Supporting Concurrent Development of Requirements and Architecture
A Model-based Approach

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Abstract: A system's requirements and its architecture are usually developed at least partly in parallel. This demands a continuous and automated assessment to confirm that the architecture conforms to its requirements. To enable such an assessment, the stepwise formalization of informal requirements has been proposed. However, there is no canonical set of artifacts and analysis techniques that has been evaluated for this task in practice yet. In this paper we propose an artifact model and a process that enables the continuous conformance assessment between requirements and architecture in a model-based context. We evaluate both in a development project with a group of students.

1 INTRODUCTION

For real-world systems requirements engineering and architecture development are often not carried out in a sequential manner but at least partly in parallel. This is especially true for brown-field development, where a system needs to be extended or adapted. The Twin Peaks model (Nuseibeh, 2001), for example, addresses this issue by explaining the development of requirements and architectural specifications as concurrent activities. This is achieved by an iterative process that produces progressively more detailed requirements and design specifications.

Etien and Salinesi (Etien and Salinesi, 2005) state that the consistency between artifacts is an important issue in such a co-evolution context. If we adopt a broad interpretation of architecture that includes the description of behavior, this consistency also reaches out to the system's functional requirements.

In traditional code-based development the usual means for continuously checking the conformance between requirements and the implementation (resembling the architecture in model-based approaches) are, for example, automated testing and architecture conformance analysis. Model-based requirements engineering techniques such as KAOS (van Lamsweerde, 2001) or iStar (Yu et al., 2011) are in general not bound to the architecture of the system, nor is there a prescribed process for co-evolution with architectural models (Whalen et al., 2013).

A systematic approach to relate requirements and architecture via tests in a model-based context has recently been proposed by (Mou and Ratiu, 2012). In their approach requirements are bound to component architectures by mapping input/output relations of requirements to input/output relations of components. This relation is verified by a testing procedure. Open questions, however, are how to derive the tests from requirements, which are usually informal in the beginning, and how to integrate them into a continuous change management.

The goal of the research presented in this paper is to define a set of artifacts and a development process, which both can be employed practically for formalizing and stepwise refining the system's functional requirements to support a continuous conformance analysis between the system's functional requirements and its architecture.

For this purpose, we propose a model-based approach that, starting from informal use cases, enables a stepwise formalization of functional requirements, which finally can be linked to the architecture of the system. The formalization steps in this approach are assisted to a large extent by formal and automated analysis tools and techniques. Thus, we gain a seamless transition from informal requirements to architecture with explicitly documented design decisions. Due to the rather formal character of the approach, especially wrt. the specification of requirements, we see its application mostly in the area of critical systems

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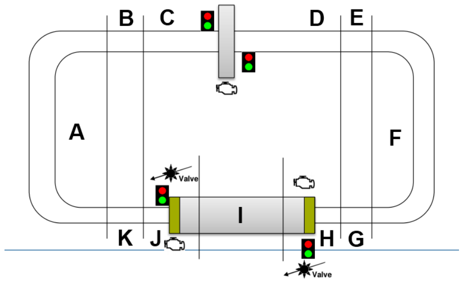


Figure 1: The topology of the canal system. There are eleven canal segments (A – K), a lock with two lock gates (bottom of the picture) and a low bridge (top of the picture). Low bridge and lock are equipped with traffic lights.

such as software intensive embedded systems. We applied the approach by means of a tool and evaluated it with a group of students, who concurrently developed requirements and architecture. The approach proved beneficial in the detection of inconsistencies between the requirements and the architecture as well as within the requirements themselves.

2 APPROACH

2.1 Running Example

We illustrate our approach with the running example of a canal monitoring and control system (CMCS). We took the requirements description of this system from a common case study that was used in the 2011 Workshop on Model-Driven Requirements Engineering (MoDRE).

The system's purpose is to control a system of canals on which ships are cruising. To surmount a difference in water level a canal may be equipped with a lock. A lock consists of two lock gates and two valves that are used to balance the water level. A second component in the canal system is a low bridge. If a ship wants to pass, the bridge needs to be opened.

