its most important internal asset [3]. Further, focusing on the case of software adoption and development within organizations, the prevalence of the available knowledge becomes even clearer and knowledge management practices have in this respect been acknowledged frequently [4]. Indeed, information technology in general can be considered as a knowledge-intensive or complex technology innovation, requiring a substantial amount of know-how and technical knowledge by the adopting firm [5]. As a result, the degree of expertise or advanced knowledge of best-practices regarding a certain software technology becomes a decisive factor in the possibility for an organization to successfully deploy and manage it. Consequently, a firm should either already (i.e., prior to the adoption) possess the advanced knowledge required to operate the software technology or engage in *organizational learning* during exploitation.

Organizational learning is generally regarded as the result of individual learning experiences of members of an organization, which become incorporated into the behavior, routines and practices of the organization the individuals belong to [5]. According to Levitt and March [6], such an organizational learning can occur in two general ways: (1) "learning by doing", which involves a learning process by self-experienced trial-and-error and (2) learning from the direct experiences of other people. While the first type of learning is typically a very profound and thorough way of knowledge gathering, it can be time-consuming, expensive and error-prone in the earliest stages. At this point, know-how, experiences and best-practices formulated by other users (i.e., the second type of organizational learning) come into play. Inside organizations, such knowledge transfers in software development can occur in many different ways, including, for example, explicit knowledge bases or experience repositories [7], "yellow pages" enabling search actions for accessible knowledgeable people [8] and mentoring programs [9]. At the inter-organizational or industrial level, the gathered knowledge can benefit from experience based on many different development projects.

In this paper, we explore how knowledge is managed within Normalized Systems (NS) theory (outlined in Section III). Furthermore we will indicate how this approach is deemed to offer additional benefits in terms of knowledge management compared to other software engineering approaches. In order to do so, the widely accepted framework of Alavi and Leidner [10] (summarized in Section II) will be used to base this claim and position how NS supports knowledge management in the development process of evolvable

software. Specifically, the role of knowledge in NS will be demonstrated according to four knowledge processes [10]:

- Knowledge Creation
- Knowledge Storage/Retrieval
- Knowledge Application
- and Knowledge Transfer.

This analysis will be presented in Section IV, after which an overview and a discussion regarding some significant differences between NS patterns and more commonly known design patterns, will be offered in Section V. Finally, we conclude the the paper in Section VI.

This paper is an extension of our previous work [1], as it offers a more in-depth analysis of knowledge management practices regarding NS and includes additional illustrating examples, guided by the widely accepted work of Alavi and Leidner [10].

II. Knowledge Management and Information Technology

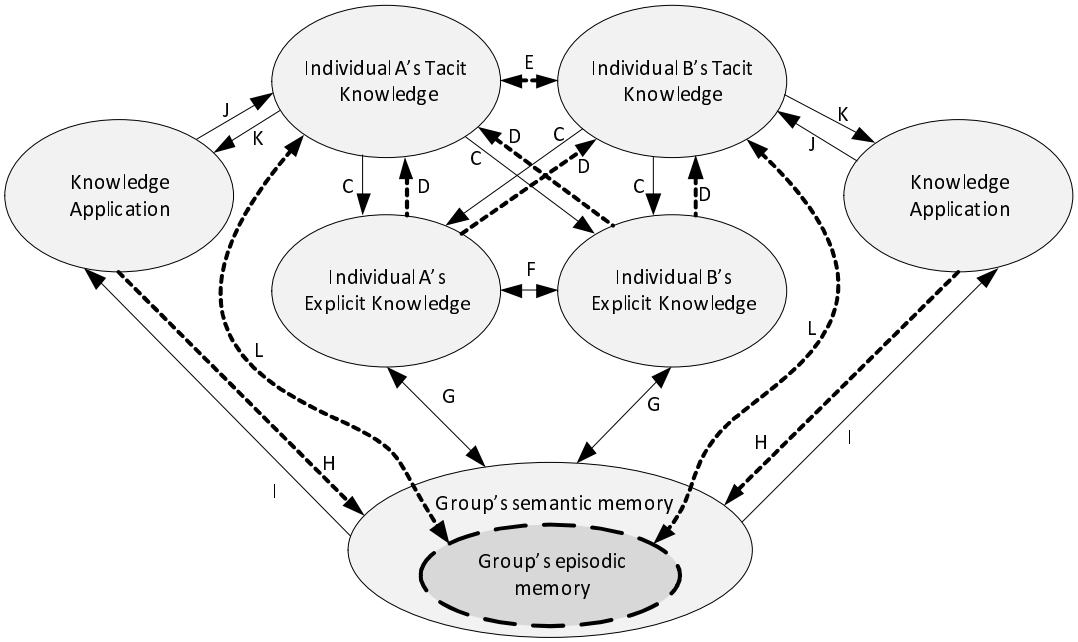
Over the last decades, knowledge and knowledge management (KM) have been the subject of research within several disciplines, such as knowledge engineering, artificial intelligence, social science, management science, information science, etc. [11]. Due to this multidisciplinary character of the research topic, knowledge and knowledge management have been defined in numerous ways. In spite of this variety of definitions, the goal of knowledge management can most ordinarily be defined as to facilitate the flow of knowledge. To define what knowledge management covers, Tuzhilin identified some common aspects among the variety of KM definitions [12]. In its essence, the management of knowledge should include the acquisition, conversion, structuring and organizing and sharing of knowledge. These essential and agreed upon components of knowledge management are very similar to the framework formulated by Alavi and Leidner [10], of which the core aspects will be summarized below. Given the fact that Alavi and Leidner [10] have performed an in-depth, overarching and widely cited overview and analysis of knowledge management aspects present during the use of information systems, we choose to discuss and employ this framework in the current paper. Hence, in this section, we highlight this particular framework to analyze and discuss how information technology and IT artifacts in general can be used to engage in knowledge management. Alavi and Leidner distinguish four main processes of knowledge management facilitated by information systems: (1) knowledge creation, (2) knowledge storage/retrieval, (3) knowledge application and (4) knowledge transfer. We will highlight each of these processes briefly in the following sub-sections. The concepts of this framework are represented in Figure 1. During our discussion, we will systematically relate each of the processes to the this figure. Also, we will illustrate the application of this framework in previous work by showing how other authors have used this framework to analyze their knowledge management efforts by using information systems [13]. Later on, we will use this framework as our starting point for analyzing how NS theory enables an efficient way of knowledge management.

A. Knowledge Creation

Before one can only begin to point out the importance of knowledge management, knowledge needs to be *created*. Such knowledge creation can both entail the development of new content or the replacement or improvement of already existing knowledge within the organization. Although this creation process always fundamentally starts from an individual, interactions between individuals are an equally important factor in the knowledge creation process [14]. These interactions are represented by the conversion types of knowledge presented by Nonaka, which are based on the differentiation of explicit and tacit knowledge [14]. Based on the conversion of knowledge between these two types, he distinguishes four possible modes of knowledge creation (although they are mentioned to be often interdependent and intertwined in reality) [10]: (1) *socialization* (the transfer of one's personal tacit knowledge to new tacit knowledge of another person), (2) *externalization* (the conversion of tacit knowledge to new explicit knowledge, such as formulated in best practices), (3) *internalization* (the conversion of explicit knowledge to one's tactic knowledge, such as truly understanding some read findings) and (4) *combination* ("the creation of new explicit knowledge by merging, categorizing, reclassifying, and synthesizing existing explicit knowledge").

Each of these knowledge creation modes are also visually represented in Figure 1. More specifically, arrow E represents socialization, arrows C represent externalization, arrows D represent internalization and arrow F represents combination. For each of the discussed knowledge creation modes, facilitating conditions or environments can be considered. Also, for these processes, the interaction with information systems and technology is twofold. On the one hand, the knowledge creation modes facilitate the amassment of knowledge on technologies and information systems used within an organization. On the other hand, information systems can be used to facilitate each of these knowledge creation modes in several ways (e.g., by the use of information systems for collaboration support).

As an example of academic efforts to identify knowledge creation, one can cite the work Lee et al. [13], who studied the knowledge management of a Korean automobile company. More specifically, they reviewed the process of making engineering changes to the finished design of automobiles from a knowledge-management perspective. They however found that little attention is payed to the knowledge creation within the knowledge-intensive process of making engineering changes. The knowledge that is amassed from a design change is documented in separate documents, without



Legend:

C: externalization
D: internalization
E: socialization
F: combination
G: the transfer of individual explicit knowledge to group semantic memory and vice versa
H: the learning derived from an individual in applying knowledge that becomes part of the group's episodic memory
I: an indiviual drawing upon group memory and applying the knowledge to a situation
J: the process of learning
K: the process of application
L: the transfer of individual tacit knowledge to group episodic memory and vice versa

process used within NS knowledge management

process uncovered by NS knowledge management

Figure 1. Visual representation of different knowledge management processes, adapted from Alavi and Leidner [10].

being captured in a knowledge base or incorporated into (other) workflows. Lee et al. therefore argue that due to the importance of the knowledge creation process, it should be supported better by proper knowledge management and a more elaborate Knowledge Management System (KMS) [13].

B. Knowledge Storage/Retrieval

To fully leverage its value, knowledge needs to be diffused across individuals within a company, research area,etc. once it has been created. Otherwise, companies lose the knowledge by simply forgetting the newly created knowledge or by forgetting it exists [15], [16]. However, this can be prevented by what literature identifies as individual and organizational memories, which are used within the knowledge storage and retrieval process [10]. Whereas the individual memory is simply referring to the knowledge of a single person, organizational memory is defined as "the means by which knowledge from the past, experience, and events influence present organizational activities" [17]. Such organizational memory can be facilitated by several means, including written documentation, databases with structured information, etc. Also, to a certain extent, organizational memory may extend traditional individual memories by including components such as organizational culture, structure, information archives, and so on. It may be subdivided in semantic memory (i.e., general, explicit and articulated memory) and episodic memory (i.e., context-specific and situated knowledge) [18]. Organizational memory is claimed to have both possible positive effects (e.g., by being able to reuse good solutions in the form of standards and procedures and by avoiding to make mistakes again) and negative effects (e.g., decision-making biases or status quo tending behavior). The authors of [10] mention database management techniques, document management

and groupware applications as typical IT means to develop and maintain (i.e., store) the "memory" of an organization. Additionally, IT artifacts in terms of design patterns have been claimed to provide useful means to store and retrieve organizational knowledge and best-practices. This is obvious within the domain of software engineering, as for instance initiated by the work of Gamma et al. [19]. The use of design patterns facilitates the translation of individual knowledge to organizational knowledge and the opposite translation (see the bidirectional arrow G in Figure 1) by offering a central organizational knowledge base (i.e., the design patterns). The design patterns within this knowledge repository can be accessed by all programmers for both storage and retrieval of the latest iteration of the design patterns. In this way, the central knowledge base acts as the organizational memory and thereby "helps in storing and reapplying workable solutions in the form of standards and procedures, which in turn avoid the waste of organizational resources in replicating previous work" [10]. In Section V, we will further elaborate on this specific way of enabling knowledge storage and retrieval by means of design patterns and how these more traditional design pattern approaches differ from the Normalized Systems theory patterns on which we focus in the remainder of the paper.

In Figure 1, the various kinds of knowledge repositories are represented by the ovals, as they represent both knowledge repositories or memories at the organizational and individual level. Obviously, as the aim in organizational knowledge management is to leverage the storage and retrieval of the organizational memory, the main focus should be placed on the ovals labeled as containing group memory. The processes of knowledge storage and retrieval, are represented by the bidirectional arrow G.

In the previously discussed research of Lee et al. [13], knowledge is stored in an intranet system. All engineering change requests (ECRs) and engineering change orders (ECOs) are automatically stored in a repository. The problem with this repository is however that it does not provide the functionality to navigate for relevant knowledge. Another important aspect that the repository lacks is the possibility of linking specific engineering changes with related problems, solutions,etc. These shortcomings clearly show the different levels and possible implementations of knowledge storage management [13].

C. Knowledge Application

The only way an organization can valorize the knowledge stored in its organizational memory, is by eventually applying the knowledge. Such applications might be realized by practices ranging between a continuum from directives (i.e., a set of specific rules, standard and procedures to make the tacit knowledge of specialists explicit for efficient communication, including non-specialists) to self-contained task mechanisms (i.e., a group of individuals with prerequisite knowledge in several domains which becomes combined in the considered team without explicitly formulated routines or procedures).

As typical examples of the usage of IT systems, corporate intranets are mentioned as useful means to access and maintain directives. Similarly, workflow automation systems and rule-based expert systems are suggested as interesting IT artifacts to enable the efficient automation of captured organizational knowledge and procedures.

Also, a large amount of codified best-practice might generate a new problem as the organizational members need to become competent in choosing the adequate best-practices to be employed.

The extent to which practitioners depend on the application of centrally available knowledge is demonstrated by Lee et al. [13]. When valuable knowledge about the incorporation of design changes is not readily available, engineers have to solely rely on their own tacit knowledge and off-line communication with colleagues to deal with challenging engineering changes. This shows that the application of knowledge highly depends on the available knowledge stored in a repository or transferred between agents.

D. Knowledge Transfer

The fourth knowledge management process discussed by Alavi and Leidner is the transfer of knowledge [10]. This process is considered to be an important process in knowledge management, as it provides the transfer of knowledge between individuals, groups, organizations and other sources. In spite of the acknowledgment of its importance, the dissociation of knowledge transfer from knowledge sharing is still unclear and both terms are often used interchangeably in academic literature [20]. Transfer and sharing can however be differentiated based on some parameters. While knowledge transfer is considered to be focused and direct communication to a receiver, sharing is far more a way of diffusing knowledge widespread (i.e., to multiple people via for example a repository). These two definitions are however just two extremes of an hypothetical continuum in which characteristics of both terms can be combined [21]. Others authors also point out that knowledge sharing is about exchanging tacit knowledge [22], while knowledge transfer exchanges more explicit knowledge [23], [24].

Within the case study of Lee et al. [13], one out of three problems related to a change in the final design of a car where not new. Because of significant differences between car models, knowledge on a specific problem (requiring a design change) on one component or car model cannot be easily transferred to another component or car model. The knowledge in this case can therefore be classified as very context-specific, consistent with the definition of episodic knowledge by El Sawy et al. [13], [18]. This example

therefore shows how the type of knowledge also impacts the transfer of knowledge.

III. Normalized Systems

The Normalized Systems (NS) theory starts from the postulate that software architectures should exhibit *evolvability* due to ever changing business requirements, while many indications are present that most current software implementations do not conform with this evolvability requisite. Evolvability in this theory is operationalized as being the absence of so-called *combinatorial effects*: changes to the system of which the impact is related to the size of the system, not only to the kind of the change which is performed. As the assumption is made that software systems are subject to unlimited evolution (i.e., both additional and changing requirements), such combinatorial effects are obviously highly undesirable. In the event that changes are dependent on the size of the system and the system itself keeps on growing, changes proportional to the systems size become ever more difficult to cope with (i.e., requiring more efforts) and hence hampering evolvability. Normalized Systems theory further captures its software engineering knowledge by offering a set of four theorems and five elements, and enables the application of this knowledge through pattern expansion of the elements. The theorems consist of a set of formally proven principles which offer a set of necessary conditions which should be strictly adhered to, in order to obtain an evolvable software architecture (i.e., in absence of combinatorial effects). The elements offer a set of predefined higher-level structures, primitives or "building blocks" offering an unambiguous blueprint for the implementation of the core functionalities of realistic information systems, adhering to the four stated principles [25].

A. Theorems

Normalized Systems theory proposes four theorems, which have been proven to be necessary conditions to obtain software architectures in absence of combinatorial effects [26] :

- *Separation of Concerns*, requiring that every change driver (concern) is separated from other concerns by separating it in its own construct;
- *Data Version Transparency*, requiring that data entities can be updated without impacting the entities using it as an input or producing it as an output;
- *Action Version Transparency*, requiring that an action entity can be upgraded without impacting its calling components;
- *Separation of States*, requiring that each step in a workflow is separated from the others in time by keeping state after every step.

In terms of knowledge management, as mentioned explicitly in [27], it must clearly be noted that the design theorems proposed are not new themselves; in fact, they relate to well-known (but often tacit or implicit) heuristic design knowledge of experienced software developers. For instance, well-known concepts such as an integration bus, a separated external workflow or the use of multiple tiers can all be seen as manifestations of the Separation of Concerns theorem [27]. Consequently, the added value of the theorems should then rather be situated in the fact that they (1) make certain aspects of that heuristic design knowledge explicit, (2) offer this knowledge in an unambiguous way (i.e., violations against the theorems can be proven), (3) are unified based on one single postulate (i.e., the need for evolvable software architectures having no combinatorial effects) and (4) have all been proven in a formal way in [26].

B. Normalized Systems Elements as Patterns

The theorems stated above illustrate that traditional software primitives do not offer explicit mechanisms to incorporate the principles. As (1) each violation of the NS theorems during any stage of the development process results in a combinatorial effect, and (2) the systematic application of these theorems results in very fine-grained structures, it becomes extremely challenging for a human developer to consistently obtain such modular structures. Indeed, the fine-grained modular structure might become a complexity-issue on its own when performed "from scratch". Therefore, NS theory proposes a set of five elements as encapsulated higher-level patterns complying with the four theorems:

- *data elements*, being the structured encapsulation of a data construct into a data element (having get- and set-methods, exhibiting version transparency,etc.);
- *action elements*, being the structured encapsulation of an action construct into an action element;
- *workflow elements*, being the structured encapsulation of software constructs into a workflow element describing the sequence in which a set of action elements should be performed in order to fulfill a flow;
- *connector elements*, being the structured encapsulation of software constructs into a connector element allowing external systems to interact with the NS system without calling components in a stateless way;
- *trigger elements*, being the structured encapsulation of software constructs into a trigger element controlling the states of the system and checking whether any action element should be triggered accordingly.

More extensive descriptions of these elements have been included in other papers (e.g., [25]–[27]). As these elaborated descriptions would offer little to no value to this paper, they were not included here. Each of the elements is a pattern as it represents a recurring set of constructs: besides the intended, encapsulated core construct, also a set of relevant cross-cutting concerns (such as remote access, logging, access control, etc.) is incorporated in each of these elements. For each of the patterns, it is further described

in [27] how they facilitate a set of anticipated changes in a stable way. In essence, these elements offer a set of building blocks, offering the core functionalities for contemporary information systems. In this sense, the NS patterns might offer the necessary simplification by offering pre-constructed structures that can be parametrized during implementation efforts. This way the NS patterns dictate the source code for implementing the pattern.

Regarding these patterns, it can be noted that their definition and identification are based on the implications of the set of theorems. For instance, the theorems Separation of Concerns (SoC) and Separation of States (SoS) indicate the need to formulate a workflow element. Contrary (and in addition) to an action element, such a workflow element allows the stateful invocation of action elements in a (workflow) construct. The SoS principle indeed requires this kind of stateful invocation and the SoC principle demands that the concern of invocation is handled by a separate construct. Next, each of the five patterns themselves contain knowledge concerning all the implications of the theorems referred to in Section III-A. Finally, each of these patterns has been described in a very detailed way. Consider for instance a data element in a Java Enterprise Edition (JEE) implementation (a widely used platform for the development of distributed systems) [28]. In [27] it is discussed how a data element `Obj` is associated with a bean class `ObjBean`, interfaces `ObjLocal` and `ObjRemote`, home interfaces `ObjHomeLocal` and `ObjHomeRemote`, transport classes `ObjDetails` and `ObjInfo`, deployment descriptors and EJB-QL for finder methods. Additionally, methods to manipulate a data element's bean class (create, delete, etc.) and to retrieve the two serializable transport classes are incorporated. Finally, to provide remote access, an agent class `ObjAgent` with several lifecycle manipulation and details retrieval methods is included. It can be argued that these elements incorporate the main concerns which are relevant for their function.

Moreover, the complete set of elements covers the core functionality of an information system. Consequently, as such detailed description is provided for each of the five elements, an NS application can be considered as an aggregation of a set of instantiations of the elements. Consider for example the implementation of an observer design pattern [19]. In order to implement this pattern in NS, three data elements (i.e., `Subscriber`, `Subscription` and `Notification`) are required. A `Notifier` connector element will observe the subject, and create instances of the `Notification` data element. These `Notification` data elements will be sent to every `Subscriber` that has a `Subscription` through a `Publisher` connector element. The sending is triggered by a `PublishEngine` trigger element which will periodically activate a `PublishFlow` workflow element. Consider that each NS element consists of around ten classes [25]. The seven identified elements therefore result in around seventy classes used to implement the design pattern, whereas the original implementation of the design pattern consists of two classes and two interfaces. Consequently, it is clear that, in order to prevent combinatorial effects, a very fine-grained modular structure needs to be adhered to.

