Information Structuring and Model Reuse for Virtual Prototyping

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***Abstract*-Virtual Prototyping is a promising approach for testing innovative ideas or assessing man-machine interactions in early stages of machine design. But due to the high cost level of present approaches, virtual prototyping does not exploit its full potential. This paper presents a multi-level approach for systematic reuse of existing simulation models in different business cases. The approach bases on theoretical reflections on conceptual modeling and on a requirements analysis among manufacturers of mobile construction machines. The resulting method is evaluated by a prototypic implementation.**

Keywords- Virtual Prototyping; Conceptual Modeling; Reference Modeling; Model Reuse; Rationale Documentation

I. INTRODUCTION

Increasing competitive pressure forces engineering companies to design and produce more efficiently. For that reason producers use virtual prototypes by constructing real time capable and multi domain simulation models combining hydraulic, mechanical and electrical aspects of a machine[1]. These prototypes are used for assessing the producer's product ideas, man-machine interactions in an early stage and technical features. Mature virtual prototypes can delay constructing real prototypes to later phases of product lifecycle. That way, resources can be saved. Furthermore, modification of the machine design can be made with less effort. A prerequisite is, however, that simulation models are structured systematically and adapted for reuse[2].

Virtual prototyping can gain a benefit within four stages of a product lifecycle (see Figure 1): Advanced Engineering, Construction, Sales and Marketing and Services[3]. We refer to these stages as business cases. Virtual Prototyping for Advanced Engineering helps to try out innovative ideas at a very early stage without entering subsequent processes. Within this stage simulation models are mainly developed for a proof of concept and assessment of the impact on machine behavior.

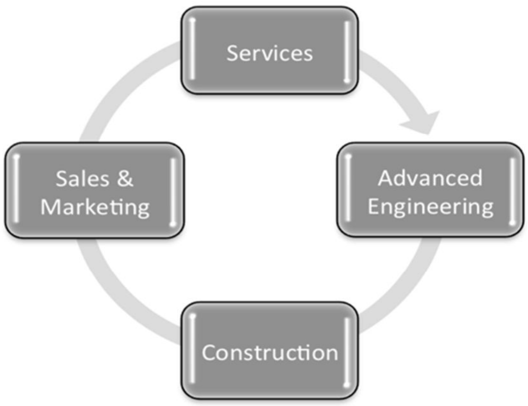

Figure 1 Product Lifecycle of Mobile Construction Machinery[3]

In Construction an overall design of the machine consisting of all relevant components and assemblies takes place. Virtual prototyping in this case can be used to foster the construction of mature physical prototypes. For Marketing and Sales an interactive simulation is an opportunity for specifying customer requirements. For this purpose the virtual environment has to meet several additional requirements such as real-time behavior of the machine, high quality graphic and a working environment close to reality. The business case Service comprises maintenance and repairing of machinery. Simulation can replicate problems that customers have experienced. That way, engineers have an opportunity to detect the cause of the problem and to gain additional technical insight[3].

In practice, a variety of simulation models have been developed within these business cases and some of these models have a close relationship to each other. However, these models are still designed from scratch for each simulation problem at hand. As the design of simulation models and the related configuration of the virtual environment are expensive and time-consuming, prior research of mechanical engineering has proposed reuse techniques[1][4][5]. Yet, these techniques do not structure information of the simulation models systematically and follow a bottom-up approach. That way, component models are assessed towards their potential to be reused and stored within a database. However, these models neither are designed for reuse, nor offer mechanisms for their application. Furthermore prior research does not distinguish its simulation models into different business cases. Yet, simulation requirements differ notably among these cases. The deficiency of systematically structured information of simulation models and of differentiating these models into business cases has a significant impact. Developing simulation models is time- and cost-intensive resulting from a duplication of work. Knowledge gained while developing the simulation models is lost and hence, a continuous improvement of simulation models is restricted.

These issues are addressed in a BMBF-funded research project Inprovy[1] (for further project details see [6][7]) that aims to systemize the application of interactive machine simulations within business processes and provides methodical support in the area of Mobile Construction Machinery. The project is interdisciplinary. Its participants stem from Mobile Construction Machinery and Information Systems (IS). Prior research of IS has broached the issue of structuring information (conceptual modeling)[8] and reuse (reference modeling)[9]. Within the collaboration of the project we apply conceptual modeling and reference modeling to the engineering discipline and develop a multi-layer approach to structure and reuse information. Using the approach practitioners can develop a systematic reuse of information without loss of knowledge and a continuous improvement of simulation models over time.