The CMCS tracks the ships which cruise on the canals and controls bridges and locks such that ships can pass. In the original requirements document the system was meant to handle a flexible canal topology. However, in order to simplify the development task we fixed a canal topology with eleven segments, one lock and one bridge. Furthermore, we included only two ships into the case study. The topology is depicted in Figure 1.

2.2 Artifact Model

Our approach is based on a fixed set of modeling artifacts and relations between them. The artifacts are

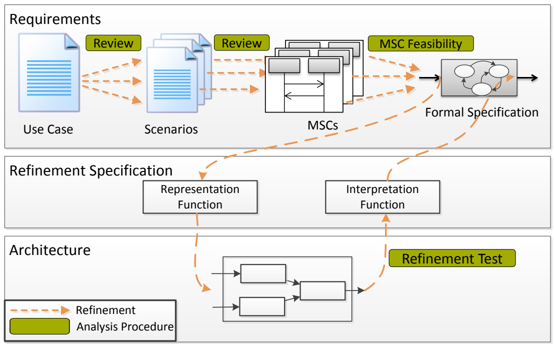


Figure 2: Artifacts, relations and analysis procedures with focus on functional requirements and their mapping onto the architecture.

used to describe requirements on different levels of completeness and detail, the system architecture and a refinement relation between requirements and architecture. All artifacts and their relations are illustrated in Figure 2. The purpose of this paper is not to introduce new modeling techniques. In fact, all of the artifacts used in our approach may also be represented for example by SysML or UML diagrams, which would be completely reasonable. The focus of this paper is to integrate the different artifacts into a specific process and link the artifacts using specific analyses.

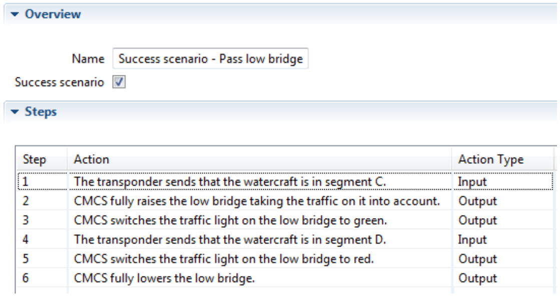
2.2.1 Modeling Requirements

To model functional requirements, we employ use cases, scenarios, message sequence charts, formal specifications and a data dictionary. Except from the data dictionary, which is a simple technique for data modelling, all model elements describe behavior at increasing levels of formality and completeness.

Use Cases. Use cases informally describe the functionality and the context of the system from a user's perspective. A use case template is provided including, amongst others actors, a description, triggers, preconditions, success and minimal guarantees as well as inputs and outputs (cf. (Cockburn, 2001)). Most of the fields are described in natural language, while few can contain links to elements from other modeling artifacts (e.g., inputs and outputs are related to architecture elements).

Scenarios. Use cases can be supplemented by scenarios providing informal descriptions about single runs of the system under development. A scenario is defined as a sequence of interaction steps between the system and its environment. The individual steps are still described in natural language. Figure 3 gives an example of such a scenario.

Message Sequence Charts (MSCs). To describe scenarios more formally message sequence charts



Step	Action	Action Type
1	The transponder sends that the watercraft is in segment C.	Input
2	CMCS fully raises the low bridge taking the traffic on it into account.	Output
3	CMCS switches the traffic light on the low bridge to green.	Output
4	The transponder sends that the watercraft is in segment D.	Input
5	CMCS switches the traffic light on the low bridge to red.	Output
6	CMCS fully lowers the low bridge.	Output

Figure 3: Example of a scenario description.

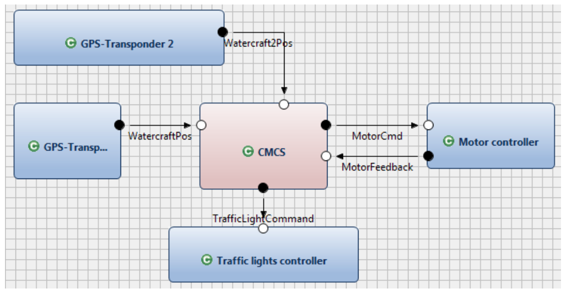


Figure 5: Example of a micro architecture specification.