C. Pattern Expansion

As stated before, in practice, the very fine-grained modular structure implied by the NS principles seems very unlikely to arrive at without the use of higher-level primitives or patterns. The process of defining these patterns and transforming them into code is shown in Figure 2. As NS proposes a set of five elements which serve for this purpose, this figure shows how the actual software architecture of NS conform software applications can be generated relatively straightforward. First the requirements of the application are translated in instantiations of the five NS elements. To achieve generated software code, these instantiations need to be created. Therefore, the instantiations are coded into so-called descriptor files, which are text- or XML-based files describing the inputs for the expanders. For example, in case of the data element pattern, the pattern expansion mechanism needs a set of parameters including the basic name of the data element (e.g., `Invoice`), context information (e.g., component and package name) and data field information (e.g., data type). The expanders then generate skeleton source code for all these instantiations, together with all deployment and configuration files required to construct a working application on one of several technology stacks, such as Java Enterprise Edition. For the invoice example, this would be the set of classes and data fields: the bean class `InvoiceBean`, interfaces `InvoiceLocal` and `InvoiceRemote`,etc. As the code generation process is typically very fast, this allows for interactive sessions to use the generated application to validate the correctness of the descriptor files. Next, extensions can be added to the generated code, but only in very specific pre-defined locations in the generated code to ensure that the extension do not compromise the control of combinatorial effects. Extensions can be inserted typically in the implementation class of an action element, or more generally in pre-specified anchors in the code. Next, these extensions are harvested by automated tools and stored separately from the skeleton code. When a new version of the expanders is built, for example with new frameworks in the web tier or in the persistence tier, or with minor upgrades, the application is re-generated by first expanding the skeleton code and then injecting the extensions.

In terms of knowledge management, it should be noted that the patterns and the expansion mechanism should not be considered as separate knowledge reuse mechanisms: rather, the pattern expansion facilitates the re-use of knowledge embedded in the patterns, as each expansion of the patterns

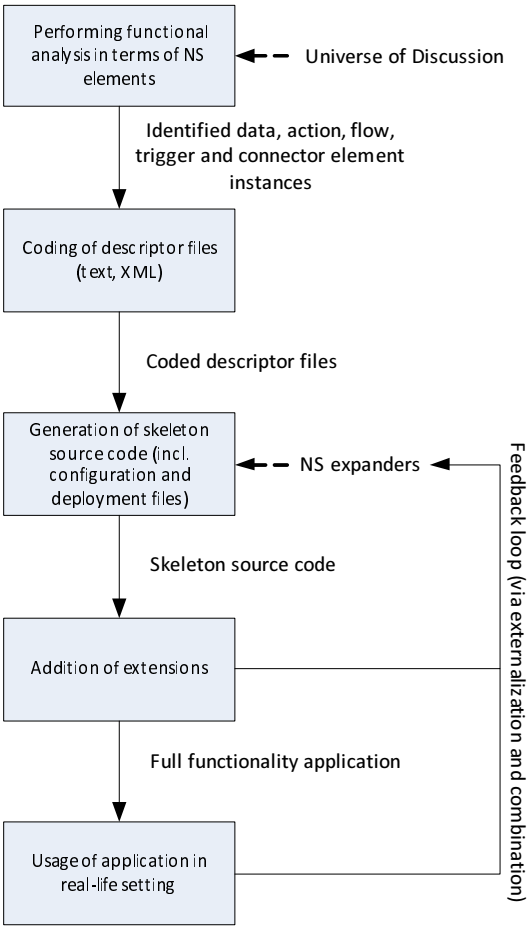


Figure 2. Visual representation of the Normalized Systems development process.

results in a new application of the knowledge encapsulated in the pattern. Through this, pattern expansion facilitates both types of learning discussed earlier (i.e., "learning by doing" and learning from experience of other people) by utilizing the knowledge contained in the patterns.

Also, the information codified in a pattern may not be sufficient to adequately transfer the intended knowledge. This is even the case when using the design patterns proposed by Gamma et al. [19]. For example, it has been claimed that the *Dependency Inversion Principle* helps to gain a better understanding of the *Abstract Factory* pattern [29]. Similarly, the structure of the NS patterns can only be understood when the NS theorems are taken into account.

IV. Normalized Systems Patterns as Knowledge Management

In the previous sections, we explained four processes that are widely regarded to be the essential processes of knowledge management. We also outlined how Normalized Systems theory employs a set of NS patterns to represent a fine-grained modular structure which can be systematically expanded to provide an evolvable software architecture. In this section, we discuss how the use of NS patterns seems to facilitate each of the four essential processes of knowledge management as identified by Alavi and Leidner [10].

A. Knowledge Creation

As discussed in section III-B, Normalized Systems theory relies on the use of patterns to capture design knowledge. One of the main purposes of the use of patterns and the associated pattern expansion mechanism, is to easily incorporate new knowledge into the patterns themselves, and the expanded NS applications in a second stage. Therefore, Normalized Systems theory can be considered to easily facilitate knowledge creation using IT artifacts (i.e., elements as design patterns). This opportunity for knowledge creation can be interpreted from two distinct perspectives.

First, improvements (i.e., new content) or changes (i.e., replacement of already existing knowledge such as typical bug fixing or a new kind of algorithm) regarding the actual functional parts of the system (i.e., the so-called 'tasks') are easily incorporated in the whole system (i.e., transformed from tacit into explicit knowledge). This because functional parts that are different change drivers are separated according to NS principles, meaning a single functional part is the only place where any modifications have to be made and the remainder of the system can easily interact with the new task (and hence, use this knowledge). In NS terms, we could call this kind of changes and expertise inclusions, knowledge dispersion at the "*sub-modular level*" as only changes and new knowledge are incorporated at the sub-modular level of the tasks (and not in the modular structure of the elements). In order to illustrate this first kind of knowledge creation in NS, consider the developments on the connector element. A *user connector* element allows a user to interact with the application, for example by offering create, read, update, delete and search (CRUDS) functionality on a data element. Such connector elements are expanded based on the parametrization of the data elements, resulting in separate CRUDS screens for every data element. In certain applications, the end users requested that CRUDS functionality for different data elements is combined within one page. This could be achieved, but only by adding extensions to the expanded code from the connector element. These extensions were performed by the same team of programmers over and over again. After several iterations, different ways of integrating CRUDS functionality emerged, which were referred to by the programmers of these extensions using specific names. For example, a screen where a linked data element is added below another data element is referred to as a "waterfall screen". For such a waterfall screen, a reoccurring extension needs to be made every time. Once the specific code for creating this screen is separated from other concerns, it can be added to the connector element. Therefore, the user connector element

will be updated to provide the expansion such waterfall screen without needing any extension. According to the programmers, this can only be achieved because all other concerns are removed from within the functional class of the connector element, allowing them to focus solely on the organization of the user interface components.

Second, knowledge can be incorporated at the "*modular level*" as well. This kind of knowledge inclusion would include change (e.g., an extra separated class in the pattern) and modifications (e.g., improved persistence mechanism) regarding the internal structure of an element (the pattern). Indeed, once the basic structure or cross-cutting concern implementation of an element is changed due to a certain identified need or improvement, the new best-practice knowledge can be expanded throughout the whole (existing) modular structure and used for new (i.e., additional) instantiations of the elements. In order to further illustrate this second kind of knowledge creation based on NS patterns, consider the following example, based on real-life experience from developers using NS.

For instance, one way to adopt a model-view-controller (MVC) architecture in a JEE distributed programming environment is by adopting (amongst others) the Struts framework. In such MVC architecture, a separate controller is responsible for handling an incoming request from the client (e.g., a user via a web interface) and will invoke (based on this request) the appropriate model (i.e., business logic) and view (i.e., presentation format), after which the result will eventually be returned to the client. Struts is a framework providing the controller (ActionServlet) and enabling the creation of templates for the presentation layer. Obviously, security issues need to be handled properly in such architecture as well. Applied to our example, these security issues in Struts were handled in the implementation of the Struts Action itself in a previous implementation of our elements. In other words, the implementation class itself was responsible for determining whether or not a particular operation was allowed to be executed (based on information such as the user's access rights, the screen in which the action was called, etc.). As a result, this "security function" became present in all instantiations of an action element type (i.e., each session). Moreover, this resulted in a combinatorial effect as the impact of a change such as switching towards an equivalent framework (i.e., handling similar functions as Struts), would entail a set of changes dependent on the number of instantiated action elements (and hence, on the size of the system). In order to solve the identified combinatorial effect, the Separation of Concern theorem has to be applied: separating the part of the implementation class responsible for the discussed security issues (i.e., a separate change driver) in its own module within the action element. In our example, a separate interceptor module was implemented, next to the already existing implementation class. This way, not only the combinatorial effect was excluded, but the new knowledge in terms of a separate interceptor class was applied to all action elements after isolating the relevant implementation class parts and executing the pattern expansion. Additionally, all new applications will use the new action element.

Considering the underlying idea of design patterns and the NS element, namely to transform tacit knowledge into explicit knowledge, one can readily understand why theories using design patterns (such as NS) mostly rely on "externalization" and "combination" regarding the relevant knowledge management aspects. Thereby, both these knowledge creation processes refer to the definition of new explicit knowledge, be it from existing tacit knowledge (i.e. externalization) or existing explicit knowledge (i.e. combination). First, the use of *externalization* is demonstrated by the fact a lot of good programming practices (i.e., best-practices) are incorporated in the structure of the elements themselves. Indeed, while the NS theorems prescribe a set of necessary conditions in order to attain evolvable and easily adaptable software architectures, the elements provide a constructive proof and explicit way of working regarding how to achieve this in reality, which is generally conceived to be only attainable by very highly experienced and skilled programmers. For instance, designing software architectures in such a way that the cross-cutting concerns are integrated in a fine-grained modular way is considered to be rather challenging. The formulation of the elements in combination with the expansion mechanism allow a way to externalize this experience and apply it at large scale. Second, one example of the use of *combination* to formulate new explicit design knowledge within NS, is the elimination of combinatorial effects within a software application. Whenever violations of the four NS principles are discovered within new software, programmers report the violations and their effects to their colleagues and supervisors. This way, a solution can be found for eliminating the violations (using both tacit and explicit knowledge).

B. Knowledge Storage/retrieval

Knowledge storage and retrieval should ensure that a certain expertise within companies is retained and placed easily at the disposal of the relevant people within the organization, in order to be applied at a later stage. In the Normalized Systems approach, a major part of the knowledge is stored within the NS elements. These elements offer a standardized way to create (i.e., generate) software applications by prescribing a set of predefined and systematically re-used modules. Consequently, the use of design patterns (i.e., the NS elements) facilitates the translation of individual knowledge to organizational knowledge by offering a central organizational knowledge base (i.e., the design patterns). The design patterns within this knowledge repository can be accessed by all programmers for both storage and retrieval of the latest iteration of the design pattern, and can hence

be considered to be a part of the organizational memory. With Normalized Systems, this advantage of re-using the "standard" design patterns is in fact exceeded by the benefit of using a solution that —from an evolvability viewpoint— is proven to be optimal.

To further position knowledge used within Normalized Systems, we can refer once more to the classification of El Sawy et al. [18], which breaks down organizational memory into semantic memory and episodic memory. As the design patterns formulate a sound software structure that is generally applicable to every software application, this knowledge should be classified as semantic knowledge. The opposite of this general and explicit semantic knowledge is the so-called episodic knowledge, which is defined as context-specific knowledge. As Normalized Systems formulates general software architecture principles for software, this type of organizational knowledge is not part of the general Normalized Systems patterns. This context-specific knowledge in incorporated in so-called extensions that are added to the software after the expansion based on the five recurrent elementary structures. Because the patterns are detailed enough to be instantiated, no manual implementation of the patterns (as is the case with the design patterns proposed by Gamma et al. [19]) is required. Consequently, an identical code structure reoccurs in every application which is created using the expansion of NS elements. The commonality of the structure of the patterns makes that once one understands the patterns, one understands all its instantiations as well. In this way, it could be argued that —at least partially— the pattern structure becomes the documentation. Therefore, no source code level documentation is required and all knowledge is stored in the NS patterns. Such advantages can only be achieved for semantic knowledge, since episodic knowledge is different is various contexts.

C. Knowledge Application

In the Normalized Systems theory rationale, the knowledge present in the NS elements is applied by employing the elements as a design template for evolvable software. Each NS compliant software application is an aggregation of a set of instantiation of one of the five NS elements. Therefore, the knowledge of NS contained in the NS elements and their accompanying expansion mechanism can be considered to be prescriptions or directives as defined by Grant [3] (i.e., a set of rather unambiguous and specific standards or rules used to guide the actions of persons). When writing a software application, a programmer retrieves the latest version of the software design patterns from the knowledge repository. Afterwards, the element instances are parametrized and configured in descriptors files (e.g., the relevant fields, relationships,etc. for a data element are specified). Hence, by combining their tacit knowledge with the described structure of the NS elements, the programmers build evolvable software.

The use of the NS elements and theorems indeed results in evolvable and easily adaptable software architectures. For instance, an important characteristic of these structures is that they separate technology-dependent aspects from the actual implementation, resulting in the fact that one can easily switch the underlying technology stack of the software. One transition that has been performed, is changing the underlying implementation architecture from Enterprise Java Beans (EJB) version 2 to EJB version 3. Because these standards encapsulate the business logic of an application, they use a different way of communicating between agents and beans. Therefore, this transition normally is a labor-intensive and difficult task. Using the architecture described in this paper, this transition can however be achieved rather easily by using the pattern expansion mechanism. This is because the expanders that perform the expansion are very similar for different technologies. This is done by clearly separating functional requirements of the system (i.e., input variables, transfer functions and output variables) from constructional aspects of the system (i.e., composition of the system). Whereas all constructional aspects are described in patterns, functional aspects are separately included in descriptor files (such as data elements, action elements,etc.). As each pattern can be conceived a recurring structure of programming constructs in a particular programming environment (e.g., classes), one can conclude that the functional/constructional transformation then becomes located at one abstraction level higher than before.

An important result from the application of knowledge is that it is often combined with a learning process. By building software using the expansion of NS elements, the programmers improve both their tacit knowledge on building (evolvable) software and explicit knowledge that will be incorporated in the design pattern (i.e., NS elements). This increased tacit knowledge ("experience") will over time also contribute to the definition of changes to the design patterns. The inherent way of working implied by the NS expansion mechanism (i.e., expanding software architectures by systematically instantiating the NS elements, and incorporating new bits knowledge again into this core of patterns) also efficiently copes with the issue articulated in Section II-C, namely that the automated ways of working should be continually kept up-to-date.

D. Knowledge Transfer

Within a knowledge system, knowledge is transferred from where it is available (i.e., a repository) to where it is needed. For Normalized Systems, the knowledge repository of the NS design patterns (NS elements) needs consistent updating to reflect the most recent software architecture for evolvable software. This is done by transferring the new explicit design knowledge created by individuals to the group semantic knowledge repository of NS elements. The use of this repository can be characterized as impersonal

and formal, which promotes a faster and further distribution and is a good way to transfer knowledge that can be readily generalized to other contexts (which is the case for NS) [10]. Analogously to the discussion in Section II, the exchange of explicit knowledge (i.e., NS elements) in NS theory can be classified most appropriately as knowledge transfer. The use of a NS repository however bears closer resemblance to knowledge sharing process. This shows that the exchange of NS knowledge should be placed on the previously discussed continuum between knowledge transfer and knowledge sharing.

V. Discussion

In this section, in order to provide a summarizing overview of our analysis presented above, we will first discuss to which extent the knowledge management practices within Normalized Systems cover all aspects as identified by Alavi and Leidner [10], based on Figure 1. Next, we will present some reflections with respect to design patterns in general and how the use of elements within Normalized Systems seems to enhance the existing practices of design patterns regarding knowledge management on several domains.

A. Overview of knowledge management aspects of Normalized Systems

To recapitulate the NS knowledge management processes, we will discuss these processes according to the representation introduced by Alavi and Leidner [10], as shown in Figure 1. This figure has been adapted to represent whether or not the defined knowledge processes are used within Normalized Systems theory. This is done by indicating those processes which are not covered by the Normalized Systems theory by dotted lines. Consequently, full lines indicate the knowledge processes that are used within NS knowledge management.

Regarding the knowledge management creation processes (i.e., *arrows C, D, E, and F*), we can notice that the Normalized Systems theory primarily enables the externalization and combination processes (i.e., the processes indicated by the *arrows C* and *F* respectively). These processes aim to make implicit knowledge and best practices explicit (as is done by the formulation of the NS theorems and elements) and to combine already existing explicit knowledge among several members of the group (e.g., discussing additional concerns which need to be separated or improvements of the current elements). While the processes of socialization (i.e., *arrow E*) and internalization (i.e., *arrow D*) might occasionally occur in the NS community, those aspects are not explicitly managed within the Normalized Systems rationale. Indeed, the aim of the Normalized Systems approach is to design evolvable software architectures based on formally proven and tested (and hence, explicit) principles and their implications.

The bidirectional interaction between an individual's explicit knowledge repository and the group's memory is visualized trough *arrow G*. In NS reasoning, such explicit knowledge (e.g., the formally known need to separate a certain external technology in a distinct module) becomes embedded in the group's memory by incorporating it in the general structure of the NS elements and might subsequently offer new insights regarding the explicit knowledge of another person as well. Also *arrows K* and *J* are relevant in a NS context. The first represents the application of a developer's new tacit insights (i.e., new possible improvements of the elements) into a trial-version of the elements, while the latter may occur in the situation where the real-life implementation of software in an organizational setting may point out that a certain part of of a 'task' implemented in an action element evolves independently in a realistic setting, thus constitutes a separate change driver and should consequently be separated.

The transfer of individual tacit knowledge to group's episodic memory (i.e., *arrows L*), is a type of knowledge transfer that is not used in NS knowledge management. This simply because the knowledge repository does not include any type of episodic memory, rendering the transfer of knowledge non-existent. Arguably the most important transfer of knowledge within NS theory is the expansion of NS elements into evolvable software. This transfer is shown by *arrows I*, which represent the repeated use of design patterns (i.e., the NS elements) for building agile software. In the opposite direction, directly learning from the application of the NS elements is not supported in the knowledge management for NS theory (i.e., *arrows H*). As the Normalized Systems rationale stipulates a deterministic and proven way of constructing evolvable software based on the NS design theory, it does not allow new knowledge to be formulated directly from the application of the NS elements. Instead, new knowledge should always be rigorously verified by traditional knowledge creation processes of externalization and combination before being added to the existing knowledge base of NS elements.

Finally, the extension of the NS knowledge management to multiple groups will add an extra layer of complexity to the management of knowledge. However, the centrality of the current knowledge base and the limited size of developers working on the development of the NS elements are the reasons these challenges are not the main point of interest at this moment.

B. Knowledge Management using Design Patterns

As discussed in the introduction, knowledge management also plays an important parts in software engineering. The specific use of design patterns in object-orientation during the 90's, exemplified by the seminal work of Gamma et al. [19], was incited by the fact that modern computer literature regularly failed to make tacit (success determining) knowl-

edge regarding low-level principles of good software design explicit [30]. Patterns provide high-level solution templates for often-occurring problems. The patterns proposed by Gamma et al. [19] were conceived as the bundling of a set of generally accepted high-quality and best-practice solutions to frequently occurring problems in object-orientation programming environments. For instance, in order to create an one-to-many dependency between objects so that when the state of one object changes, all its dependents are notified and automatically updated, the observer pattern (i.e., an overall structure of classes giving a description or template of how to solve the concerned problem) was proposed [19]. As a consequence, the use of these patterns can be considered as specifically aimed at facilitating (inter-)organizational learning by learning from direct experiences of other people — in this case experienced software engineers —, and being one specific way of knowledge transfer.

According to Schmidt [31], design patterns have been so successful because they explicitly capture knowledge that experienced developers already understand implicitly. The captured knowledge is called implicit because it is often not captured adequately with design methods and notations. Instead, it has been accumulated through timely processes of trial and error. Capturing this expertise allows other developers to avoid spending time rediscovering these solutions. Moreover, the captured knowledge has been claimed to provide benefits in several areas [32]. Such benefits include (a) documentation of software code, (b) knowledge reuse when building new applications, and (c) incorporation of new knowledge in existing software applications. In this section, we focus on these benefits, and discuss how NS elements can be considered to be an improvement on this way of working.

1) Documentation: Patterns provide developers with a vocabulary which can be used to document a design in a more concise way [19], [32], [33]. For example, pattern-based communication can be used to preserve design decisions without elaborate descriptions. By delineating and naming groups of classes which belong to the same pattern, the descriptive complexity of the design documentation (e.g., a UML class diagram) can be reduced [33]. Consequently, the vocabulary offered by patterns allows a shift in the abstraction level of the discussions. This usage of design patterns is mostly applied at the conceptual level, and neglects the source code documentation. However, the abstract nature of patterns, i.e., as a solution template, means that it is possible to implement a certain design pattern using different alternatives. Therefore, it has been argued that the addition of source-code level documentation of the pattern usage is required to perform coding and maintenance tasks faster and with fewer errors [34].

In NS, the structure of the five software patterns could be described in a similar way. The focus would then be on the different concerns which need to be separated in each element. As discussed in Section III, each concern needs to be encapsulated in a separate module (e.g., a class in the object-oriented paradigm). Consequently, the different concerns dictate the modular structure of the element. As a result, this documentation could provide similar insights as obtained by traditional design patterns. However, the NS elements are described in such detail that they can be expanded, resulting in working code. In Section IV-B, we discussed how the reoccurring code structure in itself becomes the documentation for expanded software: because a certain piece of code is identical in every expanded instance, a programmer only needs to inspect this piece of code once in order to understand how that particular piece works. This eliminates the need for including documentation in every instance of source code. In conclusion, the pattern expansion allows documentation at the pattern level to be sufficient, eliminating the need for code-level documentation.

