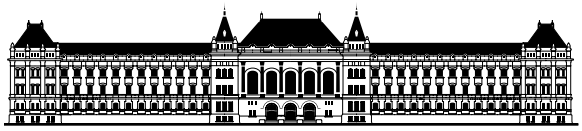

Budapest University of Technology and Economics
Department of Measurement and Information Systems

Modeling for the Dependability of Complex Services

PhD Thesis Booklet

Doctoral School of Informatics

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MSc in Technical Informatics

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Motivation and methodology

The paradigm of Service Oriented Computing (SOC) and the concepts of Service Oriented Architecture (SOA) became widely used in the integration and development of distributed services in a variety of domains, from enterprise applications to cloud-based platforms. The notion of Service refers here to an autonomous and platform-independent functional unit [1].

Although the term SOA is mainly used for XML-based distributed Web services, a number of similar approaches like REST-based services, microservices or cloud-based services are similar in the sense that independent, communicating entities are cooperating via standardized operations in a loosely-coupled manner. A common point in these approaches is the support of design and integration of composite services.

Although the functional development of services gained significant attention and tool support during recent years, incorporating quality aspects remained mostly the task of the service developer.

Considering the components of composite services, these are typically out of the control of the service integrator and may be subject of potential changes even during operation time. Therefore, runtime assurance of correct behavior, both in terms of functionality and Quality of Service became a design objective. The overall approach and positioning of the main research objectives are depicted in Fig. 1.

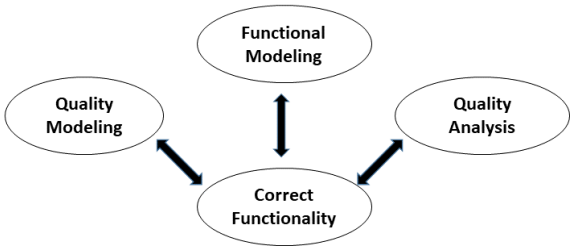

Figure 1: Research topics

My main research goals were the following:

1. Evaluate and support the possibilities of application of model-driven development (MDD) methods in the *quality-driven design* of service oriented applications, with the incorporation of extra-functional aspects in MDD.

2. Support the runtime verification/testing of SOA components to find errors caused by deviations from the specification in service behavior, i.e., guarantee *correctness* of services by detection of underlying errors.

3. Extend performance evaluation with *quantitative analysis* of performability, to assess the performance of services, considering the effects of

faults.

In SOA, there is a strong correlation between the functional refinement and the unit of implementation, as applications are typically not monolithic, but built as composite services, which often rely on invoking external service providers.

In my dissertation, the majority of the examples and illustrations are from the SOA domain. However, the application of the suggested methods is not restricted to a particular domain or technology, but can be generalized. As I followed a model-driven approach, that starts from functional models and handles logical concepts separated from implications of concrete technologies, an arbitrary application in this design space can benefit from the presented results.

Solution approach

In the recent years, design of demanding applications became more and more subject of standards. The approach presented in the thesis aims at being compliant to main de-facto and industrial standards like ISO/IEC/IEEE 42010:2011 [ISO11].

The principal idea behind this standardization is the systematic collection of requirements for the individual aspects, constraints and design to each of them with a corresponding architecture description, preferable formulated as a model in an aspect-specific modeling language. Note, that conformance to the standard alone does not assure the consistency of the individual models describing the particular aspects and constraints. Since the mid-90s, model transformation based approaches [Bon+99] put a core engineering model into the focus enriched by aspect-related elements for further analysis.

The use of a single core model, analyzed from the perspective of different constraints, supports to achieve a consistent design, assuming that aspect-specific models are derived by automated model transformations, following the principles of Model-Driven Development (MDD).

Criticality of a system implies elevated quality requirements compared to the common level. Standards like ISO250xx series describe the main notion and aspects of Quality in Use, Product Quality and Data Quality, which can be used as guiding constraints in the above mentioned architecture design process. Product Quality refers to characteristics of the product which are inherent to the design while Quality in Use refers to user-perceived attributes.

The service-based approach to system integration raises the problem of defining Service Level Agreements [MA02] (SLA) between the provider and user of the main service, and as such, it may specify the objectively measurable elements of Quality in Use. In this context, SLAs are used to describe the required quantitative parameters of a service, related to a particular client or class of clients. In order to capture aspects of critical services, I extended the scope according to [Avi+04].