We follow design science[10] to meet our goals and structure the paper as follows. In Section II we describe a requirements analysis. Based on the requirements a multi-layer solution of information structuring and reuse is developed (Section III). Section IV presents the evaluation of the approach. The paper ends with a conclusion summarizing the research results and future research potential.

II. REQUIREMENTS ANALYSIS

Structuring information for a continuous improvement as well as for reuse has been researched within IS. In this section we present prior research of the IS domain and the results of an interview to derive requirements for a solution for the engineering domain, esp. Mobile Construction Machinery.

A. Requirements from Conceptual Modeling

Conceptual models represent a perceived problem situation at hand[11]. They are commonly accepted for structuring business information, organizing, managing and improving business processes[12] as a basis for discussion, application of metrics and decision finding[13].

Figure 2 depicts the process of construction and assessment of a conceptual model. For constructing a conceptual model a modeling team negotiates perceived phenomena with regard to various objectives, individual knowledge, experiences, organizational guidelines and so on[14]. Basically we can distinguish the modeling team in model creators and model users[15][16]. According to their competencies and responsibilities model users, typically domain experts, provide relevant knowledge for solving the problem at hand whereas the model creators, typically method experts, provide knowledge about modeling methods and tools. Domain experts and method experts have to agree on modeling objectives and their weighting first. Once these are accepted and the domain is perceived a conceptual model is constructed which in turn has to be perceived, interpreted and agreed on by model users in order to utilize it for solving the real problem at hand. Thus, information is structured within a communication process of the modeling team.

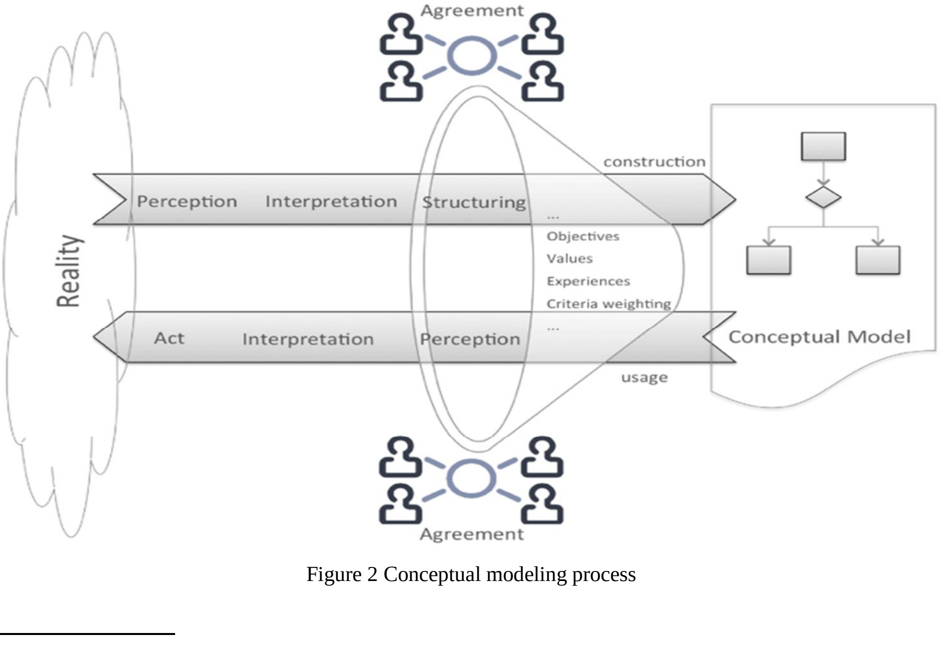

Figure 2 Conceptual modeling process

[1] The project is funded by the BMBF (support code: 02PC1110) Project Management Agency Forschungszentrum Karlsruhe (PTKA).

Besides the function as means of communication conceptual models also serve as a basis for future analyses and decisions[13] and direct transformation of information into code. Yet, the conceptual models are only valid for a specific period of time. This is why they need to be evaluated and improved continuously.

To apply these advantages of conceptual modeling to Virtual Prototyping, we require:

a) Conceptual modeling grammars for structuring information for Virtual Prototyping,

b) Structured domain terminology that can be applied to the modeling grammar,

c) A procedure model, that helps domain experts to apply the resulting modeling method and,

d) A procedure for evaluating the quality of conceptual models.

Implementation of these requirements allows structure information of the engineering domain by conceptual modeling. If information of these models should be reused for further projects, it needs to be managed. Reference Modeling of the IS Discipline has broached this issue.

B. Requirements from Reference Modeling

In consequence of an increased demand for conceptual models that addresses related design problems, research on reusable conceptual models (hereafter called reference models) has evolved[17]. Reference modeling is a part of conceptual modeling that deals with reuse. A reference model is a specific conceptual model, which is reused in different modeling situations by providing a generic solution[17][18]. Two significant design processes of conceptual models can be distinguished: Design for Reuse and Design by Reuse[17].