2) Using knowledge to build new applications: Several authors propose the usage of design patterns to create new software applications (e.g., [35]). Earlier we discussed how patterns provide high-level solution templates, and consequently, do not dictate the actual source code. As a result, knowledge concerning the implementation platform remains important. A correct and efficient implementation of a design pattern requires a careful selection of language features [31]. Clearly, design patterns alone are not sufficient to build software. As a result, the implementation of a design pattern during a software development process remains essentially a complex activity [31]. Developing software for a concrete application then requires the concrete experience of a domain and the specifics of the programming language, as well as the ability to abstract away from details and adhere to the structure prescribed by the design pattern. Nevertheless, certain companies and researchers attempt to integrate the knowledge available in design patterns in other approaches, in order to create automated code generation. For example, so-called software factories attempt to create software similar to automated manufacturing plants [36]. This should drastically improve software development productivity. However, such approaches have not yet reached widespread adoption.

The code expansion which occurs when using NS elements needs to be distinguished from this approach. Consider for example the action element. The functional class of such an element still needs to be programmed manually. However, the code for reoccurring concerns, such as remote access, can be expanded since this code is identical for different action element instantiations. Similarly, an instantiation of a data element needs to be functionally defined (i.e., through descriptor files which contain data field definitions). However, the concerns which reoccur in every data element instantiation are expanded. In Section IV-C, these are referred to as constructional elements. Consequently, the building of new applications applies code reuse to an

extent as large as possible: the common source code, which is similar for all element instantiations, is expanded, while functional requirements need to be provided by the programmer. As a result, an optimal way of using knowledge to build applications is applied, without restricting the programmer in addressing functional requirements.

3) Incorporating new knowledge in existing applications: Because of the increasing change in the organizational environment in which software applications are used, adaptability is considered to be an important characteristic. However, adapting software remains a complex task. Various studies have shown that the main part of the software development cost is spent after the initial deployment [37], [38]. Several design patterns focus on incorporating adaptability into their solution template. Empirical observations have been reported which confirm the increased adaptability when using design patterns [39]. Adaptations could be made easier in comparison with an alternative that was programmed using no design patterns, and achieved adaptability was retained more successfully because of the prescribed structure. Nevertheless, some researchers also report negative effects on adaptability, caused by the added complexity of the design patterns. By prescribing additional classes in comparison to simpler solutions, more errors have been introduced in some cases [39].

Both observations are consistent with the experiences obtained by developing NS. By separating all concerns within the elements, combinatorial effects are prevented, which allows improved adaptability. Since this is similar to how design patterns work, it shows how NS incorporates existing design knowledge. However, NS prescribes to separate more concerns than traditional patterns or methods. This leads to a very fine-grained, but complex structure. As described by Prechelt et al., such complexity reduces adaptability [39]. Therefore, the pattern expansion mechanism is a crucial component of NS, as discussed in Section III-C. We discussed how code expansion seems to be indispensable for knowledge reuse to separate concerns and prevent combinatorial effects. Moreover, the expansion mechanism also allows to make adaptations in a structured way. When changes or updates are applied to the elements, the expanded code can be updated by either re-expanding, or by using marginal expansion. Marginal expansion updates only parts of already expanded code, without replacing the expanded element as a whole. Consequently, newly generated knowledge (such as, e.g., a newly identified combinatorial effect) can be applied in existing applications as well.

C. Positioning NS as knowledge management

The approach of capturing knowledge using NS as described in this paper clearly deviates from the body of thought of other knowledge management approaches. For example, in the article by Tuzilin [12], the evolution of knowledge management systems from content management systems is discussed, and it is highlighted how the process of making tacit knowledge explicit was initially regarded to be optimal for capturing knowledge. However, as this proved to be an insurmountable challenge, future developments of knowledge management are expected to focus on the indexation of tacit knowledge. Consequently, when knowledge is needed, the responsible knowledge source can be identified, and can be shared without needing to make all tacit knowledge explicit. NS theory opposes this idea. The rate of reuse of the evolvable modular structure of software elements is too high to be supported by such communication-based approaches. Therefore, the knowledge captured in NS (i.e., being the modular structure of evolvable software patterns) is made explicit. Consider for example the implications of the Separation of Concerns theorem, as discussed in Section III-A. It implies that each concern needs to be separated in a separate module. Compare this to a non-normalized system, where multiple concerns are mixed in a module. These concerns are on a sub-modular level, and are not explicitly identified as different concerns. Nevertheless, knowledge of these concerns is vital, since they introduce combinatorial effects, and hence limit evolvability. The knowledge related to which concerns need to be separated is made explicit in NS through the modular structure, as available in the expanders.

Our discussed way of knowledge capture in NS is feasible since a specific kind of knowledge is focused on: the modular structure of software. For organizational knowledge, such a modular structure may not be well-suited, and different systems may be needed here (cf. infra). Nevertheless, many organizational issues are being studied as being modular structures. For example, coordination issues in supply chains have been claimed to be modularity issues [40]–[42]. Consequently, making knowledge concerning such issues explicit in a modular structure could be explored as well.

D. Contributions and Future Work

This paper could be claimed to have several contributions, while indicating several opportunities of future work. Regarding contributions, first, this paper might help in clarifying the particular way of how software applications are built according to the Normalized Systems way of thinking and —more specifically— how this enables the creation, storage/retrieval, application and transfer of knowledge. Our aim was to provide a practical overview, including examples, of how NS might enhance knowledge management in practice, based on a theoretically founded framework and its concepts. Second, this paper illustrates the possibility of readily applying the published framework of Alavi and Leidner [10] to analyze the knowledge management processes regarding a software development approach. To the authors' knowledge, no other researchers have described their software development approach based on this framework in such an extensive way. Therefore, this

paper illustrates the benefits researchers might realize by presenting their software development approach according to this framework for clarifying any related knowledge management benefits or issues, as well as the relevance of the considered framework for this purpose. Third, our analysis clearly highlighted how NS differentiates from the direction which is taken in other knowledge management approaches. In NS, knowledge is made explicit by capturing it into modular structures of evolvable software patterns, instead of pure textual descriptions. While we are not the first to argue that more efficient ways of knowledge management can be attained by the use of design patterns, we argued that the NS patterns could be hypothesized to be a sort of "enhanced design patterns" regarding documentation (i.e., only requiring documentation at the pattern level), knowledge usage (i.e., maximal code expansion) and new knowledge incorporation (i.e., including new knowledge by simple re-expansion or marginal expansions).

Regarding future work, we could first notice that, although the discussion in this paper is limited to Normalized Systems theory for software, the theory has recently been applied to both Business Process Management [43] and Enterprise Architecture [44] domains. As part of future research, the possible formulation and investigation of patterns on the level of business processes and enterprise architecture (and their knowledge management implications) can be studied. However, we already mentioned in Section V-C that the concerns (and hence modular structures) identified at these levels are of a different kind. Therefore, the knowledge management issues regarding the identification, storage and "deployment" of such modular structures at the organizational level should be investigated in the future as well.

Another area of future research concerns a more elaborated and detailed way of describing how the discussed knowledge management processes in NS relate to similar software development approaches. The Normalized Systems approach was shown to include and support the four widely adopted types of knowledge management processes. The question however remains how the support of these knowledge management processes by NS precisely relates to other software development paradigms and approaches. Such a comparison calls for rather extensive research efforts and is therefore suggested as part of future research.

VI. Conclusion

Creating, managing and applying knowledge is a crucial competence for organizations today. Therefore, knowledge management is a widely investigated and popular research topic. In this paper, we explored how Normalized Systems theory, and its use of elements and their expansion mechanisms in particular, support knowledge management in the development process of evolvable software. For this purpose, we employed the framework of Alavi and Leidner [10] to analyze how the four essential processes within knowledge management are facilitated in the Normalized Systems reasoning: (1) knowledge creation, (2) knowledge storage/retrieval, (3) knowledge application and (4) knowledge transfer. Our analysis shows that design patterns as a central knowledge repository facilitate the transfer of knowledge from an individual to others in an explicit and efficient way. All processes of Alavi and Leidner [10] seem to be supported by Normalized Systems reasoning. Some transformations are considered to be essential (e.g., new knowledge can be absorbed by arrow J in Figure 1 going from "knowledge application" to an individual tacit knowledge), while others are not directly (but rather indirectly) included in the NS rationale (e.g., not directly incorporating knowledge from applications into the group's memory, but through the knowledge creation processes of externalization and combination).

Further, we showed in this paper that the NS elements can be considered to be enhanced patterns for software development with benefits on three dimensions (i.e., less need for explicit documentation, more deterministic development of new applications and more convenient incorporation of new knowledge into existing applications). From interviews with developers, these benefits have shown to enhance the transfer of knowledge, success rate and the overall quality of NS developments.

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Enhancing the Performance of J2EE Applications through Entity Consolidation Design Patterns

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***Abstract*— J2EE is a specification of services and interfaces that support the design and implementation of Java server applications. Persistent and transacted *entity Enterprise JavaBean* objects are important components in J2EE applications. The persistence and transaction semantics of entity Enterprise JavaBeans, however, lead to a sometimes significantly decreased performance relative to traditional Java objects. From an application performance point of view, a J2EE-compliant object persistence and transaction mechanism with a lower performance penalty would be highly desirable. In this article, we present and evaluate two J2EE software design patterns aimed at enhancing the performance of entity Enterprise JavaBeans in J2EE applications with large numbers of JavaBean instances. Both design patterns consolidate multiple real-world entities of the same type, such as *users* and *communication sessions*, into a single *consolidated* entity Enterprise JavaBean. The entity consolidation results in a smaller number of entity JavaBean instances in a given J2EE application, thereby increasing JavaBean cache hit rates and database search performance. We present detailed experimental assessments of performance gains due to entity consolidation and show that consolidated Enterprise JavaBeans can accelerate common JavaBean operations in large-data J2EE applications by factors of more than 2.**

Keywords-Enterprise Java Beans; object caching; object consolidation; software design patterns; software performance

I. INTRODUCTION

In this article, we extend our earlier work on performance-enhancing J2EE software design patterns published in [1]. To make the article self-contained and thus easier to read, we include a comprehensive description of the research presented in [1]. The focus of our work is entity Enterprise JavaBeans (EJBs) [2]. Entity EJB objects take advantage of a plethora of platform services from EJB containers in J2EE application servers [3]. Examples of platform services are data persistence, object caching and pooling, object lifecycle management, database connection pooling, transaction semantics and concurrency control, entity relationship management, security, and clustering. EJB containers obviate the need for redeveloping such generic functionality for each application and thus allow developers to more quickly build complex and robust server-side applications.

A common and important component in J2EE application servers is an in-memory EJB cache that speeds up access to entity EJBs in an application's working set [4]. Yet, common entity EJB operations such as creating, accessing, modifying, and removing entity EJBs tend to execute much more slowly than analogous operations for traditional Java objects (J2SE objects, also often referred to as *Plain Old Java Objects* or simply *POJOs*) that do not implement the functional equivalent of the J2EE platform services. The performance of data-intensive J2EE applications, i. e., those with large numbers of entity EJBs, can therefore be much slower than desired.

Although not mandated by the EJB specification, entity EJBs are typically stored as rows in relational database tables and we will assume this type of storage in the remainder of this article. Furthermore, we will concentrate on entity EJBs with container-managed persistence (CMP) rather than bean-managed persistence (BMP). CMP entity EJBs have the advantage of receiving more platform assistance than BMP entity EJBs and are thus usually preferable from a software engineering point of view. They also tend to perform better than BMP entity EJBs because of extensive application-independent performance optimizations that EJB containers incorporate for CMP EJBs [5]. For the sake of simplicity, we will refer to CMP entity EJBs simply as "EJBs".

Note that the mapping from EJBs to database tables and the data transfer between cached EJBs and the database is the responsibility of the proprietary J2EE platform and can therefore be only minimally influenced by the EJB developer. Hence, we cannot discuss the direct impact of the design patterns presented in this article on structural or operational details of the data persistence layer of the J2EE platform. Instead, we will discuss how our technique changes the characteristics of the EJB layer that is under the control of the EJB developer and show how these changes affect the overall performance of EJB operations.

In the past, much research into improving J2EE application performance has focused on tuning the configuration of EJBs and of the EJB operating environment consisting of J2EE application servers, databases, Web servers, and hardware. In addition, some software engineering methods such as software design patterns and coding guidelines have been developed to address performance issues with J2EE applications. This article presents two J2EE software design patterns for accelerating J2EE applications. Both patterns result in specialized EJBs that we call *consolidated* EJBs (*CEJBs*). By applying the first pattern, we obtain *fixed-size* consolidated EJBs (*fCEJBs*). Fixed-size CEJBs are the topic of our earlier work published in [1]. The second, new pattern generates *variable-size* consolidated EJBs (*vCEJBs*). Both CEJB patterns attempt to optimize the caching and database storage of EJBs

for enhanced execution speed of common EJB operations (creating, accessing, modifying, and removing entities).

We devised these two software design patterns during a multiyear research project at Avaya Labs Research where we developed a J2EE-based context aware communications middleware called *Mercury*. Mercury operates on a large number of EJB instances that represent enterprise users and communication sessions (hence our *User* and *Session* EJB examples later in this article). Due to the large frequency of retrieval, query, and update operations on these EJBs, Mercury suffered from slow performance even after tuning J2EE application server and database settings. Thus, we felt compelled to investigate structural changes to Mercury's J2EE implementation as a remedy for the performance problems and arrived at the CEJB design patterns. The technical discussion in this article will show that our design patterns are more generally applicable in a wide range of J2EE applications.

The J2EE and entity Enterprise JavaBeans specifications that we refer to in this article have meanwhile been supplanted by updated standards and with a new terminology: The J2EE 1.4 specification has been replaced with Java EE 6 [6], and the entity EJBs in the Enterprise JavaBeans specification 2.1 have been replaced with entities according to the Java Persistence API 2.0 [7]. The software design patterns in this article remain equally relevant in the context of the new specifications and require mostly syntactic changes.

The remainder of this article is organized as follows. In Section II, we describe some of the related work. Section III contains an overview of the key idea behind both CEJB software design patterns. Section IV presents the fCEJB pattern and its use in J2EE applications. We describe the details of fCEJB allocation, the mapping of entities to fCEJBs, the storage of entities within fCEJBs, and retrieval of entities from fCEJBs. Similarly, Section V contains a detailed explanation of the vCEJB pattern. We compare the performance of fCEJBs, vCEJBs, and traditional EJBs in Section VI. A summary and an outline of future work conclude the article in Section VII.

II. Related Work

The performance penalty of using EJBs in J2EE applications has been well documented in the relevant literature, some of which we review in this section. A substantial number of articles present various remedies for this performance penalty, ranging from performance-tuning of application servers to alternative object persistence mechanisms to performance-enhancing EJB software design patterns. However, to our knowledge, our CEJBs are the first application-level approach that yields verified, substantial performance improvements in a wide range of J2EE applications where alternatives to EJBs are not acceptable, practical, or desirable. In our earlier research presented in [1] we introduced fCEJBs as a performance-enhancing J2EE software design pattern. However, in the presence of entities that do not have the cluster property that we describe in Section IV, fCEJBs perform no better than traditional EJBs. Our new vCEJB design pattern aims at addressing this shortcoming of fCEJBs.

Much research has been devoted to speeding up J2EE applications by tuning EJBs and J2EE application server parameters. Pugh and Spacco [8] and Raghavachari et al. [9] discuss the potentially large performance impact and difficulties of tuning J2EE application servers, connected software systems such as databases, and the underlying hardware. In contrast, CEJBs constitute an application-level technique to attain additional J2EE application speed-ups.

The MTE project [10][11] offers more insight into the relationship between J2EE application server parameters, application structure, and application deployment parameters on the one hand and performance on the other hand. The MTE project underscores the sensitivity of J2EE application performance to application server parameters as well as to the application structure and deployment parameters.

Another large body of research into J2EE application performance has investigated the relationship between J2EE software design patterns and performance. Cecchet et al. [12] study the impact of the internal structure of a J2EE application on its performance. Many examples of J2EE design patterns such as the session façade EJB pattern can be found in [13] and [14], while Cecchet et al. [15] and Rudzki [16] discuss performance implications of selected J2EE design patterns. The CEJB design patterns improve specifically the performance of EJB caches and database searches for EJBs. The Aggregate Entity Bean Pattern [17] consolidates logically dependent entities of *different* types into the same EJB while CEJBs consolidate entities of the *same* type into an EJB. Converting EJBs into CEJBs can therefore be automated by a tool whereas the aggregation pattern requires knowledge of the specific application and the logical dependencies of its entities. Aggregation and CEJBs can be synergistically used in the same application to increase overall execution speed. No performance measurements are reported in [17].

Leff and Rayfield [4] show the importance of an EJB cache in a J2EE application server for improving application performance. We can find an in-depth study of performance issues with entity EJBs in [5]. The authors point out that caching is one of the greatest benefits of using entity EJBs provided that the EJB cache is properly configured and entity EJB transaction settings are optimized.

Our CEJB design patterns comply with the EJB specification and therefore can be applied to any J2EE application on any J2EE application server. Several *J2SE*-based technologies, from Java Data Objects (JDO) to Java Object Serialization (JOS), sacrifice the benefit of J2EE platform services in return for much higher performance than would be possible on a J2EE platform. Jordan [18] provides an extensive comparison of EJB data persistence and several J2SE-based data persistence mechanisms and their relative performance. The comparison includes EJB, JDO, Java Database Connectivity (JDBC), Orthogonal Persistence (OPJ), JavaBeans Persistence (JBP), and Java Object Serialization (JOS). Interestingly, the comparison revealed that EJBs had the worst performance among the compared persistence mechanisms, while JDOs had the best

performance. The author states that "acceptable EJB performance seems unattainable at present unless dramatic changes are made to the application object model to avoid fine-grain objects when mapped to EJB". The fCEJB and vCEJB design patterns are an application-level approach to avoiding the mapping of fine-grained objects to EJBs and thus the performance penalty associated with using EJB-based persistence in J2EE applications. Not included in the study in [18] is another popular J2SE persistence mechanism, *Hibernate*. The performance of Hibernate – in comparison to the object database *db4o*, but not in comparison to EJBs – is discussed in [19].

Trofin and Murphy [20] present the idea of collecting runtime information in J2EE application servers and to modify EJB containers accordingly to improve performance. CEJBs, on the other hand, execute in unmodified EJB containers and improve performance by multiplexing multiple logical entities into one entity as seen by the EJB container.

III. CEJB Goals and Concept

The intention of both of our CEJB software design patterns is to narrow the performance gap between EJBs and POJOs in J2EE applications with large numbers of EJBs. A look at common operations during the life span of an EJB explains some of the performance differences between EJBs and POJOs:

- Creating EJBs entails the addition of rows in a table in the underlying relational database at transaction commit time, whereas POJOs exist only in memory.
- Accessing EJBs requires the execution of *finder* methods to locate the EJBs in the EJB cache of the J2EE application server or in the database, whereas access to POJOs is accomplished by simply following object references.
- Depending on the selected transaction commit options (pessimistic or optimistic), the execution of business methods on EJBs is either serialized or requires synchronization with the underlying database. Calling POJO methods, on the other hand, simply means accessing objects in the Java heap in memory, possibly with application-specific concurrency control in place.
- Deleting EJBs implies the removal of the EJB objects from the EJB cache, if they are stored there, and the deletion of the corresponding database table rows at commit time. Deleting POJOs affects only the Java heap in memory.

The preceding list identifies the interaction between EJBs and the persistence mechanism (EJB cache plus database) as a performance bottleneck for EJBs that POJOs do not suffer from. One way of decreasing the performance gap between EJBs and POJOs, therefore, is to increase the EJB cache hit rate, thereby reducing the database access frequency. In case of EJB cache misses and when synchronizing the state of EJBs with the database, we would like to speed up the search for the database table rows that represent EJBs. CEJBs are intended to significantly decrease the number of EJBs in a J2EE application. A smaller number of EJBs translates into higher EJB cache hit rates *and* faster EJB access in the database due to a smaller search space in database tables for EJB *finder* operations. In other words, CEJBs reduce the number and execution times of database accesses by increasing the rate of in-memory search operations.

CEJBs are based on a simple idea. Traditionally, when developing EJBs we map each real-world entity in the application domain to a separate EJB. Examples of such entities are users and communication sessions, to stay with the example of the Mercury system in Section I. This approach can result in a large number of EJB instances in the application. With CEJBs, on the other hand, we consolidate multiple entities of the same type into a single "special" EJB. The difference between fCEJBs and vCEJBs is in the way the entities are organized within each CEJB and the resulting impact on the overall pool of CEJBs. In the remainder of this article, when we speak of "entities", we implicitly assume "entities of the same type" unless otherwise noted.

IV. Fixed-Size Consolidated EJBs

In this section, we present the key idea, design methodology, and some practical aspects of developing fCEJBs.