Design for service quality

The architecture development standards do not define either the modeling language or the model kind. In the mainstream of model driven design, UML and its derivatives like MARTE (Modeling and Analysis of Real-time and Embedded systems, [OMG09]) are used as the core modeling approach and language. The method, starting in architecture design phase, enriches it with the notions of non-functional properties determining Quality in Use and Product Quality, facilitating a transformation of engineering models into mathematical tools.

From the modeling point of view, the faithfulness, compactness and correctness of the models demand a good expressivity of the modeling approach. Accordingly, one of my objectives was the integration of the core standards into this evaluation process for the particular field of SOA, primarily process modeling languages for the computation and platform independent modeling phase and Web service related ones, to the platform specific one. Two typical analysis methods can be distinguished:

Qualitative evaluation checks the correctness of the designated architecture, including the built-in mechanisms and measures to mitigate potential problems like faults.

Quantitative analysis already applies measures both in the specification of target requirements and delivered by designated architecture.

This way, the evaluation conformance of a candidate architecture with the requirements gets an objective set of criteria.

Service analysis by model transformations

My second objective was the elaboration of such model transformation based approaches which help to automate the generation of SOA models for evaluation purposes. Here the focus was on such aspects, which have a high priority in service oriented architectures and problems already covered in a wider class of application domains are omitted from the research scope. In my work, I modeled composite services as workflows specified in Business Process Execution Language (BPEL), but the results are applicable to other executable workflow models as well.

In the case of SOA, my work focused on reusing existing analysis methods and tools of high efficiency as far as possible. An opportunity granted for this approach is that while the algorithmic complexity of large scale SOA-based systems can exceed by orders of magnitude that of traditional monolithic applications, the strong functional and correlated architectural decomposition of the system increases the model compactness by using complex elementary functions complying to uniform rules.

Typically, any complex system undergoes multiple design checking and re-design iterations. In order to assess the effectiveness of the design-V&V process, a careful tracing of the outcomes is necessary, which is subject of a dedicated data analysis of the processing approaches and tools. This way, the elaboration of the methodology of evaluation was a priority target. As a common modeling approach, I followed the principles of VPM (Visual Precise Metamodeling, [VP03]) to capture these aspects.

New Scientific Results

Quality-driven Model-based Design of Critical Services

Based on a structural model of communicating services, I elaborated a method to model quality aspects in a contract-driven way. This method was also extended by a mapping to standard service description languages in order to support service deployment. A UML profile was developed in order to provide engineering support [2; 3]. The work was also partially mapped to additional service standard (SCA) in [4].

Contracts can describe expected behavior and serve as a basis for service monitoring. However, the correctness of a composite service should be guaranteed as well [5]. Based on a translation of composite service models to dataflow networks, I created fault models to capture improper data handling and the effects of faults in external services. These fault models were the basis for model checking.

Contribution : Quality-driven Model-based Design of Critical Services
I complemented the model-based design paradigms with quality aspects for designing critical Web services. Starting from extra-functional requirements leading to provenly sound business processes, a methodology was elaborated for the empirical evaluation of the effectiveness of the V&V process.

Contribution C.1.1 Model-based design of services subject of extra-functional requirements. Based on the analysis of requirements posed to critical services, I have proposed a model for capturing the extra-functional requirements of communicating services in the form of contracts, with an emphasis on resiliency requirements. I also specified a mapping from this model to Platform Specific Models compliant to the major standards in the field of Web services. *Related publications: [1; 6; 7; 8; 9; 10]*

Contribution C1.2 Fault modeling and proof of correctness of composite services. I developed a fault model for composite services and specified mappings from engineering models to formal model checkers to evaluate the correct variable handling of composite services described as service workflows. *Related publications: [11; 12; 13; 14]*

Contribution C.1.3 Quality modeling and sensitivity analysis of V&V processes. I developed a method based on empirical data-driven analysis of V&V quality assurance processes to support sensitivity analysis of cost estimation parameters by evaluating quality characteristics of design artifacts. *Related publications: [15; 16; 17]*

Publications connected directly to my thesis received the following number of independent citations:

- C.1.1 Model-based design of services subject of extra-functional requirements:[1]: 40, [6]: 6, [7]: 18, [9]: 3.
- C2.2 Fault modeling and proof of correctness of composite services: [11]: 31, [12]: 13.
- C2.3 C.1.3 Quality modeling and analysis of V&V processes: [18]: 3

Verification of Fault Tolerance in SOA-based Applications

In order to evaluate fault tolerance mechanisms in service oriented systems, I modeled the dynamic behavior of service components. Starting from a generic service metamodel, high-level reconfiguration primitives were defined to capture dependable services in the form of graph transformation rules, by integrating traditional fault-tolerance techniques into SOA. Basic reconfiguration steps were identified for providing reliable messaging between services

and fault tolerant service infrastructure components implementing the recovery block pattern. *Formal analysis* was carried out in order to justify the correctness of reconfigurations expressed by dynamic behavior rules. Finally, these models were extended in order to be able to generate test oracle automata for the runtime verification of services.

Contribution : Verification of Fault Tolerance in SOA-based Applications
Based on modeling of fault tolerance mechanisms in SOA, I developed a methodology for checking their appropriateness by formal V&V and/or testing.

Contribution C2.1 Modeling of fault tolerance mechanisms in SOA infrastructures. I developed a method for formally specifying the behavior of fault tolerance mechanisms based on dynamic fault mitigation using graph transformation patterns.*Related publications: [7; 14]*

Contribution C2.2 Proof of appropriateness of fault tolerant design patterns in SOA infrastructures. I developed a method based upon transforming the Graph Transition Systems representation of the state space of service components into Labeled Transition Systems. I analyzed soundness criteria of the behavior of fault tolerant mechanisms by a state space exploration. *Related publications:[19; 14].*

Contribution C2.3 Requirement-driven test generation for service infrastructure components. I proposed a requirement-driven test generation technique for service infrastructures using the Graph Transition System representation of the state space (C2.1). I proposed to use workflow mining techniques to create a Deterministic Finite Acceptor automaton checking the compliance of observation with the requirements. *Related publications:[18; 14].*

Publications connected directly to my thesis received the following number of independent citations:

- C2.1 Modeling of fault tolerance mechanisms in SOA infrastructures: [7]: 18, [14]: 3.
- C2.2 Proof of appropriateness of fault tolerant design patterns in SOA infrastructures: [19]: 18, [14]: 3.
- C2.3 Requirement-driven test generation for service infrastructure components: [18]: 4

Quantitative Analysis of Services

A proper performance characterized by metrics like throughput, timeliness, etc. is a primary indicator of service Quality in Use. However, especially large-scale complex and geographically distributed systems are subject to the fault occurrences. These, in turn, lead to performance degradation. This way the notion of *performability* is a more realistic characterization of user sensed quality of service. My work addressed a formal analysis of this aspect serving as a model-based substantiation of finding a proper trade-off between the performance, efficiency and reliability attributes of the designated system.

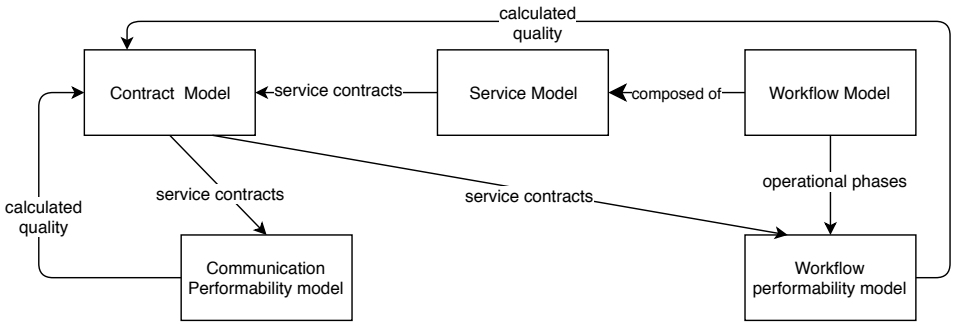

Figure 2: Models in quantitative analysis

Contribution : Quantitative Analysis of Critical Services
I extended the quantitative evaluation of critical SOA-based applications by performability analysis services and their underlying infrastructures.