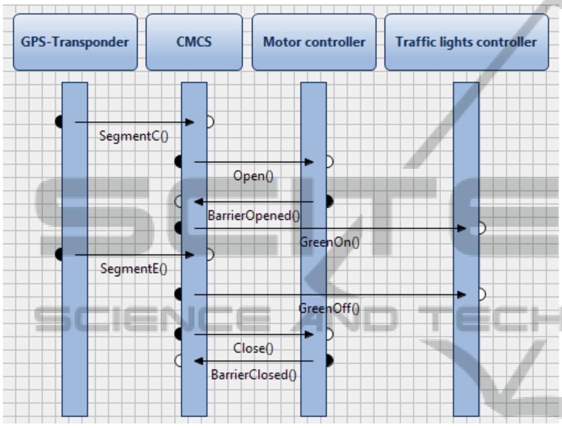


Figure 4: Example of a message sequence chart (MSC).

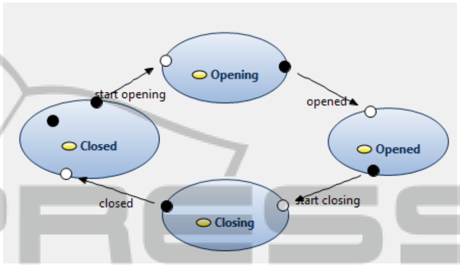


Figure 6: I/O automaton specification of a component.

(MSCs) (ITU-T, 1999) can be used. In an MSC, single steps of the corresponding scenario are represented by the exchange of one or more messages between the system and its environment. Those messages, as opposed to sentences in natural language, already have a formal character. For example, they contain source and destination ports and their messages must conform to the corresponding data type of the port. Figure 4 provides an example of an MSC.

Formal Specifications. Since MSCs only provide partial descriptions of behavior, we use formal specifications to progress towards a more completely formalized set of requirements. In our approach, a formal specification is a description of an executable input/output behavior which can, for example, be used in simulation. As modelling technique, we use I/O automata or code specifications with a Java-like syntax, which is equipped with a formal semantics. Formal specifications are intended to combine all message sequence charts related to one use case. Therefore, a formal specification captures the behavior of the system corresponding a particular use case. It is important to stress that formal specifications exhibit total behavior. This means that for every input sequence the formal specification determines an output sequence. On the contrary, message sequence charts only specify partial behavior in the form of traces consisting of exemplary input and output sequences.

Modeling a formal specification for an entire use case is a challenging task typically leading to rather complex behavior models. Therefore, we allow the decomposition of the formal specification into hierarchical components that again contain behavior modeled by automata or code specifications. We call such decompositions *micro architectures*. The components exchange messages via named channels. The interface of a component is the set of its input and output channels. The parallel composition of all components results in the complete behavior of the formal specification. Figure 5 shows such a decomposition in order to specify a total behavior for the set of messages sequence charts of one use case. Figure 6 shows the I/O automaton behavior specification of component *Motor controller*.

Finally, message sequence charts and formal specifications are related in the following way: The messages sent in the message sequence charts are inputs and outputs of the formal specification (e.g., of the I/O automaton). Compare for example the messages of MSC entity *Motor controller* in Figure 4 with the component *Motor controller* of the formal specification in Figure 5.

Other Requirements. Some requirements, such as safety requirements, might not be modeled in use cases. These requirements are typically expressed in natural language or temporal logic. The respective formulas can be used to verify the formal specification and the architecture as explained in the following section.