A. Concept of the fCEJB Pattern

In the case of fCEJBs, we store up to N POJO entities in the same EJB (the fCEJB), where N is a constant that is determined at application design time. We store the entities in arrays of size N inside the fCEJB. Hence, locating an entity within an fCEJB can be accomplished through simple array indexing operations requiring only constant time. The challenge for developing fCEJBs is devising an appropriate mapping function

$$m: K_E \rightarrow K_C \times [0..N-1],$$

where K_E is the primary key space of the real-world entities and K_C is the primary key space of the fCEJBs. Function m maps a given entity primary key k, for example a communication session ID, to a tuple (k_1, k_2) where

- k_1 is an artificial primary key for an fCEJB that will store the entity,
- k_2 is the index of the array elements inside the fCEJB that store the POJO with primary key k.

The mapping function m has to ensure that no more than N entities are mapped to the same fCEJB. On the other hand, m also has to attempt to map as many entities to the same fCEJB as possible. Otherwise, fCEJBs would perform little or no better than EJBs. Moreover, the computation of m for a given entity primary key has to be fast.

B. Developing an fCEJB

Consider a simple *communication session* entity represented as an EJB *Session* with the J2EE-mandated local interface, local home interface, and bean implementation:

- The local home interface is responsible for creating new *Sessions* through a method *create(String sessionID, long startTime)* and finding existing ones

through method *findByPrimaryKey(String sessionID)*.

- The local interface allows a client to call getter and setter methods for the *sessionID* and *startTime* properties of *Sessions*. It also contains a method *businessMethod(long newStartTime)* that changes the value of the *startTime* of the EJB.
- The bean implementation is the canonical bean implementation of the methods in the local and local home interfaces. For the sake of brevity, we omit details of the (quite trivial) bean implementation here.

In Figures 1-3, we present an fCEJB *CSession* that we derive from the *Session* EJB. To arrive at *CSession*, we first map the persistent (CMP) fields in *Session* to

- a transient *String* array *sessionIDs*,
- a transient *long* array *startTimes*,
- a persistent *String* field *encodedSessionIDs*,
- and a persistent *String* field *encodedStartTimes*,

as shown in lines 2-9 in Figure 3. Note that we do not implement *sessionIDs* and *startTimes* as *persistent* array fields. Instead, we encode *sessionIDs* and *startTimes* as persistent *Strings encodedSessionIDs* and *encodedStartTimes*, respectively, during J2EE *ejbStore* operations (Figure 3, lines 32-45). To do so, *ejbStore* creates a #-separated concatenation of all elements of *sessionIDs* and one of all elements of *startTimes* where # is a special symbol that does not appear in *sessionIDs* or *startTimes*. This technique allows us to store the sessionIDs and start times as VARCHARs in the underlying database and avoid the much less time-efficient storage as VARCHAR *for bit data* that persistent array fields require. During J2EE *ejbLoad* operations (Figure 3, lines 18-30), the *encodedSessionIDs* and *encodedStartTimes* are being demultiplexed into the transient arrays *sessionIDs* and *startTimes*, respectively. The *CSessionBean* then uses the state of the latter two arrays until the next *ejbLoad* operation refreshes the state of the two arrays from the underlying database.

The *ejbCreate* method in Figure 3, lines 11-16, assigns an *objectID* to the persistent *objectID* field. We will discuss the choice of the *objectID* later. The method also allocates and initializes the transient *sessionIDs* and *startTimes* arrays. The size of the arrays is determined by the formal parameter *N*.

In the *CSessionLocal* interface in Figure 2, we add an *index* parameter to all getter and setter methods and to the *businessMethod*. We also add the lifecycle methods *createSession* and *removeSession*. The getter and setter methods in *CSessionLocal* with the *index* parameter have to be implemented by *CSessionBean* because they are different from the abstract getter and setter methods in *CSessionBean* that are applied to the persistent *encodedSessionIDs* and *encodedStartTimes* fields. The new getter and setter methods access the indexed slot in the array fields *sessionIDs* and *startTimes*. An example of a setter method is shown in lines 62-64 in Figure 3. Similarly, we have to change the *businessMethod*, which now accesses the indexed slot in the transient *sessionIDs* and *startTimes* arrays rather than operating on persistent entity fields (lines 58-60 in Figure 3). The *createSession* method in lines 47-51 in Figure 3 first ensures that the indexed slots in the *sessionIDs* and *startTimes* are empty. If not, this session has been added before and a *DuplicateKeyException* is raised. If the slots are empty, *createSession* will assign the state of the new communication session to the indexed slots in the arrays. The *removeSession* method in lines 53-56 in Figure 3 ensures that the indexed *sessionIDs* and *startTimes* slots are not empty, i. e., the referenced session is indeed stored in this *CSession*. If so, *removeSession* deletes the state of this communication session by setting the indexed slot in the *sessionIDs* to *null*.

Figure 4 shows a class *ObjectIDMapping* that encapsulates an exemplary mapping function *m* from *Session* primary keys (*Strings*) to *CSession* primary keys (*objectIDs*). We will discuss *m* in conjunction with the code example given in Figure 5 that retrieves a *CSession* through an *ObjectIDMapping* and executes the *businessMethod* on the retrieved *CSession*. The argument for the constructor of an *ObjectIDMapping* is *N*, the maximum number of entities consolidated in a *CSession*, as shown in line 6 in Figure 4. The mapping function *m* is computed by a call to the *setObjectID* method in line 2 in Figure 5. This method maps a *Session* primary key, *objectIDArg*, to the tuple (*objectID*, *index*). In Figure 5, the *Session* primary key is *voiceCall-05-12-2012a*. The *objectID* is derived from *objectIDArg* by replacing *objectIDArg's* last character *c* with an underscore followed by *c – index*, where we interpret *c* as the ordinal value of the character in the ASCII character table (lines 14 and 16 in Figure 4). In line 15 in Figure 4, the value of *index* is computed as the result of the operation

$$c \; modulo \; N,$$

i. e.,

$$c = q \cdot N + index,$$

where

$$0 \leq index < N,$$

and q is the integer quotient of c and N. In our example, *c* is the ordinal value of *a*, the last character of *voiceCall-05-12-2012a*, so *c* = 97. If we assume *N* = 20, then *index* = 17, and *c – index* = 80. Therefore, *objectID = voiceCall-05-12-2012_80*. While *getObjectID()* (line 3, Figure 5) identifies the *CSession* in which we store an entity with *objectIDArg* as its primary key, *getIndex()* (line 4, Figure 5) identifies the slots in the CMP array fields in the *CSession* that store the given entity. In the example, the real-world entity with primary key *voiceCall-05-12-2012a* is thus stored in slot 17 in the *CSession* with primary key *voiceCall-05-12-2012_80*. Figure 6 depicts the mapping from the *Session* primary key *voiceCall-05-12-2012a* to *CSession* primary key *voiceCall-05-12-2012_80* and slot 17 in the *CSession*.

Although our definition of *m* is somewhat complex, its computation is fast and it maps at most *N* entities to each

CSession, which is a key requirement for *m*. If the *Session* primary keys had numerical suffixes such as *100*, *101*, *102* instead of alphabetical suffixes *a*, *b*, *c*, and so forth, we could modify the *setObjectID* method in Figure 4 such that *c* is the value of the integer following the year (2012) in the suffix. If our *Session* sample EJBs had entirely numeric primary keys *k*, the mapping function *m* could have been conveniently defined as

$$m(k) = (k - (k \; modulo \; N), k \; modulo \; N).$$

Many EJBs have numeric primary keys, especially if the developer delegates the assignment of primary keys to the application server, in which case the server can use consecutive integers as EJB primary keys. This is very helpful in situations where the real-world entities that the EJBs represent have no "natural" unique primary key. An example would be a product or an order for a product. We chose a string primary key for our *Session* example to demonstrate that the fCEJB pattern does not rely on a numeric primary key.

C. Design Considerations for fCEJBs

By creating a simple façade session bean we can completely hide *CSessions* from the rest of the application and expose only *POJOs* to clients. With a façade session bean, the two-step process of first building an *idMapping* and then retrieving the desired *CSession* as shown in Figure 5 can be collapsed into one step. The façade bean is quite straightforward and obvious to program and therefore we do not show it here. For more complicated entities than our *Sessions*, consolidation through fCEJBs requires more effort but is straightforward and could be supported by a tool. Ideally, such a tool would be offered as part of a J2EE development environment and convert EJBs into fCEJBs at the request and under the directions of the developer. The tool would also need to support the following scenarios:

- If *Session* implements customized *ejbLoad*, *ejbStore*, *ejbActivate*, or *ejbPassivate* methods, these need to be adapted in *CSessionBean* to reflect the fact that the state of a *Session* is stored across different arrays in the *CSessionBean*.
- *Finder* and *select* queries for *Session* must be re-implemented for the fCEJB, and with less J2EE platform support, because they need to access both a *CSession* and the arrays within a *CSession*.
- If *Session* has customized *ejbHome* methods, we need to add functionally equivalent *ejbHome* methods to *CSession*. Changes to the original *Session ejbHome* methods are only necessary if these methods access the state of a specific *Session* EJB after a prior *select* method. In this case, the *CSession ejbHome* methods need to retrieve *POJO* instead of *Sessions*.
- If *Session* is part of a container-managed relationship (CMR), consolidation through fCEJBs requires removal of the CMRs and re-implementation of the CMRs without direct J2EE support.

The mapping function *m* has a strong impact on the performance of fCEJBs and therefore needs to be defined carefully for the given application. The mapping function delivers its best performance if primary keys that occur in the application are *clustered*. Clustering here means that for every primary key *k* in the application there is a set of roughly *N* primary keys for other entities in the application that are similar enough to *k* to be mapped to the same *objectID* by *m*. The challenge is therefore to analyze the actual primary key space of the entities that are to be consolidated in a given application and to then define an efficient and effective mapping function based on this analysis. The primary key space of our sample *Session* entities fulfills the cluster property because our *Sessions* have largely lexicographically consecutive *sessionIDs* such as *voiceCall-05-12-2012a*, *voiceCall-05-12-2012b*, *voiceCall-05-12-2012c*, and so on.

```
1  public interface CSessionLocalHome extends EJBLocalHome {
2      CSessionLocal create(String objectID, int numElements) throws CreateException;
3      CSessionLocal findByPrimaryKey(String objectID) throws FinderException;
4      CSessionLocal getSession(String objectID, int numElements) throws FinderException;
5  }
```

Figure 1. Local home interface for *CSession*.

```
1  public interface CSessionLocal extends EJBLocalObject {
2      void createSession(int index, String sessionID, long startTime) throws DuplicateKeyException;
3      void removeSession(int index) throws RemoveException;
4      String getSessionID(int index);
5      void setSessionID(int index, String sessionID);
6      long getStartTime(int index);
7      void setStartTime(int index, long startTime);
8      void businessMethod(int index, long newStartTime);
9  }
```

Figure 2. Local interface for *CSession*.

```
1  public abstract class CSessionBean implements EntityBean {
2      private transient String[] sessionIDs = null;
3      private transient long[] startTimes = null;
4      public abstract String getObjectID();
5      public abstract void setObjectID(String objectID);
6      public abstract String getEncodedSessionIDs();
7      public abstract void setEncodedSessionIDs(String encodedSessionIDs);
8      public abstract String getEncodedStartTimes();
9      public abstract void setEncodedStartTimes(String encodedStartTimes);
10
11 public String ejbCreate(String objectID, int N) throws CreateException {
12     setObjectID(objectID);
13     sessionIDs = new String[N];
14     startTimes = new long[N];
15     return null;
16 }
17
18 public void ejbLoad() {
19     StringTokenizer encodedSessionIDs = new StringTokenizer(getEncodedSessionIDs(), "#"),
20                     encodedStartTimes = new StringTokenizer(getEncodedStartTimes(), "#");
21     int numElements = encodedSessionIDs.countTokens();
22     if (sessionIDs == null) {
23         sessionIDs = new String[numElements];
24         startTimes = new long[numElements];
25     }
26     for (int index = 0; index < numElements; index++) {
27         sessionIDs[index] = encodedSessionIDs.nextToken();
28         startTimes[index] = new Long(encodedStartTimes.nextToken()).longValue();
29     }
30 }
31
32 public void ejbStore() {
33     StringBuffer encodedValues = new StringBuffer();
34     for (int index = 0; index < sessionIDs.length; index++) {
35         encodedValues.append(sessionIDs[index]);
36         encodedValues.append("#");
37     }
38     setEncodedSessionIDs(encodedValues.toString());
39     encodedValues = new StringBuffer();
40     for (int index = 0; index < startTimes.length; index++) {
41         encodedValues.append(startTimes[index]);
42         encodedValues.append("#");
43     }
44     setEncodedStartTimes(encodedValues.toString());
45 }
46
47 public void createSession(int index, String sessionID, long startTime) throws DuplicateKeyException {
48     if (sessionIDs[index] != null) throw new DuplicateKeyException("Session exists already");
49     sessionIDs[index] = sessionID;
50     startTimes[index] = startTime;
51 }
52
53 public void removeSession(int index) throws RemoveException {
54     if (sessionIDs[index] == null) throw new RemoveException("Session does not exist");
55     sessionIDs[index] = null;
56 }
57
58 public void businessMethod(int index, long newStartTime) {
59     startTimes[index] = newStartTime;
60 }
61
62 public void setSessionID(int index, String sessionID) {
63     sessionIDs[index] = sessionID;
64 }
```

Figure 3. Portion of the *CSessionBean* relevant to the fCEJB discussion.

```
1  public class ObjectIDMapping {
2      private int N,
3              index;
4  private String objectID;
5
6  public ObjectIDMapping(int N) {
7      this.N = N;
8      index = -1;
9      objectID = null;
10 }
11
12 public void setObjectID(String objectIDArg) {
13     int lastElementIndex = objectIDArg.length() - 1,
14         c = objectIDArg.charAt(lastElementIndex);
15     index = c % N;
16     objectID = objectIDArg.substring(0, lastElementIndex) + "_" + (c - index);
17 }
18
19 public int getIndex() {
20     return index;
21 }
22
23 public String getObjectID() {
24     return objectID;
25 }
26 }
```

Figure 4. A class for mapping *Session* primary keys to *CSession* primary keys and array index slots.

```
1  ObjectIDMapping idMapping = new ObjectIDMapping(N);
2  idMapping.setObjectID("voiceCall-05-12-2012-a");
3  CSessionLocal cSession = csessionLocalHome.findByPrimaryKey(idMapping.getObjectID());
4  cSession.businessMethod(idMapping.getIndex(), System.currentTimeMillis());
```

Figure 5. Accessing a *CSession* EJB.

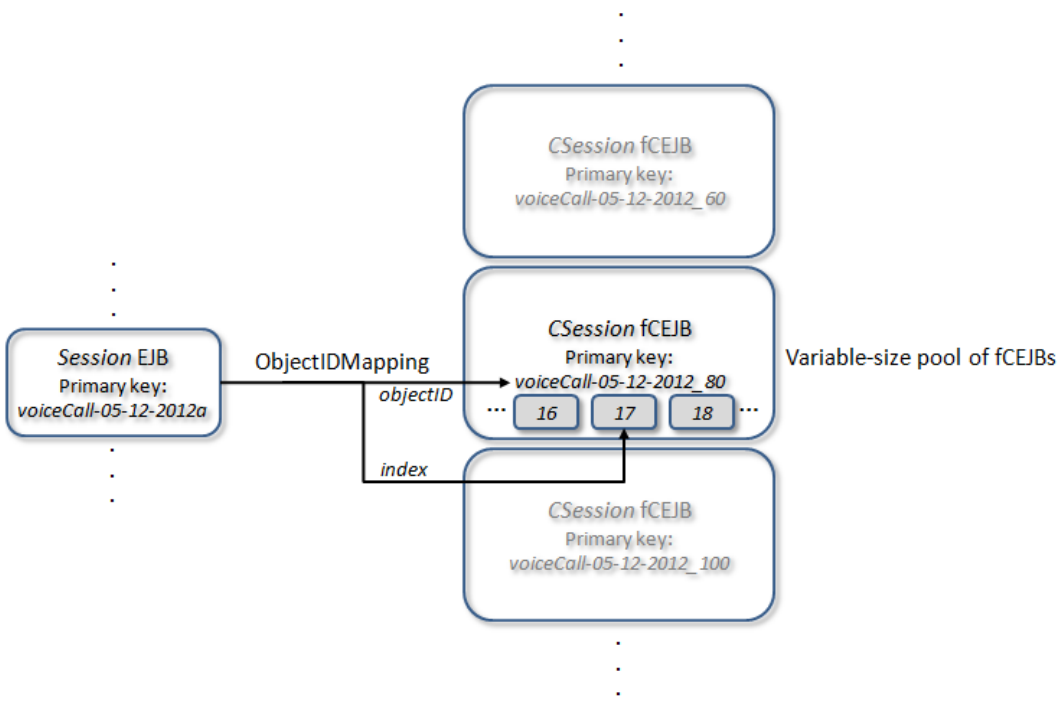


Figure 6. Mapping a *Session* primary key to a tuple (*objectID*, *index*): *objectID* is the primary key of a *CSession*, *index* is the slot in the *CSession* that stores the original *Session* entity.

V. VARIABLE-SIZE CEJBS

In this section, we describe the key idea behind vCEJBs, the design methodology, and practical aspects of developing vCEJBs.

A. Concept of the vCEJB Pattern

The fCEJBs pattern stores a fixed number of entities in each fCEJB, while the size of the pool of all fCEJBs varies with the total number of entities. In contrast, the vCEJB pattern creates a fixed-size pool of vCEJBs but each vCEJB stores a variable number of entities. Variable-size CEJBs constitute a distributed EJB equivalent of hashtables. A hashtable contains a fixed number of slots, each of which can hold a variable number of entities that are mapped to the slots based on a mapping (hash) function. A direct implementation of a hashtable as a single EJB could lead to a prohibitively slow performance for a large number of hashtable entries because

- the time for synchronizing the EJB state with the underlying database at the beginning and/or end of a transaction would be very long,
- the amount of parallelism in accessing the hashtable would be severely limited.

Therefore, we distribute the content of the hashtable across several EJBs, one EJB for each hashtable slot. The resulting EJBs are our vCEJBs. Unlike an fCEJB, a vCEJB imposes no predefined limit on the number of entities stored in the vCEJB.

The primary keys of the vCEJBs are integers ranging from 0 to *N* - 1 for a chosen value of *N* that we will discuss later. We define a mapping function from the entities' primary keys to the interval $[0..N-1]$ that determines which vCEJB stores which entity. The entities are represented as POJOs and are stored in a Java hashtable (a *java.util.HashMap*) in the vCEJBs. To store all entities of a given type in an application, *N v*CEJBs are allocated in a fixed-size pool at application startup time.

To demonstrate the fCEJB pattern, we chose the example of a *Session* entity because its primary key space has the desired cluster property that makes it amenable to the fCEJB pattern. In contrast, we will illustrate the vCEJB pattern with the example of a *User* EJB whose primary keys do not exhibit the cluster property. We assume that the primary key of our *User* entity is a unique *userID* such as a first name/middle name/last name combination, passport number, social security ID, employee number, telephone number, or similar. The uneven distribution of these identifiers makes it extremely difficult to define a mapping function *m* that would evenly map *User* entities to fCEJBs. As we will see, the performance of vCEJBs does not depend on the cluster property, and therefore vCEJBs are the preferable choice for *User* entities.

In the following explanations, we assume that *User* has two fields *firstName* and *lastName* in addition to the *userID*, Furthermore, *User* is implemented with the canonical getter/setter interfaces and local and local home interfaces. We omit additional implementation details because they are irrelevant to our vCEJB discussion.

B. Developing a vCEJB

We derive a vCEJB *CUser* from *User* in two steps. In the first step, we create a POJO equivalent of *User*, which we call *POJOUser* (omitted from the figures for the sake of brevity). *POJOUser* contains three private instance variables *userID*, *firstName*, and *lastName*, and the canonical getter and setter methods for the three variables. In the second step, we create *CUser* as an entity EJB as depicted in Figures 8-10. *CUser* has three CMP fields, *objectID* of type *Integer*, *N* of type *int*, and *users* of type *java.util.HashMap* (lines 2-7 in Figure 10). The methods in *CUserBean* pertinent to our discussion are *ejbCreate*, *createUser*, *getUser*, *setUser*, *changeUser*, and *removeUser*.

A *CUser* acts as a container for *POJOUsers* in a way that is similar to EJB containers managing EJBs. Unlike EJB containers, on the other hand, a *CUser* cannot hold objects of different classes. The lifecycle methods for a *POJOUser* (*createUser*, *removeUser*) can be found in the local interface for *CUser* (Figure 9), whereas the lifecycle methods for a *User* reside in the local *home* interface for the *User* EJB (Figure 8). EJB containers are automatically instantiated by the application server, whereas *CUsers* have to be created by the J2EE application. This also implies that the number of vCEJBs depends on the application rather than the application server.