In Design for Reuse, a modeling team deliberately constructs a reference model. Based on users' requirements and the modeling context, a modeling team searches the knowledge base for appropriate artifacts (modeling languages, patterns, suitable reference models) and consequently constructs a model[17][19]. After having constructed a reference model, it should be included into a knowledge base. At this stage the reference models' purpose is to serve as a reference for the design of future conceptual models[17].

The process Design by Reuse is based on existing reference models of a knowledge base. In particular, the reference model is reused by taking parts of one or more original models. These parts are either adapted or extended into a resulting conceptual model (mechanisms how these adaptation or extension can be achieved are presented in [20] and applied in [21]). Constructing a conceptual model by using Design by Reuse the effectiveness and efficiency of the modeling process can be improved[17].

The reference models should be managed in a way that a future modeling team can retrieve one or more appropriate reference models for the Design by Reuse process. Thus, relevant criteria to facilitate reference model retrieving need to be developed and added as meta-information to the reference models. That way the modeling context is significant meta-information to search a reference model for the Design by Reuse process[22].

Managing a reference model is not limited to assuring that it can be found and applied for Design by Reuse. As every model a reference model is only valid for a certain period of time since the domain, the reference model is about, changes or modeling tools and languages evolve. This situation mostly occurs if new versions or variants of conceptual models are constructed. In this case not only conceptual models should be updated but also the corresponding reference model should be improved[8]. Moreover the Design by Reuse process is a learning process. Learning outcomes of the modeling process need to be applied to the corresponding reference models, too.

For the development of a systematic information structuring and reuse approach for Virtual Prototyping we require from reference modeling:

e) A reference model for the development of future conceptual models,

f) A knowledge base that structures reference models and allows their retrieval,

g) Assessment of context to assign a reference model to a specific situation and,

h) Mechanisms for reference model evaluation.

So far, requirements from the IS discipline have been discussed. In the next paragraph we consider characteristics inherent to the domain, too.

C. Requirements from Mobile Construction Machinery

To structure requirements from the engineering domain, we have conducted semi-structured personal interviews in three mid-sized companies of Mobile Construction Machinery. Questions for the interviews have been prepared based on literature. Further questions were added spontaneously based on the course of conversation. A common requirement of all partners was to develop a solution that is applicable within the day-to-day business. That way, information for possible future cases should not be structured by extra effort but while developing current simulation models.

The benefit of conceptual simulation models is manifold. An appropriate view concept reduces complexity of simulation models. In addition, a graphical representation improves the ascertain ability by human task managers. Thus, their validity for possible reuse situations in subsequent lifecycle phases could be assessed in a much more systematic way. Beyond that, slight modifications could be realized in an efficient way. Furthermore cooperation projects in research and development are conceivable because of inherent mechanisms for integrating definite model fragments.

These reflections of possible use cases for conceptual simulation models reveal the requirement for considering aspects of business processes and organizational structures. These aspects go beyond the scope of plain simulation models. But the purpose of simulation within the business process defines the usefulness of certain virtual environments. The chosen virtual environment requires a certain quality of the simulation model in turn. That way, realistic visualization and real-time capability are more important for customer presentations or laboratory experiments with experienced machine operators than for research and development purposes.

These various interdependencies were a starting point for the development of a framework for virtual prototyping of Mobile Construction Machinery (see Figure 3). The framework reflects the specific requirements of a reference model-based approach for virtual prototyping. We claim its general applicability for similar challenges within other domains than Mobile Construction Machinery.