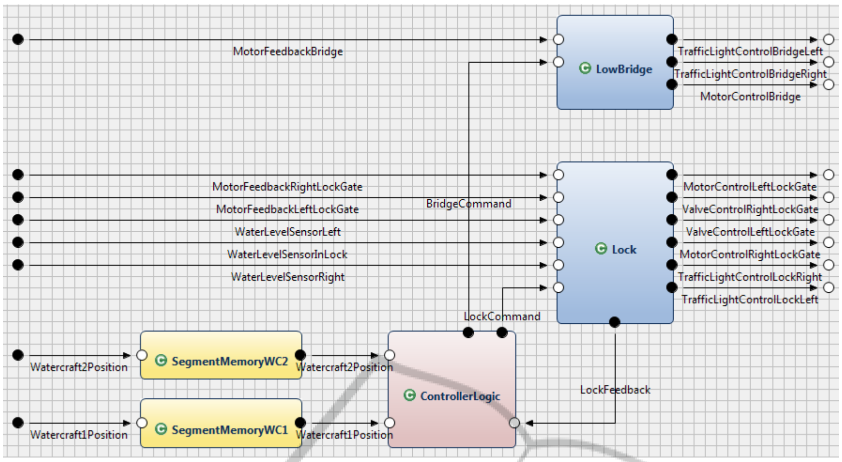


Figure 7: An architecture of a system represented by a network of communicating components.

Data Dictionary. To define simple data types for use in the formal specifications or the message sequence charts a data dictionary is provided. Custom data types may be constructed from enumerations, records, arrays and some pre-defined basic data types such as integers.

2.2.2 Modeling Architecture

The architecture of the system is modeled by the same means as the micro architecture of formal specifications, i.e., using a hierarchy of communicating components. As mentioned in the introduction we do not only capture structural properties in the architecture but also behavior. To enable behavior specification, components that are leaves in the hierarchy, can be equipped with behavior descriptions such as I/O automata. The architecture may also use the data dictionary to specify data types. Figure 7 gives an example of such an architecture. Note that, although the modeling technique for modeling the micro architecture of formal specifications and the architecture of the system is the same, the actual models and their decomposition are likely to be very different from each other (e.g., compare the micro architecture in Figure 5 with the architecture of Figure 7). This is due to different concerns of modeling. While the formal specification aims at formalizing only the functionality of one use case, the architecture of the system is supposed to implement the functionality of several use cases and additionally needs to address non-functional properties such as extendability or maintainability.

2.2.3 Binding Requirements and Architecture

As both, architecture and formal specifications (and partly the message sequence charts), describe the interface behavior, they can be related to each other at the system boundary. However, since the interface descriptions of the requirements and the architecture may not match exactly (e.g., due to different levels of abstraction) they possibly need to be translated. We use a *refinement specification* that defines this translation between the interface behavior of the architecture and the formal specification of the requirements.

Refinement Specification. A refinement specification translates between interactions of a formal specification and interactions of an architecture. Therefore, the input/output channels of the architecture are related to input/output channels of the formal specification. Typically, beyond simple channel mappings, a conversion of data types has to be carried out to compensate for a different level of abstraction.

Figure 8 illustrates an example of a refinement specification for a system that switches traffic lights according to the presence of ships. The formal specification deals with just one symbolic input stating whether ships are present or not. Furthermore, the formal specification only has one output, i.e., the color to display on the traffic light. The architecture, however, realizes the sensing of the presence of ships by using two light barriers. Therefore, the architecture has two inputs: *Light Barrier 1* and *Light Barrier 2*. The architecture has one output that switches the traffic light to green or to red.

To relate the formal specification to the architecture, we map the symbolic input of the specification to the inputs of the architecture (Representation Function) and the output of the architecture to the output of the formal specification (Interpretation Function) as shown in Figure 8. In model-based testing these functions are also known as abstraction and concretization functions (Pretschner and Philipps, 2005).

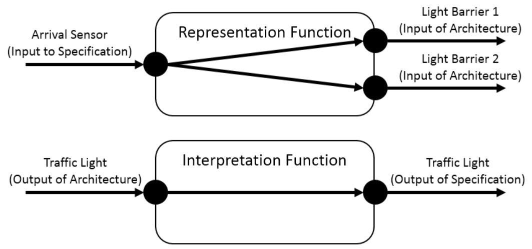


Figure 8: Refinement specification: Mapping requirements to architecture using representation and interpretation.