To consolidate *Users* into *CUsers* in a given J2EE application, the application first creates a pool of *N CUsers* with *objectIDs* ranging from 0 to *N* - 1 in increments of 1. Subsequently, the application can create, find, modify, execute business methods on, and remove *POJOUsers* inside *CUsers*. To do so, the application first executes *findByPrimaryKey* on the *CUserLocalHome* interface (see Figure 8) with the argument

new Integer(Integer.abs(userID.hashCode()) % N),

where *userID* is the return value of the *getUserID* method for the *POJOUser* in question and *%* denotes an integer division. In other words, the application maps hash values of the *POJOUser* identities to *CUser* identities in an attempt to evenly distribute *POJOUsers* across *CUsers*. Notice that due to integer arithmetic and the definition of the *hashCode* method for Java strings, the result of the *hashCode* method can be negative and therefore we apply the *Integer.abs* method to guarantee values in the range $[0..N-1]$. The return value of the *findByPrimaryKey* method is the *CUser* vCEJB that already contains or will contain the *POJOUser* that we are interested in. Figure 7 illustrates the mapping of *User* primary keys to *CUser* primary keys.

To store a new *POJOUser* in the *CUser* vCEJB, the application executes the *createUser* method on the *CUser* as shown in lines 16-24 in Figure 10. First, this method ensures that the *POJOUser* indeed belongs in this *CUser* based on the mapping of *POJOUsers*' *userIDs* to *CUser* object identities, as described in the previous paragraph. Then, the method checks whether there is already a *POJOUser* with the same identity stored in this *CUser*. This is the equivalent of the EJB container checking for duplicate object identities

when creating an entity EJB. Finally, the method stores the mapping from the *userID* to the *POJOUser* in the vCEJB's internal *HashMap*.

The equivalent of an EJB *finder* method for *POJOUsers* is the *getUser* method in the *CUserLocal* interface (Figure 9, line 3). After a prior call to the *findByPrimaryKey* method on the *CUserLocalHome* interface to obtain the appropriate *CUser*, the application calls the *getUser* method on the local interface of that *CUser* to obtain the desired *POJOUser*. The application can now execute business methods on the returned *POJOUser*. The *users* field (a *HashMap*) in *CUser* is a so-called *dependent value* object in the J2EE world. By extension, the same applies to *POJOUsers* inside the users *HashMap*. Hence, the EJB container returns a *copy* of a *POJOUser* whenever the *getUser* method is invoked, as prescribed by the Enterprise JavaBeans specification. To reflect changes to the state of a *POJOUser* due to business method calls, the application has to store the *POJOUser* back to *users*. The *setUser* and *changeUser* methods in Figure 10 in lines 33-38 and 40-49, respectively, serve this purpose. The *changeUser* method is useful in situations where we want to change the state of a *POJOUser* without a need to know the previous state of this *POJOUser*. Rather than calling *getUser* followed by *setUser*, one call to *changeUser* will suffice in that situation, hence reducing the number of accesses to the users *HashMap* and consequently the number of *HashMap* copy operations from two to one.

To delete a *POJOUser*, the application calls the *removeUser* method on the *CUser* (lines 51-56 in Figure 10). Like the *setUser*, *getUser*, and *changeUser* methods, *removeUser* first checks that the referenced *POJOUser* indeed exists in this *CUser* vCEJB. Then, *removeUser* deletes the *POJOUser* from the *users HashMap*.

C. Design Considerations for vCEJBs

By creating a simple façade session bean we can completely hide *CUsers* from the rest of the application and expose only *POJOUsers* to clients. With a façade session bean, the two-step process of first retrieving a *CUser* and subsequently accessing a *POJOUser* turns into one step for clients. The façade bean is straightforward and we will therefore not show it here.

Our sample *User* EJB is very simple. For more complicated entities, consolidation through vCEJBs requires more effort but, as with fCEJBs, is straightforward and could be automated by a tool as part of a J2EE development environment. The following is a list of considerations during vCEJB creation in the context of the *User* EJB that Section V.B did not address.

1. If the original *User* EJB implements the *ejbLoad*, *ejbStore*, *ejbActivate*, or *ejbPassivate* methods, the *CUser* methods *getUser*, *setUser*, and *changeUser* need to be modified. For example, the content of a *User ejbLoad* method needs to be moved into the *getUser* and *changeUser* methods after some modifications. The modifications reflect the fact that the state of a *User* is stored in a *POJOUser* and needs to be retrieved from a *HashMap* rather than from the CMP fields of a *User*.
2. *Finder* and *select* queries for *User* must be re-implemented for the vCEJB because they need to access the *users HashMap*. Notice that the *getUser* method in our example is derived from the *findByPrimaryKey* method for the *User* EJB. More complicated *finder* methods in *User* would require more complicated *getUser* methods in *CUser*.
3. If *User* has *ejbHome* methods, we need to add functionally equivalent *ejbHome* methods to *CUser*. Changes to the original *User ejbHome* methods will only be necessary if these methods access the state of a specific *User* EJB after a prior select method. In this case, the *CUser ejbHome* methods need to retrieve *POJOUsers* instead of *Users.*
4. If *User* is part of a container-managed relationship (CMR), consolidation through vCEJBs requires removal of the CMRs and re-implementation of the CMRs without direct J2EE support.
5. Variable-size CEJBs aggravate the existing problem of variable-size data structures in EJBs. EJBs with variable-size data structures as CMP fields and databases as persistent storage require a design-time decision for the maximum length of each database column that stores a variable-size CMP field. If such a maximum size is exceeded a runtime error will occur during EJB storage in the database. *CUser* contains a variable-size CMP field (*users*) even though *User* does not. To safely use vCEJBs, we require knowledge of the maximum number of EJBs that are stored in each CEJB and have to appropriately size the database column that stores the *users HashMap.*

D. Configuring the vCEJB Pool Size N

By consolidating a large number of EJBs into a small number of vCEJBs, the number of rows in a relational database required to store entity EJB state can be substantially reduced. At the same time, the degree of locality in EJB operations increases, which has a positive effect on the efficacy of the EJB cache in a J2EE application server. In our example, we can reduce the number of database rows and EJB cache entries for storing n user entities from n to N.

With *CUsers*, the time for retrieving a user entity is divided into time for searching cached or uncached *CUsers* and time for an in-memory search within a *HashMap*. In the extreme case of $N = 1$, there is only one *CUser* and it is likely to be present in the EJB cache of the application server. In this case, the vCEJB is essentially a persistent and transacted *HashMap*. Even if the *CUser* is not cached, it can be located very quickly in the database. Most of the search time is spent in memory within the *HashMap* of the *CUser*. However, this *HashMap* grows potentially very large (to n entries) and can itself turn into a performance bottleneck. Moreover, the time for synchronizing the in-memory representation of *CUser* with the database at transaction commit time could be very long. The same applies to loading the *CUser* from the database at the beginning of a transaction with J2EE commit options B and C [2]. Note that for a

clustered J2EE application server commit options B and C are mandatory. Lastly, like fCEJBs, vCEJBs can restrict the degree of parallelism in the J2EE application. If two transactions attempt to access two POJOs that happen to be in the same vCEJB, one of the transactions may lock out the other transaction. The likelihood of this situation increases with decreasing values for *N*.

The other extreme is $N = n_{max}$, where n_{max} denotes the maximum number of concurrently existing user entities throughout the lifetime of the application, provided such a maximum exists. With $N = n_{max}$, we arrive at the same situation as with EJBs except that with vCEJBs every access to an embedded POJO requires an additional step relative to EJBs. In other words, with $N = n_{max}$ we can expect a performance *penalty* relative to using EJBs.

The ideal value for *N* therefore lies between these extremes. Clearly, this value depends on the size and structure of the EJB cache in the J2EE application server, the implementation of the EJB container, the database specifics, and the hardware on which the application server and the database run. Since we typically have no insight into the inner workings of a J2EE application server or the database, there is no general way of determining the best choice for *N*. In addition, the value of n_{max} may not be known and n_{max} may not even exist, which complicates the configuration of *N*.

One of our future research directions is therefore a self-adjusting vCEJB technique, where a session façade bean for vCEJBs would create vCEJBs dynamically as needed. The session façade bean would monitor the vCEJB performance and dynamically shrink or enlarge the size of the vCEJB pool accordingly, similar to automatic hashtable resizing techniques. After creation or destruction of vCEJBs, the façade bean would reallocate the existing POJOs across the modified set of vCEJBs. By appropriately sizing the vCEJB pool, the façade bean would also ensure that the size of the *HashMap* in each vCEJB does not exceed the limit imposed by the maximum size of the corresponding database column (see bullet item 5 in Section V.C). We believe that such a self-adjusting vCEJB technique may be beneficial in applications with slowly changing sets of real-world entities where dynamic reallocations would take place rarely and thus the performance cost of the reallocation itself would be limited.

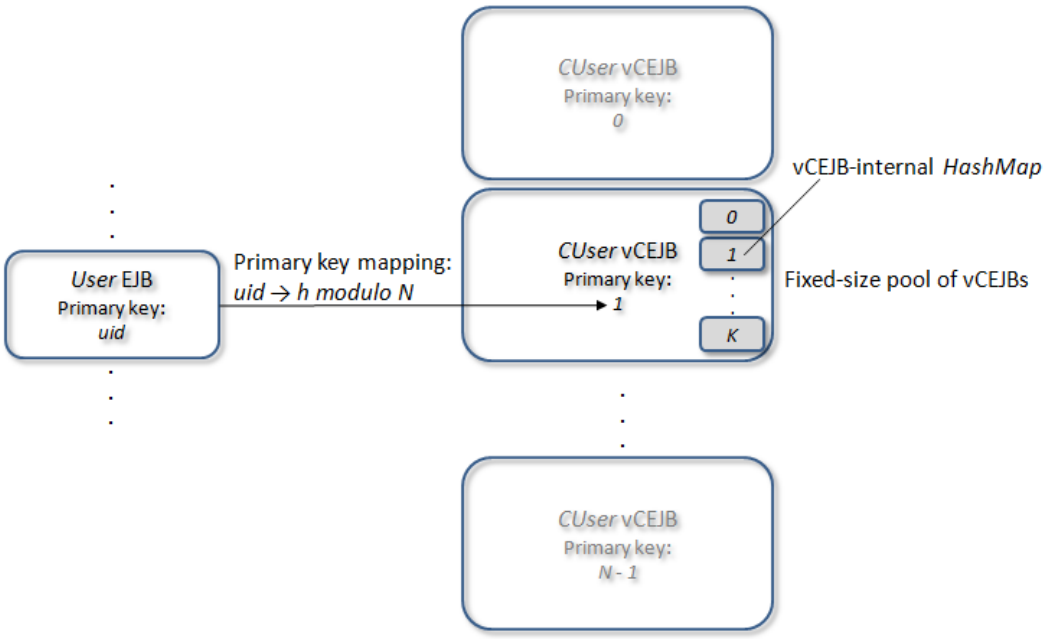


Figure 7. Mapping of a *User* primary key *uid* to a *CUser* primary key, where *h* is the absolute value of the hashcode for *uid*.

```
1  public interface CUserLocalHome extends EJBLocalHome {
2  CUserLocal create(Integer objectID, int N) throws CreateException;
3  CUserLocal findByPrimaryKey(Integer objectID) throws FinderException;
4  }
```

Figure 8. Local home interface for the vCEJB *CUser*.

```
public interface CUserLocal extends EJBLocalObject {
void createUser(POJOUser user) throws DuplicateKeyException, CreateException;
POJOUser getUser(String userID) throws FinderException;
void setUser(POJOUser user) throws FinderException;
void changeUser(String userID, String firstName, String lastName) throws FinderException;
void removeUser(String userID) throws FinderException;
}
```

Figure 9. Local interface for the vCEJB *CUser*.

```
public abstract class CUserBean implements EntityBean {
    public abstract Integer getObjectID();
    public abstract void setObjectID(Integer objectID);
    public abstract int getN();
    public abstract void setN(int N);
    public abstract HashMap getUsers();
    public abstract void setUsers(HashMap users);

public Integer ejbCreate(Integer objectID, int N) throws CreateException {
    setN(N);
    setObjectID(objectID);
    setUsers(new HashMap());
    return null;
}

public void createUser(POJOUser user) throws DuplicateKeyException, CreateException {
    HashMap allUsers = getUsers();
    int p = getN();
    if (Integer.abs(user.getUserID().hashCode()) % p != getObjectID().intValue())
        throw new CreateException("Cannot store user in this CEJB.");
    if (allUsers.get(user.getUserID()) != null) throw new DuplicateKeyException();
    allUsers.put(user.getUserID(), user);
    setUsers(allUsers);
}

public POJOUser getUser(String userID) throws FinderException {
    HashMap allUsers = getUsers();
    POJOUser user = (POJOUser) allUsers.get(userID);
    if (user == null) throw new FinderException();
    return user;
}

public void setUser(POJOUser user) throws FinderException {
    HashMap allUsers = getUsers();
    if (allUsers.get(user.getUserID()) == null) throw new FinderException();
    allUsers.put(user.getUserID(), user);
}

public void changeUser(String userID, String firstName, String lastName)
    throws FinderException {
    HashMap allUsers = getUsers();
    POJOUser pUser = (POJOUser) allUsers.get(userID);
    if (pUser == null) throw new FinderException();
    pUser.setFirstName(firstName);
    pUser.setLastName(lastName);
    allUsers.put(userID, pUser);
}

public void removeUser(String userID) throws FinderException {
    HashMap allUsers = getUsers();
    if (allUsers.get(userID) == null) throw new FinderException();
    allUsers.remove(userID);
}
```

Figure 10. Portion of the *CUserBean* implementation relevant to the vCEJB discussion.

VI. PERFORMANCE EVALUATION

This section contains an assessment of the comparative performance of fCEJBs, vCEJBs, and traditional EJBs in a test environment that simulates different usage profiles.

A. Methodology

We compared the performance of "traditional" EJBs with one real-world entity per EJB, fCEJBs, and vCEJBs in a J2EE test application. The entities that the test application creates have lexicographically consecutive strings as primary keys (as shown in our *Session* example in Section IV). For fCEJBs, the application uses the mapping function *m* in Figure 4. The test application executes a sequence of operations either on traditional EJBs (*EJB mode*), fCEJBs (*fCEJB mode*), or *vCEJBs* (*vCEJB mode*). In EJB mode, the application executes the following sequence of steps:

1. Create *n* EJBs. We call each entity creation a *creation operation*.
2. Find EJB with randomly selected primary key and read its state through *getter* operations. Repeat *n* times. We call each such operation a *find and read operation*.
3. Find EJB with randomly selected primary key and execute a business method on it. The business method changes the state of the EJB, and thus requires synchronization with the underlying database at transaction commit time. Repeat *n* times. We call each such operation a *find and change operation*.
4. Delete all EJBs through EJB *remove* operations.

Between any two consecutive steps, the test application creates 20000 unrelated EJBs in order to introduce as much disturbance as possible in the application server EJB cache and in the connection to the underlying database. During our performance testing, however, it turned out that these cache disturbance operations had a negligible effect on the performance *differences* between the CEJB and EJB modes.

In fCEJB mode, the application performs the same steps on fCEJBs instead of EJBs. Also, in step 4 in fCEJB mode, the application sequentially deletes all entities in each fCEJB but not the fCEJB itself. We varied the maximum number *N* of entities per fCEJB, from 2 to 250 in consecutive runs of the test application. The performance of the test application peaked around $N = 20$. We therefore present only the performance results for $N = 20$.

In vCEJB mode, the application first creates *N* vCEJBs, followed by the same steps as the test application in fCEJB mode but with vCEJBs instead. We varied *N* in consecutive runs of the test application in vCEJB mode and determined that the performance of the test application peaked roughly at $N \approx n/10$, i. e., when approximately 10 entities are stored in each variable-size vCEJB on average. We will only present the performance results for $N = n/10$.

We configured the test application with two different transaction settings in two different experiments: in *long transaction mode*, each of the four steps of the test application is executed in one long-lived transaction. In *short transaction mode*, the application commits every data change as soon as it occurs, i. e., after each entity creation, change, or removal. Here, the application performs a large number of short-lived transactions. In successive runs of the test application, *n* iterated over the set {1000, 10000, 50000}. After each run, we restarted the database server and the application server and deleted all database rows created by the application.

We deployed the test application on an IBM WebSphere 5.1.1.6 J2EE application server with default EJB cache and performance settings. The hardware is a dual Xeon 2.4 GHz server running Microsoft Windows 2000 Server. An IBM DB2 8.1.9 database provides the data storage. All EJBs use the WebSphere default commit option C.

B. Performance Analysis

Figures 11-16 display the results of our performance testing with the test application in long and short transaction modes for the three different values of *n*. Each figure shows the time that each entity creation, entity find/read, entity find/change, and entity removal operation takes in milliseconds when using traditional EJBs, fCEJBs, and vCEJBs, respectively. In each figure, for each of the four types of entity operations, there is one bar indicating the speed of the operation when using EJBs, fCEJBs, and vCEJBs, respectively. In addition, we show the speedup for the operation when using fCEJBs instead of EJBs and the speedup when using vCEJBs instead of EJBs. The speedup in the figures is defined as the time for an EJB operation divided by the time for the equivalent f/vCEJB operation. Speedup values greater than 1 indicate results where f/vCEJBs outperform EJBs, values of less than 1 indicate EJBs performing better than f/vCEJBs. For the vCEJB performance tests, our figures do not show the time for creating the *N* vCEJBs because we consider this fixed overhead at application startup time.

In long transaction mode, fCEJBs significantly outperformed EJBs. For $n = 50000$ (Figure 13), for example, creating entities through fCEJBs was more than twice as fast as with EJBs, finding and reading entities was more than 5 times faster, finding and changing entities was more than 7 times faster, and deleting entities with CEJBs was more than 14 times faster. Our performance tests also show that fCEJBs are consistently faster than vCEJBs.

Because in fCEJB mode the mapping function *m* in our test application clusters the primary keys of the entities, the fCEJBs consolidate almost the maximum possible number of entities (20 per our definition of *N*). Hence, the number of fCEJBs necessary to store all entities in the test application is about $1/20^{th}$ that of the number of EJBs in EJB mode, which translates into much improved application server caching behavior and accelerated database search times. Once an fCEJB has been retrieved, extracting the desired entity from the fCEJB is a simple and fast array indexing operation. It is only insignificantly slower than retrieving the state of a traditional EJB from the EJB fields and faster than retrieving an entity from the internal *HashMap* in a vCEJB. Writing the state of an fCEJB back to the underlying database is much faster than the analogous operation for a vCEJB with its large internal data structure, which explains why fCEJBs perform reading and changing operations much faster than

vCEJBs. It also explains why the latter are only about 23% faster than EJBs for this type of operation (see find and read operations in Figure 13). However, if the chosen mapping function *m* for fCEJBs in a given application does not yield the desirable cluster property, vCEJBs may outperform fCEJBs, which is why we developed the vCEJB pattern as an alternative to the fCEJB pattern.

Although fCEJBs perform better than vCEJBs in our tests due to the distribution of the primary keys and the selection of the fCEJB mapping function *m*, there is still a significant speed-up when using vCEJBs as opposed to EJBs, with the exception of creation operations. For n = 50000 (Figure 13), finding and reading entities is more than twice as fast in vCEJB mode than in EJB mode, finding and changing entities is about 23% faster, and removal is more than three times faster in vCEJB mode than in EJB mode. Variable-size CEJBs are only at a performance disadvantage over EJBs in the case of creating entities. Here, retrieving an entry in the potentially large CEJB-internal *HashMap* for the purpose of checking for *DuplicateKeyExceptions*, the subsequent storage of a new entity in this *HashMap*, and the occasional re-sizing of the *HashMap* costs more time than the consolidation of entities saves.

Unlike in EJB mode, entity deletion in either CEJB mode does not force the deletion of EJBs in the application server or the database. Instead, entity deletion in CEJBs is accomplished through the removal of entities *inside* EJBs. Not surprisingly therefore, deleting entities in both CEJBs modes is much faster than in EJB mode.

In short transaction mode, our performance testing shows a very different outcome (Figures 14-16). For example, Figure 16 (n = 50000) shows that both types of CEJBs only offer performance advantages over EJBs for finding and reading operations. Fixed-size CEJBs are about as fast as EJBs for finding and changing operations and for entity removal but much slower in creating entities. Variable-size CEJBs are consistently slower than EJBs except for finding and reading entities. In short transaction mode, transaction commits after EJB state changes dominate the execution time of the test application and void many performance advantages due to consolidation. J2EE applications that eagerly commit every EJB state change will still experience a significant speed-up as a result of consolidation but only if EJB read operations outnumber EJB write operations by a significant margin.