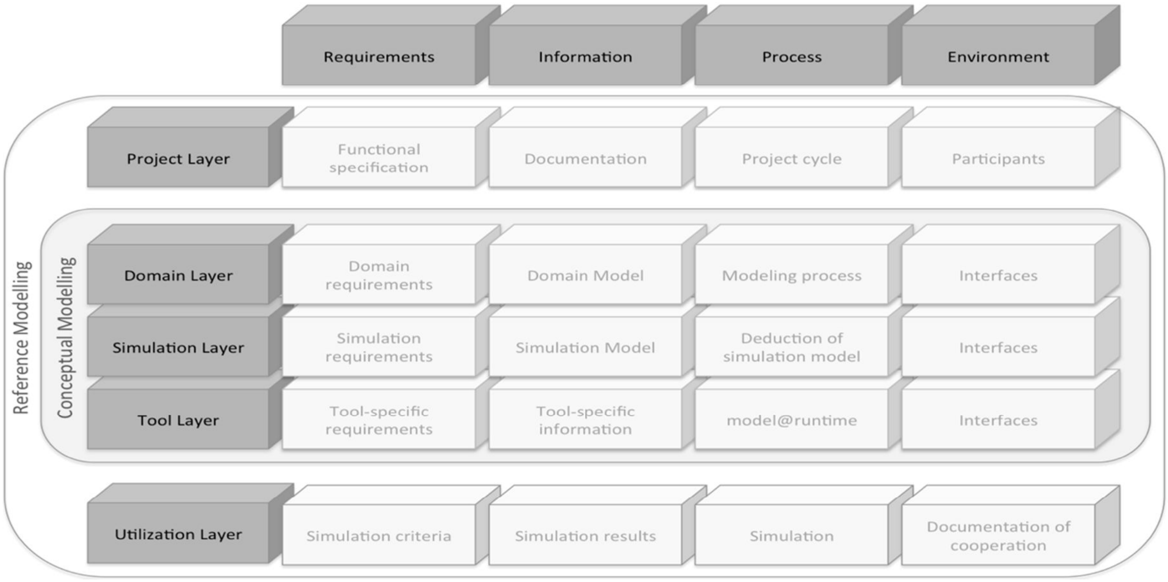

Figure 3 Framework for Virtual Prototyping of Mobile Construction Machinery

The framework is structured in five layers and four views. Layers represent a certain level of abstraction for the simulation task, whereas views structure the information relevant for the respective level (for similar framework ideas in information systems see [23][24]).

The structure of a conceptual simulation model comprises three core layers: Domain-, Simulation-, and Tool Layer. The domain layer is defined for embedding the simulation model in business context. The business context describes the real machine structure (information), interfaces and cooperation relationships with suppliers (environment), business metrics like purchase prices of components (information), etc. The information should be presented for a discussion with project team members and stakeholders such as customers or suppliers, depending on the business case (information, environment).

The simulation layer comprises the problem-adequate modeling of machine simulation. Central information is structured as model equations necessary for calculating machine behavior. The simulation model enriches information of the domain layer with simulation relevant information from engineering domain such as specifics from mechanics, hydraulics and electrics (information). Furthermore the process how the simulation model can be derived from the domain model in a semi-automatic way needs to be specified (process). On a higher level of maturity, process descriptions guide the reuse of existing simulation models and their fragments. For this purpose appropriate authorization concepts (environment) have to be implemented in order to protect intellectual capital.

Within the tool layer requirements of the applied computer system are considered. Depending on the purpose of the simulation and the nature of the constructed simulation model a desktop could be sufficient or a cluster has to be established. The information view contains a systematic and structured description of all tool specific information. The execution of simulation models and the configuration of hardware components is part of the process view. The environment view describes machines, software and their interfaces.

For reusing existing simulation models more information is relevant for assessing their validity. For this purpose we developed the frame Reference Modeling containing the layers Project Layer and Utilization Layer.

The project layer captures all project relevant information useful for understanding the context, like a specific business case, a simulation model was constructed in. Thus, the participants of the project, their experiences and their roles within the project have to be documented (environment). The circumstances, underlying conditions and purpose of the project (requirements) are parameters to assess the quality of the simulation model regarding innovation and reliability. Project inherent design decisions (information) and the project schedule (process) are documented.

The utilization layer is central for evaluating a conceptual simulation model. The preparation, execution and reflection of a certain simulation are key issues. This layer is intertwined with the domain layer very strongly due to the handover of simulation results to subsequent activities within the business process. Requirement information comprises e.g. safety regulations, organizational policies or academic rigor. Results of the simulation execution and the respective analysis (information) are documented according to the requirements of the domain layer. How to prepare, execute and evaluate the simulation is described within the process view.

Based on the framework we can derive the following requirements for a systematic information structuring and reuse approach:

i) Reuse of simulation models and model fragments;

j) Time -and cost reduction while developing simulation models;

k) Information of simulation models structured for different business cases, and as a basis for discussion for different stakeholders;

l) Semi-automatic transformation of business layer information to simulation code;

m) Business metrics such as delivery time and costs can be applied;

n) A non-intrusive application of a resulting method.

Based on the requirements from conceptual modeling, reference modeling and the engineering domain a multi-layer approach for information structuring and reuse is developed and presented within the next section.

III. DESIGN OF A MULTI-LAYER-APPROACH FOR REFERENCE MODELING IN VIRTUAL PROTOTYPING

To meet the identified requirements a multi-layer-approach for conceptual modeling and reuse was constructed (see Figure 4). The principle activities affect the Design for Reuse by establishing a knowledge base for structured and reusable simulation models. The main outputs of these activities are structured along the four layers numbered within Figure 4.