2.3 Review and Analysis Procedures

One advantage of a seamless model-based approach is that it explicitly defines the relationships between the models. In some cases, the consistency of these relationships can be assured by precise and expressive analysis techniques. Especially, if the analyses can be performed (semi)automated, we expect a great impact on artifact consistency over the development lifecycle. This supports the incremental and concurrent development of requirements and architecture.

In the following, we describe the analysis techniques that are used to assure the consistency of model relations along the artifact model as described in the previous section. Figure 2 provides an overview over the analyses techniques used in our approach.

2.3.1 Manual Review between Use Cases, Scenarios and MSCs

As described in the artifact model, use cases and scenarios are structured but still informal artifacts. That means, the ability to automatically check a consistent relation between use cases, their scenarios, and the transformation of these scenarios into MSCs is limited. Therefore, we perform manual reviews to check the consistency of the relation between these three artifacts. Within the review, we use checklists with properties that need to be fulfilled including the following:
Between a use case and its scenarios:

- Does every scenario start with the same precondition and trigger as stated by the use case?
- Does every scenario end with the minimal guarantee as stated by the use case?
- Is the list of actors consistent between the use case and the scenario?
- Are the action types of the scenarios consistent with the list of inputs and outputs of the use case?

Between a scenario and its MSC:

- Is every step of the scenario translated to at least one message in the MSC?
- Are all actors of the scenario translated to roles in the MSC?
- Are the action types consistent to the direction of messages in the MSC?

2.3.2 Automated MSC Feasibility Checks between MSCs and Formal Specifications

As described in the artifact model, the formal specification of a use case must adhere to all MSCs that are related to that use case. More precisely, an MSC provides a sequence of messages that is exchanged between the system and its environment. The behavior of the formal specification must reflect this sequence of messages. We can automatically check this property by an *MSC Feasibility Check*.

This check transforms the sequence of messages of the MSC into a temporal logic proposition and uses a model checker to evaluate whether the formal specification is a model for the logical proposition. If so, the model checker provides an execution of the formal specification as evidence.

2.3.3 Automated Refinement Tests between Formal Specification and Architecture

The formal specification serves as a partial specification for the system behavior. In the last section, we showed how this specification is connected to the actual architecture of the system by a refinement specification. To ensure that the system behavior actually refines the specification we use a *Refinement Test* (cf. (Mou and Ratiu, 2012)). In a Refinement Test, test cases are automatically generated with respect to the formal specification. Each test case provides a valid input/output relation given by the formal specification. The test cases are then automatically translated to test cases for the architecture by means of the refinement specification as described in the last section. The test cases are executed on the architecture and the output results are afterwards translated back to the specification level and compared to the output results of the original test case. If the results of the test case execution deviates from the formal specification, we have found an error.

3 EVALUATION

We applied the approach during two consecutive master-level practical courses on model-based engineering for students at our university. The task was to develop the control software for the CMCS.

3.1 Setting

The overall 15 students that participated in the two courses were divided into two groups in both courses. The first group took the role of the requirements engineers, while the second group was responsible for the system architecture (the architects). The task of the requirement engineers was to document functional and non-functional requirements and to formalize them as use cases with scenarios, MSCs, formal specifications and temporal logic assertions. They also performed the MSC feasibility checks. The architects developed the system architecture and created the refinement specifications. Both groups together performed the refinement tests and in case of test failures decided on the actions that need to be taken. Both the requirements and the architecture was continuously reviewed by the course supervisors. The system was developed incrementally. As two main functions we identified controlling the bridge and controlling the lock. The requirements engineers and the architects worked in parallel. While the requirement group documented and formalized the requirements, the architects came up with a first rough architecture.

3.2 Tool Support

The whole system, the requirements and the architecture, was developed using the tool AutoFocus3 (AF3)[1]. AF3 is originally a CASE tool for the model-based development of embedded systems. It supports the creation of hierarchical, component-based software and hardware architectures. Components in the architecture hierarchy can be equipped with behavior specifications, for example using state machines, I/O tables or code specifications.