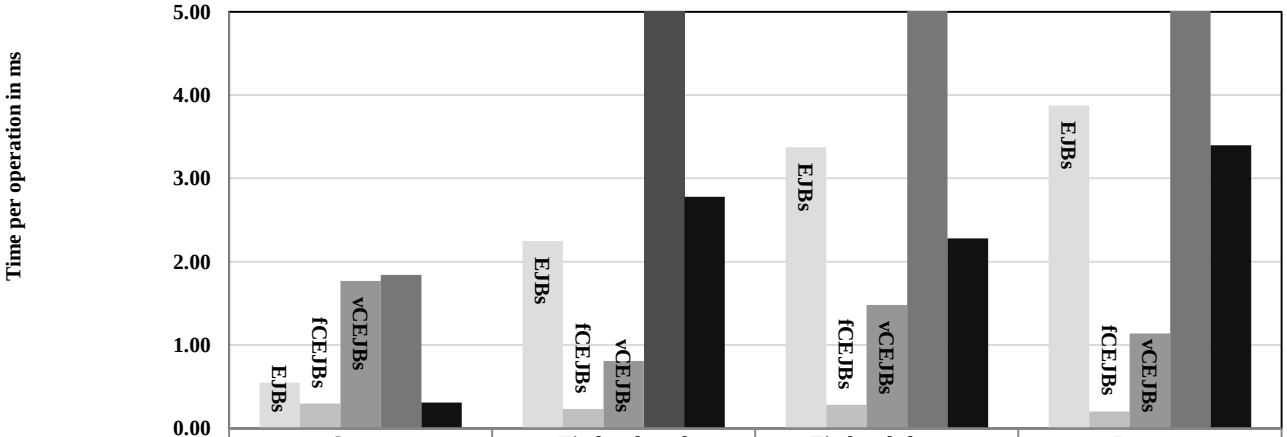
In conclusion, fCEJBs provide strong performance advantages over EJBs if (1) the application contains a large number of EJBs, (2) it accesses EJBs either in long-lived transactions or in short-lived transaction with a large EJB read to write ratio, and (3) if a mapping function *m* can be found for the EJB primary key space that exhibits the cluster property. If no such function can be found but (1) and (2) are true, vCEJBs can be used to considerably increase application performance.

Our test application is designed to execute a large number of common EJB operations in a repeatable fashion. As such, the test application is somewhat artificial. It does not involve human interactions and arbitrary timing delays due to human input. The pattern of EJB operations is highly regular and maximizes the number of EJB accesses, whereas other J2EE applications may have irregular EJB accesses and also contain computationally or I/O-intensive tasks. Our *Session* and *User* EJBs are simple while EJBs in common J2EE applications can be more complex and may also be linked to each other. However, we believe that our test application realistically captures the performance *differences* between EJBs and f/vCEJBs in a large class of J2EE applications that are characterized by high numbers of entities, a high frequency of EJB accesses with a large degree of regularity (e. g., certain data mining applications such as our Mercury system), and a predictable and regular primary key space for the entities.

VII. Conclusion and Future Work

We presented two J2EE software design patterns that consolidate multiple entities in J2EE applications into special-purpose entity EJBs that we call consolidated EJBs (CEJBs). Our first design pattern maps entities to fixed-size CEJBs (fCEJBs), whereas our second pattern constructs variable-size CEJBs (vCEJBs). Consolidation increases the locality of data access in J2EE applications, thus making EJB caching in the application server more effective and decreasing search times for entity EJBs in the underlying database. In J2EE applications with large numbers of EJBs, CEJBs can therefore greatly increase the overall application performance. Using a test application, we showed that especially fCEJBs can outperform traditional EJBs by a wide margin for common EJB operations. For example, the fCEJB equivalent of an EJB *findByPrimaryKey* operation is more than five times faster in one of our experiments, and the execution of a data-modifying business method on an EJB is more than seven times faster in fCEJBs. In applications that do not lend themselves to the fCEJB design pattern, the second design pattern, vCEJBs, can enhance the application performance, albeit by smaller factors. In our experiments, we measured a speed-up of entity finder and access operations by a factor of more than two for vCEJBs versus traditional EJBs. Both types of CEJBs conform to the EJB specification and can therefore be used in any J2EE application on any J2EE application server.

We have several future research goals for CEJBs. First, we would like to modify CEJBs in such a way that applications with short-lived transactions and a small ratio of EJB read to EJB write operations perform better than our current patterns. Secondly, we intend to investigate mapping functions for fCEJBs that (1) perform well if the primary key space for EJBs is irregular or unpredictable (such as user names, phone numbers, or national IDs), and (2) that can be automatically defined without requiring complex developer decisions. Thirdly, we would like to address a currently open question for our f/vCEJB design patterns: how can we modify the f/vCEJB patterns so that they are beneficial in *most* J2EE applications and thus could ultimately become a standard way of implementing entities in J2EE applications? Lastly, a tool that would assist the developer in converting traditional EJBs into CEJBs would be highly desirable.



	Create	Find and read	Find and change	Remove
EJBs	0.55	2.25	3.38	3.88
fCEJBs	0.30	0.23	0.28	0.20
vCEJBs	1.77	0.81	1.48	1.14
Speedup fCEJBs->EJBs	1.84	9.62	12.01	19.00
Speedup vCEJBs->EJBs	0.31	2.78	2.28	3.40

Figure 11. Test application performance in long transaction mode, n = 1000.

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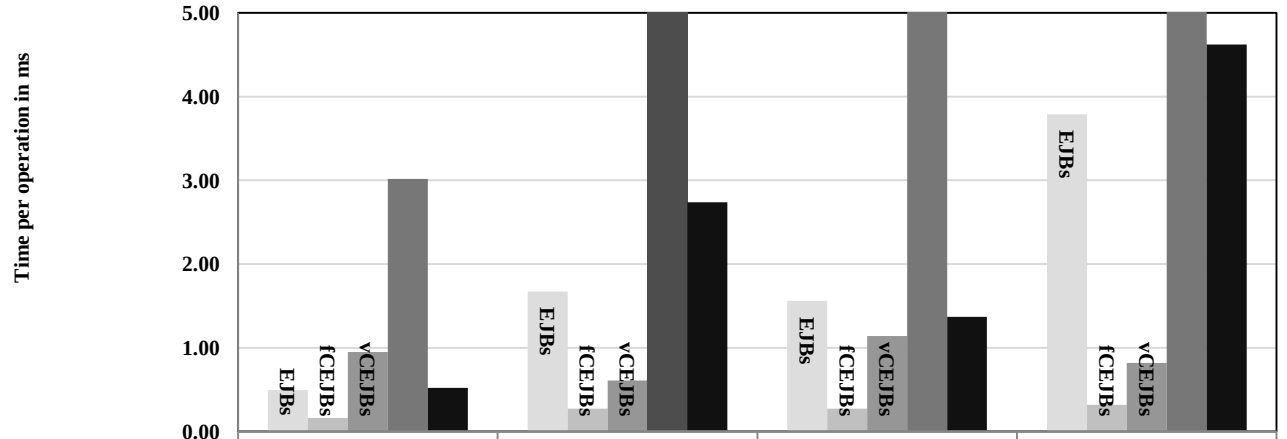
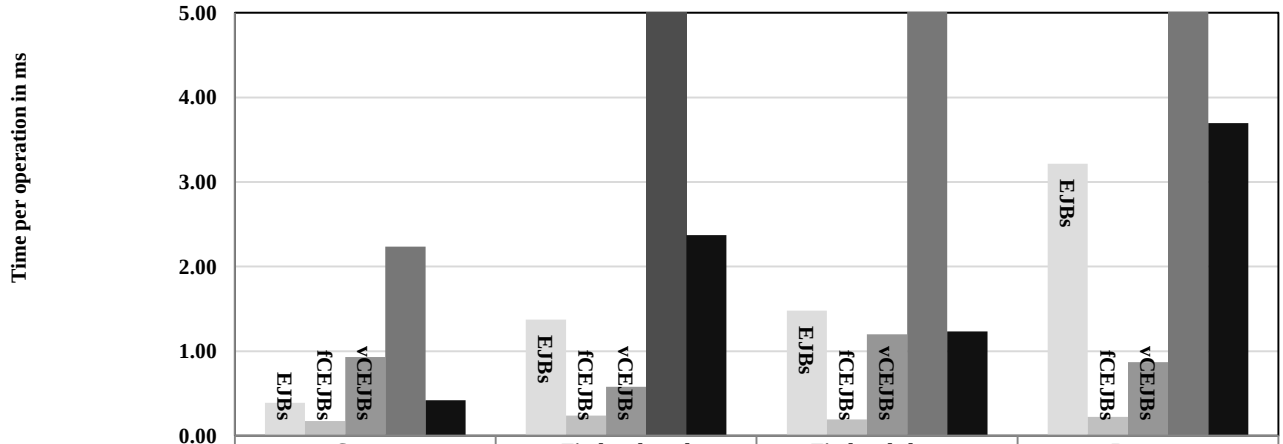


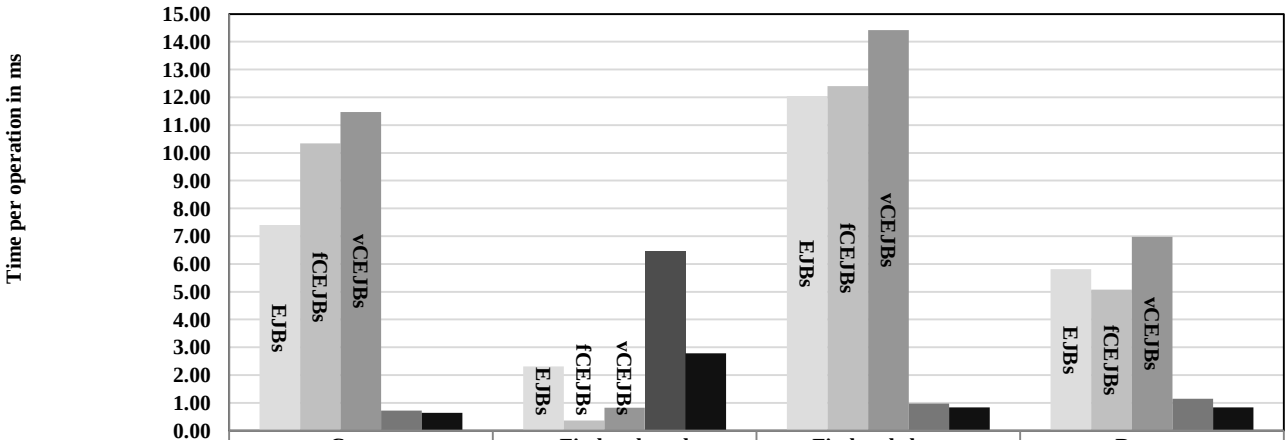
	Create	Find and read	Find and change	Remove
EJBs	0.50	1.67	1.56	3.79
fCEJBs	0.16	0.27	0.27	0.32
vCEJBs	0.95	0.61	1.14	0.82
Speedup fCEJBs->EJBs	3.02	6.14	5.72	11.84
Speedup vCEJBs->EJBs	0.52	2.74	1.37	4.62

Figure 12. Test application performance in long transaction mode, n = 10000.



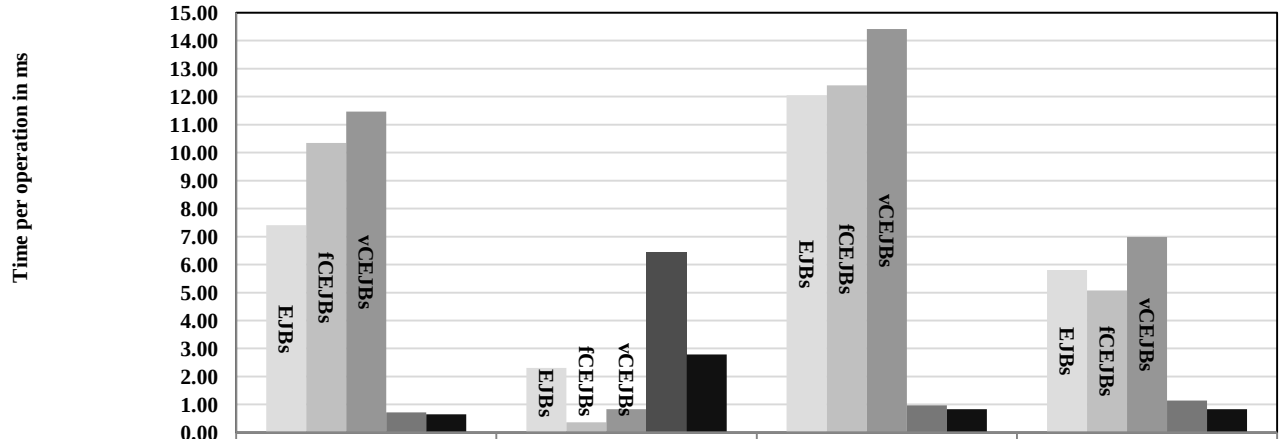
	Create	Find and read	Find and change	Remove
EJBs	0.39	1.38	1.48	3.21
fCEJBs	0.17	0.24	0.20	0.23
vCEJBs	0.93	0.58	1.20	0.87
Speedup fCEJBs->EJBs	2.24	5.75	7.58	14.28
Speedup vCEJBs->EJBs	0.42	2.37	1.23	3.69

Figure 13. Test application performance in long transaction mode, n = 50000.



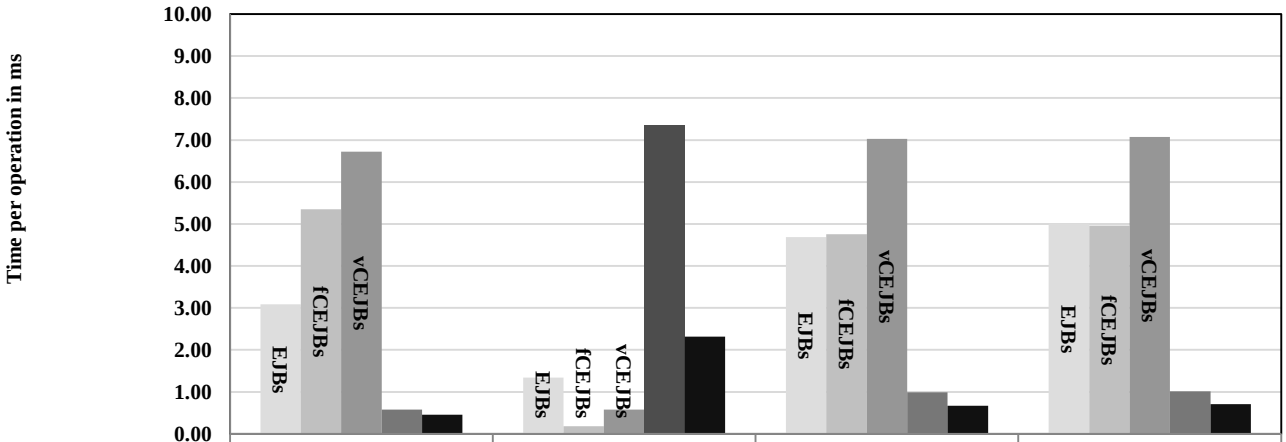
	Create	Find and read	Find and change	Remove
EJBs	7.41	2.31	12.05	5.81
fCEJBs	10.34	0.36	12.41	5.08
vCEJBs	11.47	0.83	14.42	6.98
Speedup fCEJBs->EJBs	0.72	6.44	0.97	1.14
Speedup vCEJBs->EJBs	0.65	2.79	0.84	0.83

Figure 14. Test application performance in short transaction mode, n = 1000.



	Create	Find and read	Find and change	Remove
EJBs	7.41	2.31	12.05	5.81
fCEJBs	10.34	0.36	12.41	5.08
vCEJBs	11.47	0.83	14.42	6.98
Speedup fCEJBs->EJBs	0.72	6.44	0.97	1.14
Speedup vCEJBs->EJBs	0.65	2.79	0.84	0.83

Figure 15. Test application performance in short transaction mode, n = 10000.



	Create	Find and read	Find and change	Remove
EJBs	3.08	1.34	4.69	5.01
fCEJBs	5.35	0.18	4.75	4.96
vCEJBs	6.72	0.58	7.03	7.07
Speedup fCEJBs->EJBs	0.58	7.34	0.99	1.01
Speedup vCEJBs->EJBs	0.46	2.32	0.67	0.71

Figure 16. Test application performance in short transaction mode, n = 50000.

VIII. ACKNOWLEDGMENTS

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Automated Software Engineering Process Assessment: Supporting Diverse Models using an Ontology

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***Abstract*—Current software engineering process assessment reference models rely primarily on manual acquisition of evidence of practices. This manually collected data is then correlated with expected model attributes to assess compliance. Such manual data acquisition is inefficient and error-prone, and any assessment feedback is temporally detached from the original context by months or years. Yet in order to automate the process data acquisition and assessment, one is confronted with various challenges that such diverse project-specific software engineering environments involve. This paper presents an ontology-based approach for enhancing the degree of automation in current process assessment while simultaneously supporting diverse process assessment reference models (CMMI, ISO/IEC 15504, ISO 9001). It also provides an in-the-loop automated process assessment capability that can help software engineers receive immediate feedback on process issues. The evaluation showed the approach's technical feasibility, model diversifiability across various process assessment models (CMMI, ISO/IEC 15504, ISO 9001), and suitable performance and scalability. The approach can reduce the effort required to determine process compliance, maturity, or improvement, and can provide more timely and precise feedback compared to current manual process assessment methods and tools.**

Keywords-software engineering process assessment tooling; semantic technology; Capability Maturity Model Integration; ISO/IEC 15504; ISO 9000

I. INTRODUCTION

This article extends our previous work in [1]. Processes - be they technical, managerial, or quality processes, are an inherent part of software engineering (SE), and subsequently so is process assessment and process improvement [2]. Software process improvement typically involves some assessment, and common reference model assessment standards utilize external audits (CMMI [3], ISO 15504 [4], and ISO 9001 [5]) that are performed manually to gather compliance evidence. Often the maturity of software organizations is assessed based primarily on their process-orientation and correlation of processes to a reference model.

If SE processes were supported or enacted by process-aware information systems (PAIS), then the efficiency of data acquisition and analysis for process assessment could also be improved. One prerequisite - the adoption and use of automated process enactment support is relatively rare in SE projects. This can be attributed to a number of factors: (1) software development projects face a high degree of new and changing technological dependencies (typically impacting project tool environments, knowledge management, process integration, and process data acquisition); (2) significant process modeling effort is necessary and PAIS usage has been somewhat restrictive [6]; (3) SE processes are knowledge processes [7], so that the exact operational determination and sequencing of tasks and activities is not readily foreknown; and (4) most current process models are too inflexible to mirror such detailed operational dynamics.

We developed the Context-aware Software Engineering Environment Event-driven frameworK (CoSEEEK) [8] to improve SE process support and guidance in an automated fashion. That way, enhanced support features are possible, such as automatically gathering information from the environment and users, uniting it with information from a knowledge base, and utilizing this information for on-the-fly process optimization (Section IIIC provides more information on CoSEEEK). Given such a context-aware event-driven automated process guidance system, we investigated the feasibility of enabling in-the-loop automated process assessment support. Our ontology-based approach semantically enhances a PAIS for SE operational process enactment and assessment support.

The paper is organized as follows: Section II describes the attributes of three common SE process reference models used in later sections. Section III describes general requirements and the solution approach for automated process assessment. An evaluation of this approach is described in Section IV. Section V positions related work relative to the solution approach. Section VII concludes the paper.

II. PROCESS ASSESSMENT MODELS

Three of the most mature and prevalent process assessment approaches used in software projects (CMMI, ISO/IEC 15504 / SPICE, and ISO 9001) are described in order to later show how automation was achieved. Despite the differences, with ISO 9000 being more of a requirement model and CMMI and SPICE meta-process models, they are similarly used for assessing process compliance or maturity. All three models have several basic concepts in common:

They define basic activities to be executed in a project such as 'Identify Configuration Items' for configuration management. (These will be mapped by a concept called *base practice* in our approach.) These activities are grouped together (e.g., 'Establish Baselines' in the configuration management example, with these groupings being mapped by a concept called *process* in our approach.) In turn, the latter are further grouped (e.g., 'Configuration Management') to allow further structuring. (This will be mapped by a concept called *process category* in our approach.) To be able to rate these practices and processes, the assessment models feature a *performance scale* to quantify the assessment. Finally, most models use the quantified assessments to assign *capability levels* to processes.

A. CMMI

CMMI (Capability Maturity Model Integration) [3] is one of the most widely used assessment models. It exists in different constellations, from which CMMI-DEV (CMMI for Development) is utilized in our context. The CMMI staged representation model comprises five *maturity levels* (1-'Initial', 2-'Managed', 3-'Defined', 4-'Quantitatively Managed', 5-'Optimizing'). The levels indicate 'Degree of process improvement across a predefined set of process areas, in which all goals within the set are attained' (cf. [3]). To implement this, each of the levels has subordinate activities that are organized as follows: A maturity level (e.g., '2') has *process categories* (e.g., 'Support') that have *process areas* (e.g., 'Configuration Management') that have *specific goals* (e.g., 'Establish Baselines') that finally have specific practices (e.g., 'Identify Configuration Items'). To illustrate the CMMI, the maturity levels, categories, and areas are shown in the following table:

To quantify the assessment, CMMI has a performance scale (1-'unrated', 2-'not applicable', 3-'unsatisfied', 4-'satisfied'). Using these concepts, process assessment is applied as follows:

- Rate each generic and specific goal of a process area using the introduced performance scale.
- A maturity level is achieved if all process areas within the level and within each lower level are either 2 or 4 (cf. the performance scale introduced).