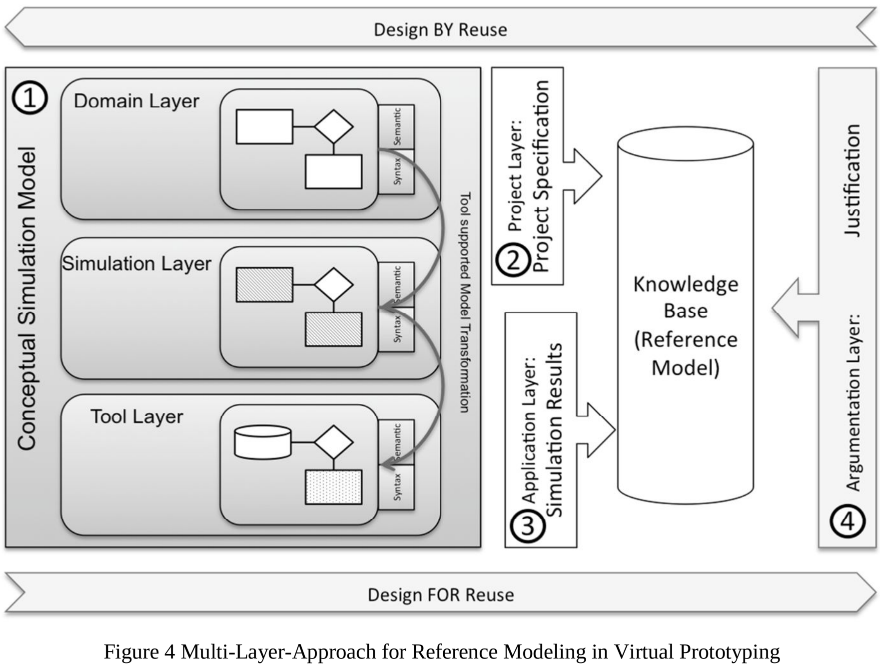

Figure 4 Multi-Layer-Approach for Reference Modeling in Virtual Prototyping

On Layer 1, the basic simulation tasks are structured with respect to the domain, simulation and tool sublayer by means of conceptual models (similar to enterprise architecture frameworks, see e.g. [25]). Appropriate modeling languages are customized to requirements of the three core-layer of the framework described in Section II. Beyond the layer-specific modeling grammar, the unified metamodel includes interlayer relationships and counterparts. For assuring a common understanding of the conceptual model, a technologic dictionary was defined by consensus building among project partners. Vertical integration rules[26] intertwine the resulting models and thus, enable a semi-automatic model transformation into subsequent layer or code. Beyond that, the applied modeling tool provides a syntax check for evaluating the syntactic quality of the conceptual simulation model.

By this means, targeted modifications of conceptual simulation models could be realized cost- and time-efficiently. The rigor of structuring the problem domain of virtual prototyping enables engineers to detect relevant model elements and dependencies. Thus, the exchange of machine components and/or simulation environments is supported in a systematic and methodological way.

On Layer 2, the conceptual simulation model is enhanced by project-specific data basing on the idea of contextualization of conceptual models[27]. These meta-data capture the pragmatic of model construction such as project aim, involved parties, date and duration. The benefit of these information is twofold. First, they are research criteria for effective model retrieval. Second, they serve as a basis for comparing project contexts, which is inevitable for assessing the validity of existing simulation models for a certain reuse-situation[22]. The more formal a project specification is, the more automatable the comparison could be. On the basis on a significant amount of representative projects appropriate project types could be derived similar to the clustering approach described in [28]. In addition to the project specification belonging to the archived conceptual simulation model, a specification of potential reuse situations, like business cases, is valuable. At best a ranked recommendation of existing conceptual models could be provided according to entered project specification.

On Layer 3, simulation results are recorded and analyzed with respect to the quality of the conceptual simulation model. The analysis results are relevant for any quality dimension as they could reveal errors in terms of syntactical, semantic or pragmatic issues. Syntactical and/or semantic problems could be caused by an insufficient discussion of the scope of the conceptual simulation model. As a consequence, shortcomings in defining the modeling grammar and the technological dictionary occur. Regarding pragmatic issues, simulation results could reveal improperness of simulation algorithms and/or simulation environments. Information gathered on Layer 3 supports an experience-based improvement of conceptual simulation models or their fragments resulting in a permanent evolutionary cycle[8]. The knowledge base should also include failing simulation models along with conclusive explanations in order to avoid repeating errors.