Recently, AF3 has been extended by a requirements module called MIRA (Teufl et al., 2013). With MIRA requirements engineers can document and formalize requirements directly in AF3 and link them in various ways to the architecture. One form of requirements that is supported by MIRA are use cases with scenarios. The scenarios can be formalized using MSCs. Furthermore, formal specifications for requirements can be developed using the same modeling techniques as for the architecture.

Furthermore, AF3 supports all types of analyses mentioned above out of the box, like MSC feasibility checks, refinement tests or checking temporal logic assertions. For these analysis, AF3 uses NuSMV as a model checker and Yices as an SMT solver

3.3 Experiences

In this section we report on our experiences applying the approach outlined above on the case study. Overall, the approach worked well and the system was successfully developed by the students. Due to the high amount of cross checks between the different artifacts of requirements and architecture there is a high confidence in the correctness of the developed system.

3.3.1 Correctness of Requirements

We found that, as MSCs can reference entities of the data dictionary and of the high-level architecture (such as ports), they tended to be very concrete. Thus, the requirement engineers uncovered several misconceptions regarding the behavior of the environment very early. For example, among the requirement engineers there was a different understanding what kind of information a ship sends to the system (current GPS position or current canal segment), which was then decided during the creation of the MSCs.

3.3.2 Concurrent Development of Requirements and Architecture

Due to the precise definition of the artifact relations and their continuous assessment, concurrent development of requirements and architecture was supported by the proposed approach. Changes and refinements within the requirements or the architecture were immediately checked for conformance with the related models. Requirements and architectural elements could be linked right from the beginning. In the course of the development the requirements and the architecture were further refined and formalized allowing for more expressive analyses to ensure the correct relation between requirements and architecture. All artifacts were continuously updated and consistent with each other. A typical situation, where our approach proved beneficial in comparison to simple informal tracing links, occurred, when the architects had to change the system design due to a change in the requirements of one use case. In many cases, the changed system design fulfilled the altered requirements, however, also introduced bugs wrt. some other use case. These bugs were revealed by the analysis procedures and led in many cases also to the revision of other requirements, showing that information flows not only from requirements to architecture but also in the other direction.

[1] http://af3.fortiss.org

3.3.3 Explicit Design Decisions

Another aspect of the artifact relation links is that they explicitly express the design decisions taken during development. Each model carries information that originates from information of another model. The relation links between these models document the design decision made at the transition between models and make them explicit. For example, the transition from the formal specification to the architecture is captured by the refinement specification. Rather abstract signals like "a ship approaches a bridge" are translated into concrete logical signals like "BridgeSensor sends a signal". The design decision to express the event of the requirement as this specific sensor input is explicitly documented in the refinement specification between the formal specification and the architecture. This was especially helpful to assess, if a specific requirements is fulfilled by the chosen architecture. The same applies for the transition of an informal step in a scenario to a formalized sequence of events in an MSC.

3.3.4 Scalability

Our approach aims at a modular specification that allows to break down the functionality of a system into smaller parts and to assess them individually. It is still an open question if analysis procedures and checks can be performed in a reasonable amount of time. The previously described system consisted of two use cases with an overall of 10 scenarios that were refined into MSCs. All requirements of use cases in the original specification could be modeled according by our approach. We additionally elicited 17 further requirements that were first formalized separately by means of temporal logic expressions and then mapped to the two formal specifications that resulted from the two use cases. 3 of the 17 additional requirements could not be formalized in the a formal specification because they were too abstract (i.e., an additional clarification step with the stakeholder is necessary). The more complex specification of the 2 resulting formal specifications had an overall state space of 10,976 states. However, the ability to model this specification by means of a micro architecture made it possible to model this specification by a set of automatons with a maximum of seven states. The most time consuming automated analyses were the MSC Feasibility checks that lasted up to 100 seconds for an MSC with 36 steps and the above mentioned specification. We think that these numbers are promising for the application of the approach also to larger systems.