In addition to these concrete activities and maturity levels, CMMI features *generic goals* (e.g., 'Institutionalize a Managed Process') with *generic practices* (e.g., 'Control Work Products'). These are subordinate to capability levels (0-'Incomplete', 1-'Performed', 2-'Managed', 3-'Defined', 4-'Quantitatively Managed', 5-'Optimizing'). The latter indicate 'Achievement of process improvement within an individual process area' (cf. [3]). SCAMPI (Standard CMMI Appraisal Method for Process Improvement) [9] is the official CMMI appraisal method. It collects and characterizes findings in a Practice Implementation Indicator Database. According to SCAMPI, there is a direct relationship between specific and generic goals (SG and GG), which are required model components, and the specific and generic practices (SP and GP), which are expected model components. Satisfaction of the goals is determined by a detailed investigation, and alternative practices could be implemented that are equally effective in achieving the intent of the goals.

TABLE I. CMMI

Mat. Level	Category	Process Area
2	Support	Configuration Management (CM/SCM)
2	Support	Measurement and Analysis (MA)
2	Project Man.	Project Monitoring and Control (PMC)
2	Project Man.	Project Planning (PP)
2	Support	Process and Product Quality Assurance (PPQA)
2	Project Man.	Requirements Management (REQM)
2	Project Man.	Supplier Agreement Management (SAM)
3	Support	Decision Analysis and Resolution (DAR)
3	Project Man.	Integrated Project Management (IPM)
3	Process Man.	Organizational Process Definition (OPD)
3	Process Man.	Organizational Process Focus (OPF)
3	Process Man.	Organizational Training (OT)
3	Engineering	Product Integration (PI)
3	Engineering	Requirements Development (RD)
3	Project Man.	Risk Management (RSKM)
3	Engineering	Technical Solution (TS)
3	Engineering	Validation (VAL)
3	Engineering	Verification (VER)
4	Process Man.	Organizational Process Performance (OPP)
4	Project Man.	Quantitative Project Management (QPM)
5	Support	Causal Analysis and Resolution (CAR)
5	Process Man.	Organizational Performance Management (OPM)

B. ISO/IEC 15504 (SPICE)

The SPICE (Software Process Improvement and Capability Determination) [4][10] model is an international standard for measuring process performance. It originated from the process lifecycle standard ISO/IEC 12207 [11] and maturity models such as CMM (the predecessor of CMMI). SPICE comprises six *capability levels* (0-'Incomplete process', 1-'Performed process', 2-'Managed process', 3-'Established process', 4-'Predictable process', 5-'Optimizing process'). Each of the latter has one or multiple *process attributes* (e.g., '2.1 Performance Management'). In the following table, the capability levels and process attributes are shown:

A process reference model was included in the initial version of the standard. This was later removed to support different process models (or the ISO/IEC 12207). Thus, mappings to various process models are possible. In this paper, the examples use the initial process model specifications for illustration. These comprised *process categories* (e.g., 'Organization') with *processes* (e.g., 'Improve the process') that contained *base practices* (e.g., 'Identify reusable components'). SPICEs measurement model applies the following performance scale for

assessment: 1-'not achieved' (0-15%), 2-'partially achieved' (16% - 50%), 3-'largely achieved' (51% - 85%), and 4-'fully achieved' (86% - 100%).

TABLE II. SPICE

Cap. Level	Name	Process Attribute
0	Incomplete process	-
1	Performed process	Process Performance
2	Managed process	Performance Management Work Product Management
3	Established process	Process Definition Process Deployment
4	Predictable process	Process Measurement Process Control
5	Optimizing process	Process Innovation Process Optimization.

SPICE does not use assessments of practices to directly determine whether an overall capability level is achieved, but uses them to assign to each process one or more capability levels and to use them to recursively calculate assessments for projects and organizations. The assessment comprises the following steps:

- Assess every base practice with respect to each of the process attributes.
- Determine the percentage of base practices of one process that have the same performance scale with respect to one process attribute.
- Assessment of the processes: Assign the capability level for process attributes where all base practices of the process have performance scale 3 or 4 and for all lower capability levels, the same applies with performance scale 4.
- Assessment of a project is done by using the mathematical mean of the ratings of all of its processes.
- Assessment of an organization is done by using the mathematical mean of the ratings of all of its projects.

C. ISO 9001

ISO 9000 comprises a family of standards relating to quality management systems. ISO 9001 [5] deals with the requirements organizations must fulfill to meet the standard. Formal ISO 9001 certifications have gained great importance for organizations worldwide. The ISO 9001 assessment model uses no capability scale; it only determines whether a certain practice is in place. Therefore, a simple performance scale suffices: 0-'not satisfied', 1-'satisfied'. The assessed practices are structured by *process sub-systems* (e.g., 'Organization Management') that contain *main topic areas* (e.g., 'Management responsibility'). In turn, the latter contain *management issues* (e.g., 'Define organization structure'). Based on these concepts, a recursive assessment can be applied rating an organization by its *process sub-systems* and the contained *management issues* with a pass threshold of 100%. Our approach is targeted at creating more quality awareness in companies, not at replacing or conducting formal reviews. Therefore, the standard ISO 19001:2011 (Guidelines for auditing management systems) [12] is not taken into account here.

D. Summary

As shown by these three assessment models, the approaches to process assessment differ significantly. This applies for the concepts utilized as well as for the applied procedures: For example, CMMI knows two different types of levels that have subordinate activities. For ISO/IEC 15504, the levels have certain attributes that serve to assess all existing practices. As opposed to the two other models, ISO 9001 does not apply levels or different performance scales. These differences hamper convergence to a unified model or approach and present the primary technical challenge.

III. AUTOMATED PROCESS ASSESSMENT

This section describes the approach taken to provide automated process assessment including the requirements elicited for such an approach, application concept, conceptual framework, and procedure applied. The approach extends and annotates process management concepts, enhancing them with additional information required for assessment. The aim of our approach is not to replace manual ratings of processes conducted by humans or to be used in formal process audits. It shall rather contribute to the quality awareness of a company and provide information on the current state of the process as it is executed. Therefore, our approach, despite adding automated rating facilities, still integrates and relies on manual ratings or confirmations for ratings.

A. Requirements

This sub-section briefly elicits basic requirements for providing automated integration of process assessment and process execution facilities into SE project environments. These requirements are:

- R:Proc: If a system aims at automatically integrating assessments with the executed process, the first basic requirements is that the system must be aware of the process and be able to govern the latter.
- R:Cntx: To be able to not only be aware of the planned process, but also integrate with the real operational process as it is enacted by SE project members, facilities must be in place the provide usable context information to the system.
- R:MultModel: To be able to provide flexible support for diverse projects and organizations, the assessment approach should not be tied to a single assessment model. It should support implementation and customization of various models.
- R:Integrate: An automated assessment approach should not produce much additional effort or disturb users in their normal work. Therefore, the assessment facilities should integrate seamlessly with normal process execution.

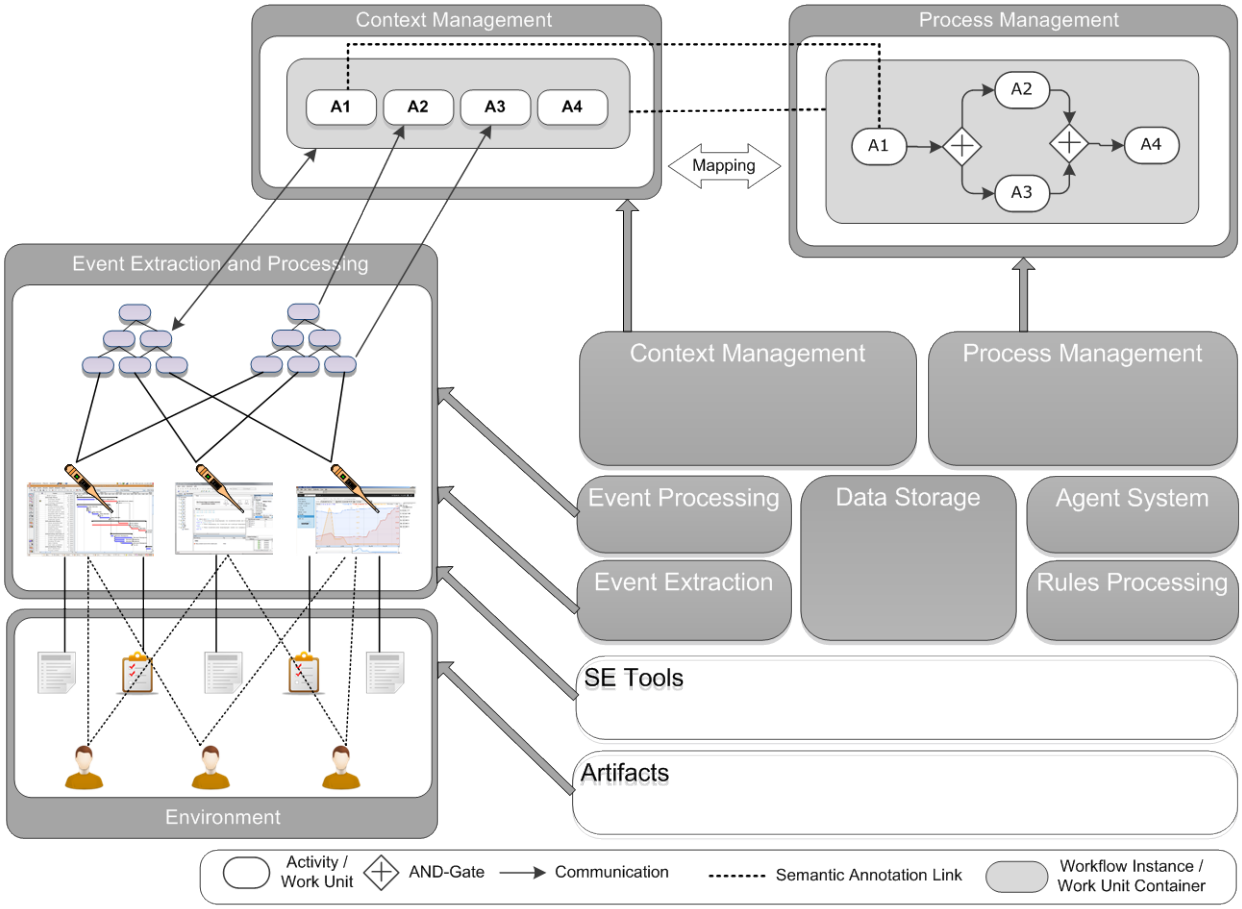

Figure 1. Application concept for automated process assessment.

- R:Auto: To avoid unnecessarily burdening users, an automated assessment approach should enable automate ratings to the degree feasible . However, it must also incorporate facilities for humans to interfere or override automated ratings.

B. *Concept for Application*

As aforementioned, to be able to integrate process assessment tightly into the software developments process and everyday work in SE projects, our approach is realized within the CoSEEEK framework [8]. The latter provides holistic process and project support by integrating various technologies for context awareness and management as well as dynamic and adaptive process management. The different components of the framework and the contextual integration capabilities are illustrated in Figure 1.

The different components of the framework are loosely coupled and feature reactive event-based communication via the central *Data Storage* component. As the framework shall be context-aware, a way of acquiring context data is necessary. In an SE project, context consists mostly of different actors that use SE tools to manipulate a variety of SE artifacts. To gain an awareness of these, the following approach is taken: The *Event Extraction* component of the framework features a set of sensors that are integrated into various SE tools. These sensors generate events as users change the states of various artifacts. As these events are of rather atomic nature, the *Event Processing* component aggregates them to derive higher-level events that contain more semantic value.

To be able to utilize contextual knowledge directly for process guidance, the *Process Management* and *Context Management* components work tightly together: The former enables the dynamic implementation and execution of processes (cf. requirement R:Proc) while the latter stores, processes and evaluates the context information (cf. requirement R:Cntx) using an ontology and reasoning. Furthermore, it encapsulates the *Process Management* from the other components. Thus, all process communication is routed over the *Context Management* component, which enhances it with context information and utilizes it to adjust the process execution.

To enable a reasonable level of dynamicity and automation, CoSEEEK also features to further components: The *Rules Processing* component enables the flexible and simple definition and execution of certain automatisms as rules. The *Agent System* component enables CoSEEEK to react to different dynamic situations in which different conflicting goals have to be evaluated and decisions made.

Based on these components, CoSEEEK provides a variety of different functionalities that support different aspects of automated process and project support for SE projects:

- Quality Management: CoSEEEK enhances the automated detection of quality problems in the source code by facilitating the automated assignment of software quality measures to counteract these problems. The measures are seamlessly integrated into users' workflows to minimize user disturbance and maximize efficiency. For further reading on this topic, see [13].
- Knowledge Management: CoSEEEK enables the collection and management of knowledge in SE projects. This information is semantically enhanced, and thus CoSEEEK can automatically provide the appropriate knowledge to the users at the appropriate point in the process. For further reading on this topic, see [14].
- Exception Handling: CoSEEEK enables a flexible and generic exception handling approach that is capable of detecting various exceptions related to activities as well as artifacts. Furthermore, the appropriate exception handling, the responsible person for applying that handling, and the appropriate point in the process to apply it can be automatically determined. For further reading on this topic, see [15].
- Task Coordination: CoSEEEK features the ability to automatically coordinate activities of different areas of a SE project. This comprises the automatic notification of users in case of certain changes to artifacts or activities as well as the automatic issuing of follow-up actions required by other actions or changes. For further reading on this topic, see [16].
- Extended process support: CoSEEEK incorporates facilities to implement a greater coverage of activities carried out in SE projects as SE process models. Many dynamic activities and workflows that are not covered by the models can be modeled and executed, featuring a suitable simple modeling and transformation facility. For further reading on this topic, see [17].

C. Conceptual Framework

To achieve extended assessment functionality, process management concepts were enhanced. These are defined in the *Context Management* component and are associated with a *Process Management* component that manages process execution. Thus, assessment concepts can be tightly and seamlessly integrated with process execution (cf. requirement R:Integrate). Figure 2 shows a simple workflow in the *Process Management* component: This workflow is defined by 'Workflow Template 1' that contains four activity templates. Both of these concepts are mirrored in the *Context Management* component by the *Work Unit Container Template* that contains *Work Unit Templates*. When the workflow is to be executed, it is instantiated in the *Process Management* component and then represented by a workflow instance ('Workflow Instance 1') containing the activities to be processed. These two concepts are again mirrored in the *Context Management* component by the *Work Unit Container* that contains *Work Units*. These have explicitly defined states that are automatically synchronized with the states in the *Process Management* component. That way, the *Context Management* component is aware of the current execution state of workflows and activities.

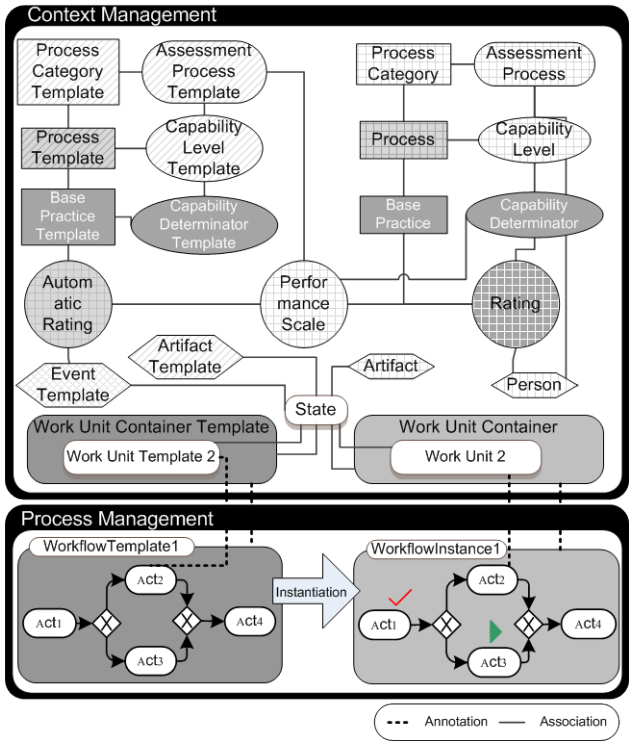

Figure 2. Conceptual framework for automating process assessment.

Similar to the *Work Unit Containers* and their templates, the concepts for process assessment are separated into template concepts for definition and individual concepts holding the actual values of one execution. These concepts are abstract and generic to be applicable to various models (cf. requirement R:MultModel). The *Assessment Process Template* defines one process assessment model. In alignment to the aforementioned assessment approaches, it features templates for *Process Categories*, *Processes*, and *Base Practices* as well as *Capability Levels*. The latter are general level concepts used to model various capability or maturity levels that can be calculated for other concepts such as *Base Practices* or *Assessment Processes*. To explicitly configure how the capability level achievement will be determined, *Capability Determinator Templates* are used. The *Assessment Process Template* also defines a number of *Performance Scales* that are used for the assessment later. For all these concepts, there are individual counterparts used for each concrete assessment that are based on the template concepts. Table 1 depicts their relevant properties including a short description.

TABLE III. CONCEPTS PROPERTIES

Property	Description
Assessment Process Template	
capabilityLevels	all defined capability levels templates
procCatTempls	all defined process category templates
Capability Level Template	
calcFor	concept, for which the level is calculated
capDet	attached capability determinator templates
perfScale	required performance scale for achievement
scaleRatio	ratio of capability determinators that must meet required performance scale
subCL	subordinate capability level template
subCLPerfScale	required performance scale of subordinate level
Level	number indicating the level
Capability Determinator Template	
Source	base practice to be assessed
Target	capability level, for which this determinator is used

For flexibility in the assessment calculation, the *Capability Level Templates* have a property 'calcFor' that is used to attach them to the target concept to be calculated (e.g., the whole assessment process when calculated for a project of a single process). As proposed by the three introduced models, level achievement calculation can rely on the assessment of the designated practices (be they required or expected) or subordinate levels. Therefore, the achievement of a capability level is determined by the following properties: 'perfScale' defines which *Performance Scale* the attached *Capability Determinators* has, and via 'scaleRatio' a ratio of *Capability Determinators* can be defined as required for the *Performance Scale*. Additionally, as the *Capability Levels* are connected to other subordinate levels, the *Performance Scale* of their determinators can also be used (cf. SPICE, required by the 'subCLPerfScale' property).

The assessment of the concrete individual concepts is then applied via the explicit *Rating* concept, which connects a *Performance Scale* with a *Base Practice* and a *Capability Determinator*. It can also be connected to a concrete *Person* who will then be asked to do the assessment. To support automation in the assessment procedure and unburden the users, it is also possible to automate ratings with *Automated Rating*. It can be connected to an *Event Template* concept that, in turn, is connected to the *States* of *Artifacts* or *Work Unit Containers*. That way, it can be configured so that when the *Concept Management* component receives certain status change events, a certain *Performance Scale* is assigned to a certain rating. Examples of such a definition include: 'Assign *Performance Scale* 1 if workflow x is present (created)' or 'Assign *Performance Scale* 2 if workflow x is completed' or 'Assign *Performance Scale* 3 if *Artifact* y is in state z'.

D. Assessment Procedure

The concrete assessment procedure applied to rate process performance is shown in Listing 1. The following algorithm describes how a concrete *Assessment Process* is created from its template, how the ratings are applied to the different *Base Practices* contained in the process, and how achievement of maturity/capability levels is determined.

Listing 1. The Rate Process Performance algorithm in pseudocode.

```
Require: Project P, AssessmentProcessTemplate APT,
Person Pers
01: AssessmentProcess AP ← createConcept(APT)
02: linkConcepts(P, AP)
03: for all APT.processCategoryTemplates PCT do
04:  ProcessCategory PC ← createConcept(PCT)
05:  linkConcepts(AP, PC)
06:  for all PCT.processTemplates PT do
07:    Process PR ← createConcept(PRT)
08:    linkConcepts(PC, PR)
09:    for all PRT.basePracticesTemplates BPT do
10:      BasePractice BP ← createConcept(BPT)
11:      linkConcepts(PR, BP)
12:    end for
13:  end for
14: end for
15: for all APT.capabilityLevelTemplates CLT do
16:  CapabilityLevel CL ← createConcept(CLT)
17:  linkConcepts(AP, CL)
18:  linkConcepts(CL, CLT.calculatedFor)
19:  for all CLT.capabilityDeterminatorTemplates
          CDT do
20:    CapabilityDeterminator CD ←
              createConcept(CDT)
21:    linkConcepts(CL, CD)
22:    List relatedBPs ← getRelatedBasePracts(CD,
                          AP)
23:    for all relatedBPs BP do
24:      new rating(CD, BP,
           AP.getStandardPerformanceScale,Pers)
25:    end for
26:  end for
27: end for
28: automatedRating(AP)
29: manualRating(AP)
30: for all AP.capabilityLevels CL do
31:  checkAchievement(CL)
32: end for
```

The algorithm requires a concrete project and an *Assessment Process Template* to be used for that project. The first part of the algorithm (lines 01-14) then creates a structure comprising *Process Categories*, *Processes,* and *Base Practices* for the new *Assessment Process*. For this paper, the following two functions are used: 'createConcept' creates an individual concept from a given template and 'linkConcepts' links two individual concepts together.