To gain the entire benefit of establishing a knowledge base for reusing existing simulation models we claim the deliberate construction of a reference model. Within the Design for Reuse-context a reference model is constructed by generalizing specific problem situations and by providing a set of possible modeling solutions. Within the Design by Reuse-context an individual model could be derived from the reference model according to valid configuration operations[20]. Due to the generic nature of reference models reasonable modifications could occur to meet project specific requirements. The user of the reference model has to reflect the model statements and to assess their validity for the situation at hand. Additional information concerning crucial design decisions could support the construction of good individual models and the evolution of good reference models, respectively. On the other side feedback information from model use are essential for a user appropriate evolution of the reference model. Methodically sound approaches for capturing these kinds of rationale information are developed and accepted already in software engineering (see e.g. [29][30]).

On Layer 4, a targeted evolution of the reference model is enabled by capturing and by analyzing model rationale. On the basis of relevant literature about design rationale and its adaptations (see, e.g. [29][30][31]) we have elaborated a proposal for integrating rationale information in reference models. Similar to the distinction between construction rationale and use rationale in method engineering research[32], the rationale captured in the Design for Reuse-process represents the reference model construction rationale whereas a part of the rationale captured in the Design by Reuse-process represents the reference model use rationale. The former one supports the understanding of the construction performance done by the reference model creator, which is essential for the usage and maintenance of reference models. The latter one is starting point for an evolutionary reference modeling due to the experience-based feedback information.

IV. EVALUATION AND PROTOTYPING

We first assess if this solution meets our requirements. Secondly, we show how this solution can be applied with a demonstrator prototype.

In Section II we have derived requirements from conceptual modeling, reference modeling and mobile construction machinery. Most of these requirements can be attributed to a specific layer (such as the layer of conceptual simulation model). Yet, two of these requirements are necessary conditions for the multi-layer approach and are thus classified as underlying paradigm. How these requirements are met by our approach is described as method concept in Table I.

TABLE I EVALUATION OF THE MULTI-LEVEL APPROACH FOR REFERENCE MODELING IN VIRTUAL PROTOTYPING

Level	Method Concept	RRequirement
Underlying Paradigm	Multi-Layer-Approach for Reuse in Virtual Prototyping	non-intrusive application (n)
	Framework for Virtual Prototyping for Mobile Construction Machinery	procedure model (c)
Level 1	Information structuring by means of conceptual modeling	conceptual modeling grammar (a) semi-automatic transformation (l)
	Technologic dictionary	structured domain terminology (b)
	Domain-specific languages for each layer	conceptual modeling grammar (a) business metrics (m)
	Tool-supported syntax check	procedure for evaluating quality (d)
	Vertical integration rules	
Level 2	Repository of conceptual models and (including project specification)	knowledge base (f) time- and cost reduction (j)
	Project specification for reference model in repository	assessment of context (g) reuse (i)
	Specification of potential business cases	information of simulation models (k)
Level 3	Evaluation of simulation results	procedure for evaluating quality (d)
	Support for improvement of model construction by pro-vision of simulation results of conceptual models	reference model (e)
Level 4	Methodically guided configuration of conceptual models by intentionally constructed reference models	
	Configuration management to trace model derivation and modification	reference model evaluation (h)
	Rationale documentation for the design of the reference model and regarding the use of the reference model (design and use rationale)	assessment of context (g) reference model evaluation (h)
	Deliberately constructed reference model	information of simulation models (k)

For a prototypical application of our approach we have worked on three different machines: A wheel loader, a skid steer loader and a concrete pump. The resulting prototypes are implemented and used in the product development activities of our partners now. Since information of these machines is restricted we present our approach with a mobile excavator MH City prototype that we have implemented for demonstration. In this stage we cannot report results from industrial cases since the approach needs to be applied over time and to evolve to justify proposed advantages such as time- and cost-reduction. We already can show the results of our MH City prototype.

For our prototypes we have used Cubetto Toolset for conceptual modeling and SARTURIS and PyMBS for machine simulation. For the first layer of the multi-layer approach we have developed modeling languages for the domain-, simulation- and tool sub layer, which we have vertically integrated to allow a semi-automatic transformation into code. Modeling languages of the domain sub layer allow defining general components of a machine and its mechanical and hydraulic interfaces as well as concrete supplier information such as disposability, delivery time and costs. Besides information of the domain sub layer, the modeling languages of the simulation layer provide constructs to model simulation relevant information such as rigid bodies and coordinates. Information of the domain layer has not to be modeled for the simulation layer again, but can be directly transformed. Afterwards, relevant information is added manually and a further automatic transformation takes place into code (Python, Modelica). This code can directly be used for an interactive machine simulation. Figure 5 presents relevant models assigned to the three core layers.