3.4 Problems

A problem was that the formal specifications got very complex. Therefore, the requirements engineers started to structure them hierarchically which resulted in the above-mentioned micro architectures. This seemed to be problematic at first as apparently the work for structuring the functionality was done twice, in the formal specification and in the architecture. However, we noticed the rationales behind the structuring were quite different between requirement engineers and architects. Where the requirement engineers mainly strove for easy understanding, the architects had goals such as high reuse or an efficient deployment in mind. If parts of the functional micro architecture can be used for the system architecture is a question that we want to look at in the future.

4 RELATED WORK

Our approach follows an artifact-oriented view onto a development process. That means we focus on the artifacts to be developed, rather than on the process steps. REMsES (Braun et al., 2010) provides a process guide for supporting requirements engineering processes in the automotive industry. The artifact model of this approach provides a basic structure for the definition of necessary artifacts, their assignment to abstraction layers and content categories, and the relations between the artifacts. It defines general control flow dependencies within requirements engineering processes. A similar approach for the application domain of business information systems is provided by (Méndez et al., 2010). Our approach follows this idea and extends it by providing concrete modeling concepts to be used in the artifacts and analysis techniques to verify the consistency between them. This allows for a more precise definition of dependencies between artifacts.

When models are used as artifacts to describe different views onto a system, the integration of those models is an important task. In (Nuseibeh et al., 1994), the authors relate those views to different ViewPoints and state that "It is necessary to express and check the relationships between the resultant specification fragments". The artifact types that are introduced in this paper can be considered as ViewPoints, and their relations can be considered as inter-Viewpoint relationships. A more formal and precise way of describing relations between models can be achieved by the use of macromodels. In (Salay et al., 2012), an application of macromodels for the formalization of model relationships is shown. The work shows positive impacts on inter model consistency during evolution of the system. Similar to the ViewPoint templates, macromodels could be used to further formalize the relationships between the models of our approach. While we follow an analytical approach, i.e., models are constructed separately and their consistency is maintained and checked by analysis procedures, there also exist several constructive approaches, i.e., models are transformed (semi)automatically and thus are *correct-by-construction*. (Gutiérrez et al., 2008) describe an approach to automatically transform Use Cases into Activity Diagrams. In our approach, this technique could be used to derive an initial micro architecture for the formal specification of a use case as the micro architectures often resemble a kind of activity oriented architecture. (Sinha et al., 2008) follow the same ideas as proposed in this paper by stepwise extending the use case notion to add precision without discouraging practitioners, who might not be familiar with formal languages. Their two-phased definition of a use case, which accepts use case descriptions in their imprecise form and then assists in adding precision through a wizard driven process, might be a valuable extension of our use case artifact model. Since scenario and interaction models are only partial descriptions of the system's functionality, there also exists work that aims at the integration of several scenarios into one specification (e.g., (Liang et al., 2008)). The work presented in (Krüger et al., 1999) could for example be used to derive a formal specification from the set of MSCs in our approach.

5 CONCLUSIONS AND FUTURE WORK

In this paper we introduced a model-based approach for the stepwise concurrent development of requirements and component architecture. We structured the used modeling concepts of the approach in an artifact model and defined their relations to each other. We furthermore showed how these relations can be backed up by analysis procedures that are formal and automated to a large degree.

Our experiences from a feasibility study show that our approach allows for detecting inconsistencies in requirements early because of the early employment of (semi)formal techniques. Furthermore, the approach facilitates concurrent development of requirements and architecture due to continuous checks that guarantee consistency between requirements and architecture. These checks can be done in early phases and therefore allow for concurrently developing requirements and architecture from these phases to the end of development. In addition, the relations between the proposed artifacts capture design decisions explicitly. Furthermore, as far as we can see, the approach scales well for bigger systems because of the decomposition of requirements and architecture.

While the approach currently focuses on functional requirements in the form of use cases, we think that it is well suited to also integrate nonfunctional requirements into the formal specifications. The idea is that formal specifications integrate the formalized functional requirements from a use case as well as other behavioral properties related to the use case, e.g., safety or reliability properties. This idea is based on the hypothesis that many nonfunctional properties manifest themselves in behavioral properties of the system. An idea on how to formalize availability properties and reflect them as behavioral properties is for example given by (Junker and Neubeck, 2012).

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