The second part of the algorithm (line 15-27) creates the *Capability Level* structure. Therefore, the *Capability Levels* and their attached *Determinators* are created first. Thereafter the *Determinators* are linked to the *Base Practices* they use for determining capability. This is done using the function 'getRelatedBasePractices' that gets all *Base Practices* in the current *Assessment Process* that are configured to be connected to a certain *Capability Determinator* via their templates. For each of these *Base Practices*, a new *Rating* is created linking them to the *Capability Determinator*. To this *Rating*, a standard *Performance Scale* (usually the one equal to 'not achieved') and a responsible person are attached.

The third part of the algorithm (lines 28-32) deals with the concrete assessment. During the whole project, an

automated rating is applied whenever a matching event or status change happens. At the end of a project (or anytime an assessment is desired), the manual rating is applied, distributing the rating information to the responsible person (cf. requirement R:Auto). The latter can then check the automated rating, rate practices that have not yet been rated, or distribute certain parts of the assessment to others who can provide the missing information needed to rate the practices. The final action applied is to check the achievement for each *Capability Level* of an *Assessment Process*.

E. Technical Realization

This section gives insights on the technical realization of our process assessment concept and the CoSEEEK framework. The technical implementation of each of CoSEEEK's components is shown in Figure 3.

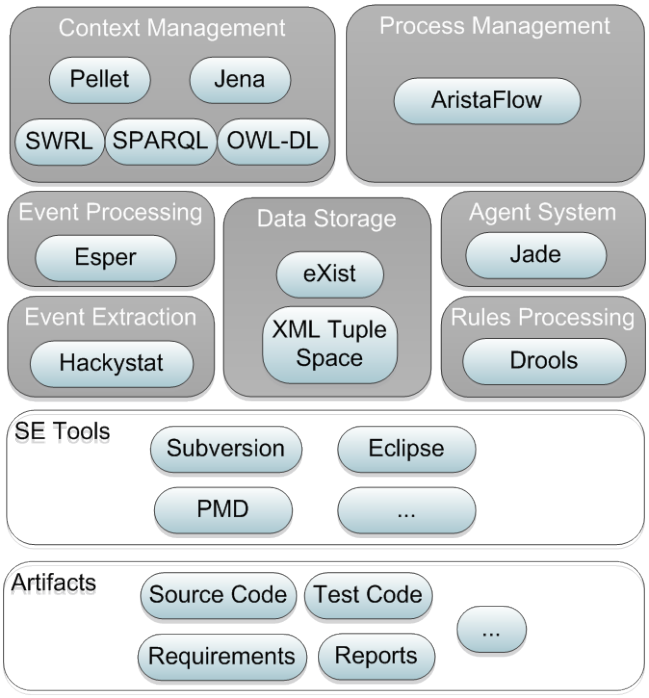

Figure 3. Technical Realization.

As mentioned before, CoSEEEK's context awareness builds primarily on sensors that are integrated into various applications. Applications with sensor support include, as shown in the figure, the version control management system Subversion, the integrated development environment Eclipse, or the quality measurement tool PMD. Artifacts whose state can be monitored this way include source or test code, requirements, or various reports.

The *Event Extraction* component is implemented with the Hackystat [18] framework. The latter provides a rich set of sensors for the aforementioned applications. Furthermore, it features an open architecture for the implementation of new sensors. The aggregation of these events is done via complex event processing (CEP) [19] enabled by the tool esper [20]. The latter provides easy facilities to define and execute CEP patterns. This, together with the sensors, enables the recording of various activities people really execute using SE tools like IDEs (Integrated Development Environments). Thus, the execution of several activities relating to the assessment of the process can be automatically detected and their achievement level can be adjusted.

The communication of the different components is realized via the tuple space paradigm [21]. The latter, in turn, is implemented via a tuple space that has been built on top of the XML database eXist [22]. The *Agent System* component is implemented via the FIPA [23] compliant JADE framework [24] and the *Rules Processing* component with JBoss Drools [25].

The *Process Management* component is implemented with AristaFlow [26]. The latter was chosen due to its capabilities concerning correctness and flexibility. It enables the correct adaptation even of running workflows. In particular, during run-time, selected workflow instances can be dynamically and individually adapted in a correct and secure way; e.g., to deal with exceptional situations or evolving business needs. Examples of workflow instance changes supported by AristaFlow include the dynamic insertion, deletion, or movement of single workflow activities or entire workflow fragments respectively.

The *Context Management* component applies semantic web technology. This comprises an OWL-DL [27] ontology for knowledge organization and Pellet [28] as reasoner for inferences and logical classifications. The usage of ontologies reduces portability, flexibility, and information sharing problems that are often coupled to technologies like relational databases. Furthermore, ontologies support extensibility since they are, in contrast to relational databases, based on an open world assumption and thus allow the modeling of incomplete knowledge.

IV. EVALUATION

This section evaluates our approach by applying it to the three different process assessment models introduced in Section II, and further elucidates technical realization details. A selection of the applied concepts is shown in Figure 4 for all of the three models.

A. CMMI

An excerpt of the implementation of the CMMI model is shown in Figure 4(a). On the upper half, the templates for defining the CMMI concepts are shown: The assessment of the process is carried out in a slightly different way than the reference model of the CMMI, since our concept does not feature explicit goal concepts. Moreover, the assessment for the maturity levels is done directly with the specific and generic practices and not by using the latter for the goals and these, in turn, for the maturity levels.

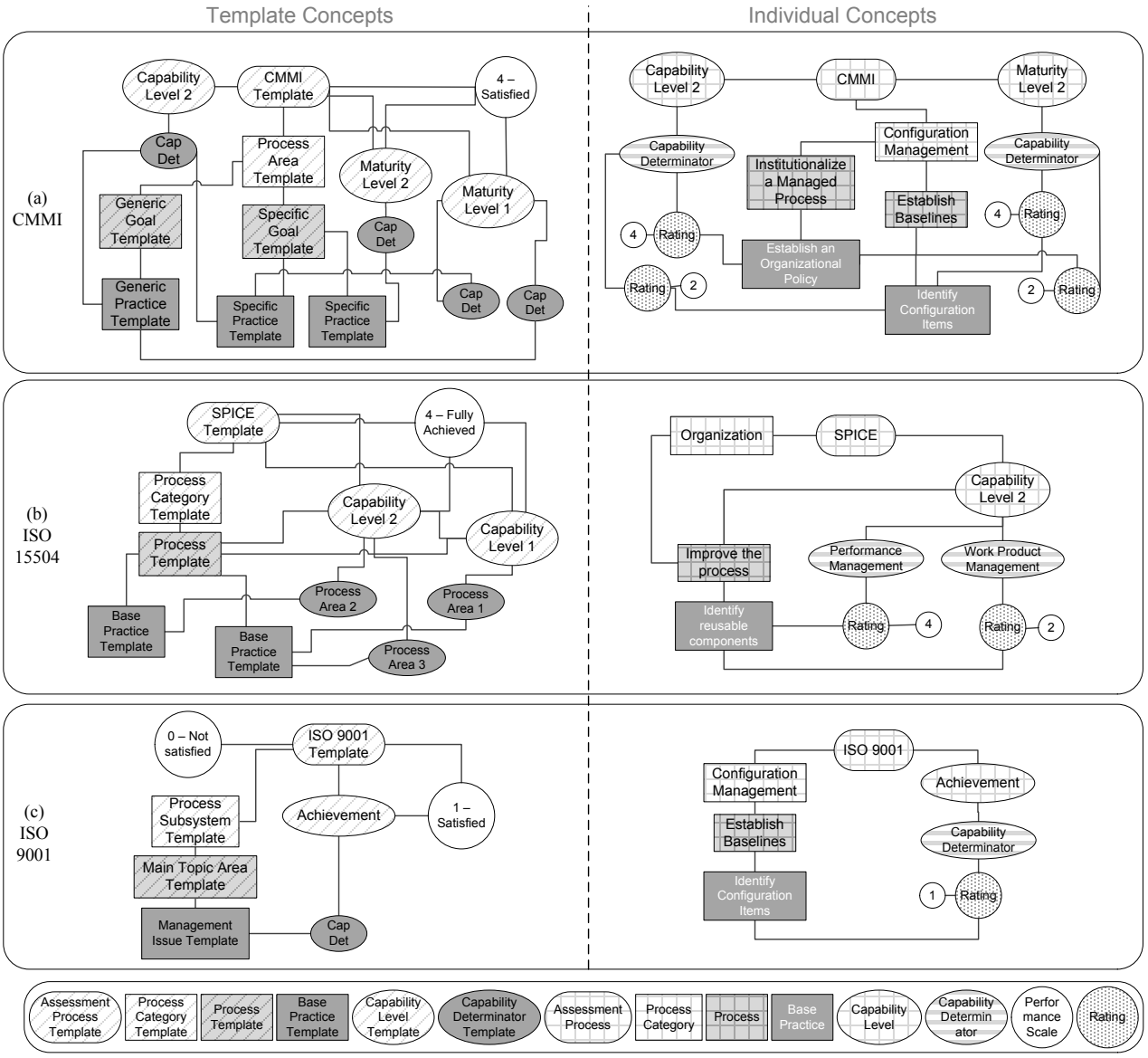

Figure 4. Realization for specific reference models: (a) CMMI (b) ISO 15504 (c) ISO 9001.

The structure of the process is built by the *Process Category Template* (used for the process areas CMMI), the *Process Template* (used for the specific goals CMMI), and the *Base Practice Template* (used for the specific practice of CMMI). Connected to the 'CMMI Template' (implemented by the *Assessment Process Template*) are also the 'Maturity Levels' (implemented by the *Capability Level Template* concept). In addition to this structure with the specific goals and maturity levels, the applied concepts can also be used to implement the generic goals of CMMI with their generic practices and the relating capability levels as illustrated. For the *Assessment Process Template*, the maturity levels are connected to the *Capability Determinators* of all specific practices that belong to the relating maturity level. The *Capability Determinators* also realize connections to *Base Practices* that implement CMMIs generic practices applied to the respective process area (implemented by a connection from the Base Practice, the Process, and the Process Category, cf. 'Establish an Organizational Policy', 'Institutionalize a Managed Process', and 'Configuration Management' in Figure 4). Similar connections can be established for the capability levels, so that the staged or the continuous representation of CMMI to assess respectively the maturity of a whole organization or its capabilities concerning the different process areas. For the capability determination, the *Assessment Process Template* is also connected to the *Performance Scales* that will be used for it. The figure shows one example of them (4 – Satisfied).

On the lower part of Figure 4(a), the individual concepts for the assessment of one concrete project with CMMI are illustrated. It shows one exemplary maturity level and one process area with one specific goal with one specific practice. The *Capability Determinators* of the maturity level are connected to the specific practices that shall be rated via the *Rating* that has an assigned *Performance Scale*. A similar excerpt of the structure is shown for the capability levels and generic goals in the figure.

The achievement calculation for the maturity levels is done with the 'perfScale' and 'scaleRatio' properties of the *Capability Level Template*: That way it can be defined that 100% of the *Capability Determinators* must have the Performance Scale '4' or '2' as defined in the CMMI model. If calculations for all of the projects of an organization were in place, maturity indicators for the entire organization could use the lowest maturity level achieved by all projects.

B. ISO/IEC 15504 (SPICE)

An excerpt of the implementation of the SPICE model is shown in Figure 4(b). In this case the names of the concepts match with the names used in SPICE (e.g., for capability levels or base practices). The *Performance Scales* are defined for the *Assessment Process Template* similar to the CMMI implementation, e.g., 4 – Fully Achieved (86%-100%) as shown in the figure. The process areas that are subordinate to the capability levels in SPICE are implemented using the *Capability Determinator Templates*. Each of the latter is connected to all *Base Practice Templates* to enable their rating concerning all process attributes as required by SPICE.

The lower part of Figure 4(b) again shows an excerpt of the individual concepts used for the assessment of a concrete project. It comprises an exemplary capability level with its two process attributes and an exemplary process category with one process and one base practice.

The SPICE assessment works as follows: All base practices are rated according to all process attributes, and capability levels are determined for the processes. A level is achieved if all its related process areas have only ratings with *Performance Scales* '3' or '4', and the process areas of the subordinate levels all have *Performance Scale* '4'. The assessment of the project is the mathematical mean of the assessments of the processes, and can thus be easily computed without explicit modeling. The same applies to the assessment of a whole organization.

C. ISO 9001

As ISO 9001 is a requirement and not a process model, it must be mapped to the organization's process. This can be applied by connecting *automated ratings* to *events* occurring in the execution of *work unit containers* representing the real execution of a related workflow or be applied manually by a person doing a manual rating. An excerpt of the implementation of the ISO 9001 assessment model is shown in Figure 4(c). In this case, the upper part of the figure again shows the template concepts for defining the model. Compared to the other two models, ISO 9001 is simpler: It knows no capability levels and only two performance scales (as shown in the figure). Therefore, there is only one *Capability Level Template* defined that is used to determine achievement for the whole ISO 9001 assessment. That template has one *Capability Determinator Template* for each management issue.

The lower part of Figure 4(c) again shows the individual concepts used for a concrete assessment using a concrete example for a process subsystem, a main topic area, and a management issue. The assessment is applied by the 'perfScale' and 'scaleRatio' properties of the single *Capability Level*, specifying that all *Capability Determinators* must have the *Performance Scale* '1'. As ISO 9001 knows no project level, this can be added by using a separate Assessment Process for each project, and cumulating the assessment over the whole organization (if all projects have achieved, the whole organization has achieved).

D. Performance and Scalability

Process assessment approaches often comprise dozens or even hundreds of concepts (e.g., SPICE has over 200 base practices), which implies the creation of an even higher number of concepts in the ontology to enable automated assessment. Therefore, the utilization of a separate ontology for process assessment is considered to keep the operational ontology of the CoSEEEK framework clean. Furthermore, to support stability and performance, the CoSEEEK ontologies are not managed as plain files but stored in a database (using Protégé functionality). The test configuration consisted of a PC with an AMD Dual Core Opteron 2.4 GHz processor and 3.2GB RAM with Windows XP Pro (SP3) and the Java Runtime Environment 1.5.0_20, on which CoSEEEK was running networked via Gigabit Ethernet to a virtual machine (cluster with VMware ESX server 4.0, 2 GB RAM allocated to the VM, dynamic CPU power allocation) where the AristaFlow process server is installed.

The approach supports model diversity, and thus the ontology size can vary based on various reference models. Scalability of the approach was assessed, since a large number of concepts can be required with complicated models such as SPICE - which has over 200 *Base Practices* that require linking to all process areas and calculation of all *Capability Levels* for the *Processes*. The most resource intensive point is when the entire *Assessment Process* for a project is created, thus performance and scalability tests were conducted for the automatic creation of linked ontology concepts, scaling the number of concepts to account for smaller to larger models.

The results obtained were: 1.7 seconds for the creation and linking of 100 concepts, 14.2 seconds for the creation and linking of 1000 concepts, and 131.4 seconds for the creation and linking of 10000 concepts. The results show that the computation time is acceptable with approximately linear scaling. The slight reduction in average creation time for a single concept is perhaps explainable by reduced initialization percentages and caching effects. At this stage, the performance of the Rate Process Performance algorithm (Listing 1) was not assessed since it is fragmented across a project timescale (at the beginning the concepts are created

and later the ratings are applied), it is dependent on human responses (manual ratings), and live project data has not as yet been collected.

V. Related Work

This section reviews different areas of related work: At first, approaches covering the basic requirements for implementing automated process assessment support are reviewed. This includes automated process and project support as well as the contextual integration of process management. After that, approaches enabling semantic extensions to process management concepts are examined. Finally, approaches aiming at directly supporting automated assessments are discussed.

A. Automated Process Support

To integrate automated assessments with operational process execution, holistic process support should be enabled by that system. In related work, many approaches target that topic. However, many of them focus strongly on governing activities and their dependencies. One of them is the framework CASDE [29]. It utilizes activity theory to provide a role-based awareness module managing mutual awareness of different roles in the project. The collaborative SE framework CAISE [30] enables the integration of SE tools and the development of new SE tools based on collaboration patterns. Caramba [31] provides coordination capabilities for virtual teams. It features support for ad-hoc workflows utilizing connections between different artifacts, resources, and processes. For pre-modeled workflows, UML activity diagram notation is used. For ad-hoc workflows not matching a template, an empty process is instantiated. In that case, work between different project members is coordinated via so-called Organizational Objects. The process-centered SE environment EPOS [32] applies planning techniques to automatically adapt a process instance if certain goals are violated. All of these approaches have capabilities for supporting and automating process execution in SE projects, yet none enacted an entire SE process model and thus failed to provide holistic project support.

B. Contextual Process Integration

As discussed in the requirements section, to be integrated with the real operational process of SE projects, a system providing process support must also take into account contextual data. In related work, numerous approaches for context modeling exist, including frameworks like Context Management [33], CASS [34], SOCAM [35], and CORTEX [36]. These provide support for gathering, storing, and processing context data, but leave the reaction to context changes to the application, or use rule-based approaches that are hard to maintain. There are only few approaches combining context-awareness with workflows. One of these is inContext [37] that makes heavy use of context knowledge for supporting teamwork. However, inContext does not offer the necessary capabilities to implement whole SE process models.

C. Semantic Process Extensions

As aforementioned, the assessment concepts elaborated in this work are implemented as semantic extensions of process management concepts. This enables tight integration with process execution. In related work, there are various approaches implementing such extensions to process management for different purposes: COBRA [38] focuses business process analysis and, for that purpose, presents a core ontology. With the latter, it supports better and easier analysis of processes to comply with standards or laws like the Sarbanes-Oxley act. [39] presents a semantic business process repository that fosters automation of the business process lifecycle and offers capabilities for checking in and out, as well as locking and options for simple querying and complex reasoning. The approach presented in [40] features multiple levels of semantic annotations: a meta-model annotation, a model content annotation, and a model profile annotation as well as a process template modeling language. With these annotations, it aims at facilitating process models across various model representations and languages. A concept for machine-readable process models is presented by [41]. It targets achieving better integration and automation and utilizes a combination of Petri Nets and an ontology, whereby direct mappings of Petri Net concepts in the ontology are established. [42] describes an approach that proposes an effective method for managing and evaluating business processes via the combination of semantic and agent technology to monitor business processes. None of these approaches provides a general semantic extension that allows direct interaction with and management of process execution as well as extensibility to achieve an integration between the latter and process assessment approaches.

D. Automated Process Assessment Support

The core area of related work for this paper is automated process assessment. In this area, a number of approaches exist. One of these constitutes a multi-agent system approach that is presented in [43], to enable automatic measurements for the SW-CMM (Software Capability Maturity Model). The latter is combined with the GQM (Goal-Question-Metric) [44] method, where Goals of the SW-CMM are used as a first step for GQM.

An OWL ontology and reasoner approach for CMMI-SW (CMMI for Software) is presented in [45]. In contrast to our approach, the size of the ontology caused issues for the reasoner. A software process ontology in [46] enables the capturing of software processes on a conceptual level. An extension includes specific models such as SPICE or CMMI. Ontological modeling of both CMMI and ISO 9001 as well as certain process interoperability features is shown in [47]. The authors identify issues in consistently implementing both models simultaneously. This problem was addressed in our approach by including concepts abstracted from a single model. In [48], a Process-Centered Software Engineering Environment supports process implementation focused on CMMI and a Brazilian process improvement model. For CMMI-specific appraisals, multiple supportive tools are available such as the Appraisal Assistant [49]. However, these focus only on CMMI / SCAMPI support.

We provide a more general and flexible approach, since the applied concepts are abstracted from a single model. In contrast to above related work that focused on one or two specific models, ours is capable of assessment model diversity as shown in Section IV. Furthermore, it integrates automated SE process enactment support and supports a combination of automated and manual ratings. That way, the assessment is tightly and automatically integrated with SE process execution support, providing the option of automatic on-the-fly assessments while preserving the ability for humans to manually rate practices and processes. This can support quality awareness.

VI. Conclusion and Future Work

This paper has described an ontology-based multi-model holistic approach for automating the assessment of software engineering processes. Extending our prior work in [1], richer technical details were presented and related work was expanded. Also general requirements for such an approach were described, those being R:Proc, R:Cntx, R:MultModel, R:Integrate, and R:Auto. Then the differences between three common SE process reference models were elucidated. Thereafter, our conceptual framework with semantic extensions to a process-aware information system was presented. It was shown how process reference models such as CMMI, ISO 15504, and ISO 9001 were unified in the ontology and the algorithm that performs the assessment was described. The evaluation demonstrated the technical feasibility, model diversity, and that performance with current technology for expected application scenarios is sufficient.

Our approach is not meant to replace manual ratings or formal appraisals. In our opinion, this is not possible in an automated fashion due to the many factors influencing such ratings in real world process execution. However, our approach can support automatic data collection, supplement manual ratings of practices or processes, contribute to the quality awareness of an organization, and (automatically) highlight areas for process optimization. Furthermore, it can help prepare an organization for a formal appraisal.

Future work involves empirical studies to evaluate the effectiveness of the approach in industrial settings with a variety of software organizations, with various SE process lifecycle models in various projects, at various process capability levels and utilizing different process assessment standards simultaneously.

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