Contribution C3.1: Performability Analysis of Infrastructure Services. I developed a performability analysis method of fault-tolerant service infrastructures to estimate the performance penalty of communication middleware for assuring dependability. I specified a mapping from high-level service models extended with extra-functional parameters (as in C1.1) to process algebra models amenable to performance analysis. *Related publications: [20; 21; 14]*

Contribution C3.2: Performability Analysis of Composite Services
I developed a method to model composite business processes following the Phased Mission System (PMS) paradigm to evaluate SLA compliance regarding performance and availability constraints. The temporal behavior of the application is decomposed into steps of an execution time approximated by constants, and the underlying services are expected to be subject of random failures, characterized by a constant fault rate. *Related publications:[22; 23].*

Publications connected directly to my thesis received the following num-

ber of independent citations:

- C2.1 Performability Analysis of Infrastructure Services: [20]:9, [21]:3, [14]: 3.
- C3.2: Performability Analysis of Composite Services: [22]: 24, [23]: 2.

Conclusions and future work

The focus of my thesis was model-driven methods for quality-driven modeling, synthesis and analysis of critical services implemented over the Service Oriented Architecture paradigm. My work focused on service components, contract and composite service description, with the primary aim to support dependability evaluation, starting from engineering models. The ambition of the thesis was a proper coverage of the critical phases of the lifecycle, primarily addressing the question how the Quality in Use can be assured from the aspect related to dependability during design and runtime. By following the best practice of model transformations I generated the frameworks for checking the correctness and efficiency of fault tolerance mechanisms and assuring the proper performability of the designated system even in the case if faults are present.

My three major contributions were the following:

- Evaluate and support the possibilities of model-driven development (MDD) methods in the **service quality-driven design** of service oriented applications.

  Contribution: I complemented the model-based design paradigms with quality aspects for designing critical Web services. Starting from extra-functional requirements leading to provenly sound business processes, a methodology was elaborated for the empirical evaluation of the effectiveness of the V&V process.

- Support the runtime verification/testing of SOA components to find errors caused by deviations from specification, i.e., guarantee **correctness** of services by early detection of underlying errors.

  Contribution: Based on modeling of fault tolerance mechanisms in SOA, I developed a methodology for checking their appropriateness by formal V&V and/or testing.

- Extend performance evaluation with **quantitative analysis** of performability, assessing the performance of the service considering the effects of faults in an uncontrolled environment.

  Contribution: I extended the quantitative evaluation of critical SOA-based applications by performability analysis of services and their underlying infrastructures.

The presented approaches are designed to be extendable with aspects as well. Their practical use in other architectural paradigms than SOA is however limited, as the elaborated methodologies implicitly exploit the strong functional-architectural correlation. While at the first glance it seems to be only a simplification, a proper generalization would need the embedding of the core information on the PIM-PSM mechanism (which is quite straightforward in the case of SOA).

The novel methodologies presented in the thesis rely on existing analysis tools. While model transformations deal with the static models, and scale well with the increasing size and complexity of the models, the same is not valid for the analysis especially if dynamic state space exploration is involved. This way, the main limitation originates in the mathematical analysis as I tried to generate compact analysis models at the highest level of abstraction which still maintains a proper faithfulness.

Note that the most promising way to overcome these constraints is hierarchical analysis by following the assume guarantee principle, however, this was left as subject of further research. From the domain point of view, further research and experimentation is needed in order to adapt these to other fields like micro-services, an important paradigm which offers a lightweight approach for creating distributed services.

Evaluation and usage

My research results were used in the following ways:

Research projects and application

- The model-driven deployment approach was adapted in the CoMiFin EU project in order to generate monitoring configurations for SLA-driven trust assurance in critical Financial Infrastructures. The generated code was deployed on a distributed testbed in 3 countries. Connected publications: [24] (*Nr. citations: 13*), [25] (*Nr. citations: 2*).

- Results of C1.3 were used on data from project partners Critical Software and Resiltech in the CECRIS EU project where data from critical aerospace and railway projects were analyzed.

- I was working on creating verification workflows in the DECOS EU project with colleagues of BME MIT FTSRG, where we created a framework for process-driven verification, based loosely coupled tools [26; 27; 28] *Nr. citations: 12,8,22*.

- In the SENSORIA EU project, results were used to create a demonstrator which was presented at Systems and CEBIT international industrial fairs, integrated to Sensoria Development Environment (SDE). (C1.1, C1.2, C2.2, C3.1).