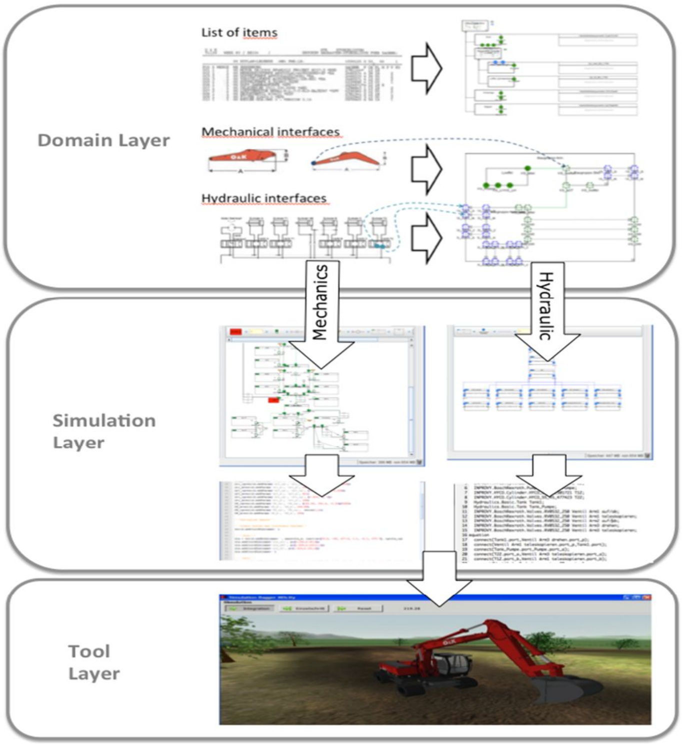

Figure 5 Draft of a conceptual simulation model (level 1) based on [33]

To apply the second level we have designed conceptual models of all three layers for reuse. For our demonstrator prototype we have specified the context as construction business case, where the overall design of the Mobil Excavator MH City is tested. In particular, we have assessed the concept-tual models in a Design by Reuse process by changing the component adjustment arm to a monoblock for a test of mechanics with the simulation environment PyMBS.

After the component has been changed within the domain layer we can derive the simulation layer model automatically from the original reference model. An automatic model comparison detects definite fragments of the reference simulation layer model pertaining to the changed component (adjustment arm). These fragments were deleted and replaced by corresponding model fragments of the new component (monoblock). These new constructs have to be connected to the rest of the simulation layer model constructs. Afterwards an automatic transformation into code (Python) is conducted and used with PyMBS in the tool layer. Figure 6 represents this process of changing a component of a reference model.

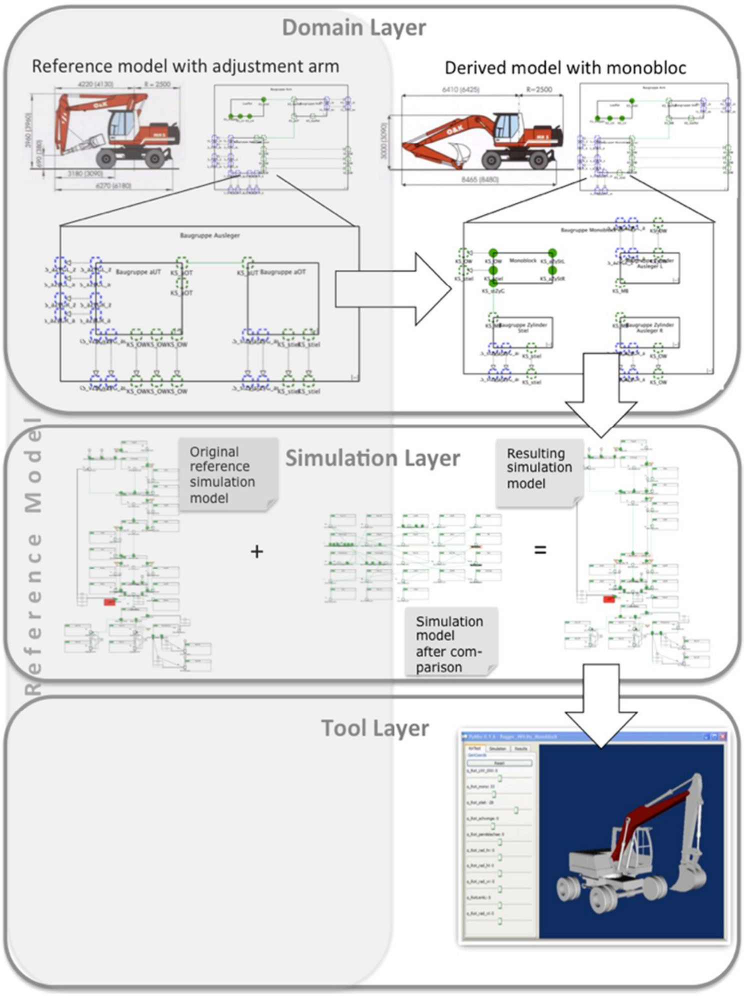

Figure 6 Reuse of simulation information (Level 2) based on [33]