- In the e-Freight EU project we were using a similar approach to model aspects of service integrations in international multi-modal logistics. Connected publications: [29].
- Transformations for performability (C1.1., C3.1) were reviewed and applied in a proof of concept of the SENSORIA project in the domain of financial services.
- Dependability analysis of composite services by Phased Mission System were part of the deliveries of the ReSIST NoE project.
- A similar graph transformation-based approach to C2.1 was used for Wireless Sensor Network performability simulation in a Hungarian-French bilateral project in order to evaluate the optimal period length of the Controlled Greeds Sleep algorithm [30] (*Nr. citations: 28*).

Connected research

- The transformation specified in C1.2 was extended in [Heg14] to support back-annotation of transformation execution traces. The method as also extended in [12] to cover compensation handling of workflows as well.
- Our research group is investigating intensively the theoretical and applicability issues of blockchain platforms. Connected to this research, I served as an advisor (the only one from the academy) for a grant proposed by Linux Foundation on the business process based generation of smart conctracts for the Hyperledger private blockchain platform [1]. This research was connected to results of C1.2 and will be also presented at the most important global technical forum of the Hyperledger community (Dec 2018, [2]). The work has already been presented at an international workshop [31].
- A similar approach was adapted to generate Complex Event Processing configurations [32] in order to guarantee that all important services are monitored properly.
- In multiple bilateral collaborations with IRISA-INRIA Rennes and LIRMM Montpellier, I was investigating multiple level of QoS in services based on Wireless Sensor Networks. A novel algorithm (Controled Greedy Sleep) was created and extended to capture service level requirements [33; 34; 35], *Nr. citations: 27,10,2*. Enhanced routing algorithms were proposed to improve data quality of measurements in [36; 37; 38].

[1] https://www.hyperledger.org/blog/2017/08/29/congratulations-to-the-hyperledger-interns-and-mentors-on-completed-summer-internships

[2] https://sched.co/G8sC

Education

- Transformations and the method for performability analysis (3.1) were included in the material of the Sensoria Summer School (2009).
- Results of C1.1 and C1.2 were used directly in the SENSORIA project, in the SENSORIA Summer School and in multiple BSc and MSc courses of BME MIT FTSRG (System modeling, Service integration). Research results were used not only at BME but also at different other universities (LMU München, Univ. Oslo).

Publications

The following table summarizes my publications according to MTMT (also contains some non peer-reviewed papers and abstracts at local conferences which are not detailed in the publication list of the thesis).

Number of publications:	48
Number of peer-reviewed journal papers (written in English):	11
Number of articles in journals indexed by WoS or Scopus:	11
Number of publications (in English) with at least 50% contribution of the author:	13
Number of peer-reviewed publications:	42
Number of independent citations:	153 (in MTMT), 322 (google scholar)

Table 1: Publications

Besides scientific publications, a number of students work was related to the topics I was working on, including 3 works with faculty first prize.

Future work and research directions

Besides the adaptations mentioned above, I plan to adapt and extend my results in three major topics:

Analysis and quality assurance of data-driven processes. Recently, data-driven services gain more and more attention. These services are typically supported by data processing and analysis services, where a fault in the input data may lead to failures, which are often hard to identify, because of the different data processing, manipulation and analysis steps which typically do not preserve metadata about the origin of a specific piece of information. My intended research aims at creating modeling and analysis methods in order to strengthen the Quality in Use of these services of rapidly growing importance.

Model driven data analyis. The methods presented in the dissertation assumed that metrics of a specific quality aspect can be identified in a

top-down approach. In a lot of practical cases, however, identification of the metric to be evaluated (metric selection) and validation of early analysis results (originating either in visual or computational methods) needs special domain expertise. This kind of data selection and result validation is often the most critical part in the design of a data-driven service (e.g., a service evaluating the status of a large-scale distributed infrastructure). Based on our recent research cooperations in this field, I plan to develop methods and algorithms to support these operations.

Model-driven design of smart contracts in blockchain platforms. Our research group is investigating intensively the theoretical and applicability issues of blockchain platforms. Connected to this research, I served as an advisor for a grant proposed by Linux Foundation on the business process based generation of smart contracts for the Hyperledger platform. In the frame of this research, correctness issues and the extension of model-driven methodology will be also investigated.

Publications

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