Our demonstrator prototype was designed to test Levels 1 and 2. We did test Level 3 with the wheel loader and concrete pump prototype. The concrete pump was subject to the Advanced Engineering Business Case and tested within an interactive simulation by potential customers. Results were documented and added as meta-information to the reference model. For the wheel loader (also subject to Advanced Engineering) simulation results were obtained within a survey of simulation probands. The results of the first test run were used for adjustments of simulation algorithms, integration rules and for detecting modeling errors within the tool layer. Most of the information can be characterized as learning nature and we added our experiences as rationale to the relevant design decision, which is part of Level 4.

On Level 4 rationale concerning crucial design decisions is added to the reference model. Model users need this information for assessing the validity of the reference model for the situation at hand. Figure 7 depicts an example for capturing rationale by a semiformal model basing on a gIBIS meta-model (as it is used in [32]).

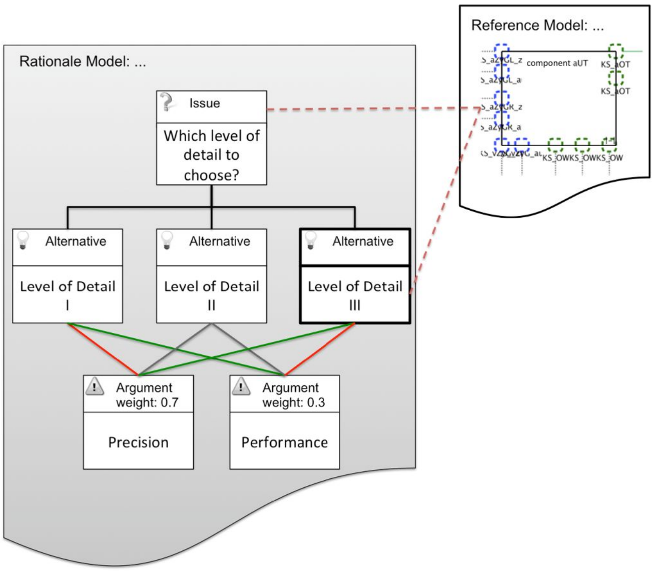

Figure 7 Rationale Model (Level 4)

The design issue of choosing an adequate level of detail for the respective simulation task is discussed by commenting on alternative solutions. Supporting and objecting arguments like precision and performance are weighted and assigned to the identified alternatives. Recommendations to support the final decision making could be calculated basing on a specific weighting algorithm. The consequent design decision is bold-framed.

Within a reusing-context this rationale information can be crucial. Other business cases could require variant VR-environments, which require a certain level of detail in turn. In this situation the reference model or its components could be insufficient due to an inadequate level of detail, although the conceptual simulation model covers the desired mobile construction machine and any corresponding components.

V. CONCLUSIONS

Starting from a requirements analysis within the scope of mobile construction machinery, we have developed a framework for virtual prototyping to support the reuse of simulation models and thus, to decrease the effort for the application of virtual prototypes in various business cases. We have used experiences in conceptual modeling and reference modeling to guide information structuring and the implementation of reuse mechanisms. Based on this requirements analysis we have developed a multi-layer approach for reference modeling in virtual prototyping, that provides retrieval support, continuous improvement of simulation models and systematical evolution of reference models. The multi-layer approach was subject to an evaluation. We have developed a prototypic implementation to show how the approach can be applied.

The support of systematic reuse of simulation models and their fragments, respectively, contributes to the decrease of development effort for a specific simulation task. Thus, our approach influences the cost-benefit ratio in a positive way. Starting from the lifecycle of a mobile construction machine, a systematic exchange of simulation models could gain benefit within previously uneconomical use cases. It is conceivable that simulation models, constructed within the advanced engineering phase, are reused for sales and marketing purposes or for fault finding for breakdown or dysfunction of the real machine.

In addition, the modular structure and the methodical exchange of simulation model fragments enable the development of suitable technologies for integrating external supplied component models. A common modeling language enables the integration of simulation models for sub-assemblies provided by the respective supplier. Cooperative research and development activities are supported and the competitive position could be strengthened.

So far we have demonstrated the use of a multi-level approach. Yet, we do lack experiences how this solution is applied within day-to-day business of virtual prototyping companies. Further investigation of a profound knowledge base and its hazards of researching reference models, documenting and retrieving decision information as well as evolving existing reference models are required.

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