D I S S E R T A T I O N

Monitoring Quality of Service in Service-oriented Systems: Architectural Design and Stakeholder Support

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Doktors der technischen Wissenschaften

unter der Leitung von

Univ.-Prof. Dr. Schahram DUSTDAR

E 184

Institut fur Informationssysteme

eingereicht an der Technischen Universität Wien

Fakultät für Informatik

von

Dipl.-Ing. Ernst Oberortner

0027144

Poststrasse 4

A-9551 Bodensdorf

Wien, Februar 2011

Abstract

In a service-oriented system, services are utilized to perform inter- and cross-organization business tasks with few human intervention. Between a service provider and a service consumer contracts can exist containing performance-related Quality of Service (QOS) agreements, called Service Level Agreement (SLA). A services provider must prevent SLA violations in order to avoid serious financial consequences and a diminished reputation. Service consumers want to ensure that they get the service they pay for. In order to prevent and detect violations of the performance-related agreements during the SLA's validity, a monitoring infrastructure is required. To design an architecture of a QoS monitoring infrastructure, many architectural design decisions must be faced, depend on business and technical requirements. At early stages, the infrastructure's requirements are fuzzy and incomplete, making later changes inevitable. The design process and the specification of the negotiated performance-related QoS properties involve various differently skilled stakeholders, ranging from business to technical experts.

In this thesis, we present an architectural design decision model that covers design decisions about measuring, storing, and evaluating performance-related QoS properties. The model proposes architectural solutions for the design decisions that fulfill the requirements. Model-driven Development (MDD) makes it possible to generate the QoS monitoring infrastructure almost automatically. To support the differently skilled stakeholders to specify the performance-related agreements, we utilize Domain-specific Language (DSL). The specified performance-related agreements are then monitored during the SLA's validity. We develop the model-driven DSLs using an incremental development approach. We evaluate our work in the scope of an industrial case study dealing with advanced multi-media services that have to comply with performance-related QoS agreements.

The presented architectural design decision model guides the designers through the decision making process. Utilizing model-driven DSLs, business stakeholders can specify the performance-related agreements without technical knowledge. The stakeholders with a technical expertise describe the technological artifacts to monitor the performance-related agreements during the SLAs' validity. Developing model-driven DSLs incrementally helps the developers to deal with permanent changing requirements.

Kurzfassung

In service-orientierten Systemen werden Services angeboten welche inner- und außerbetriebliche Aufgaben hauptsächlich automatisch abarbeiten. Zwischen den Service Anbietern und den Service Konsumenten können Verträge vereinbart werden, welche Klausen über die Performanz der Services definieren. Solche Verträge werden als Service Level Agreements (SLA) bezeichnet. Ein Service Anbieter muss sicherstellen, dass die vertraglichen Vereinbarungen erfüllt werden um Pönale zu vermeiden sowie, viel schlimmer noch, seinen Ruf zu schädigen. Ein Service Konsument möchte gerne wissen, ob der Service Anbieter auch wirklich die Vereinbarungen erfüllt bzw. nach Vertragsende erfüllt hat. Daher ist eine Überwachung der Performanz der Services bezüglich der vertraglichen Vereinbarung unabdinglich. Ziel der Arbeit ist es, systematisch die Messung und die Überwachung von QoS-Parametern in service-orientierten Systemen zu unterstützen. In der Entwurfsphase einer Überwachungsinfrastruktur müssen Lösungen für Architekturentscheidungen getroffen werden, welche die betrieblichen und technischen Anforderung erfüllen. Außerdem sind viele Akteure involviert welche unterschiedliches Hintergrundwissen und Interessen haben. Überdies sind die Anforderungen an die Überwachungsstruktur zu Beginn nicht klar definiert. Dadurch sind spätere Änderungen in der Architektur und in dessen Implementierung unumgänglich.

In dieser Dissertation wird ein Modell vorgestellt um den Entwurf einer Überwachungsstruktur zu vereinfachen. Das Modell stellt Architekturlösungen für die Architekturentscheidungen vor, welche grundlegende Anforderungen erfüllen. Das vorgestellte Entwurfsmodell hilft Designern eine betriebsoptimale Überwachungsstruktur zu entwerfen. Modell-getriebene Softwareentwicklung ermöglicht eine automatische Generierung der Überwachungskomponenten. Damit die Akteure die vertraglichen Vereinbarungen spezifizieren können, werden modellgetriebene domänen-spezifische Sprachen verwendet. Die Verwendung von modellgetriebenen Sprachen ermöglicht Business-Experten die vertraglichen Vereinbarungen zu definieren ohne über ein technologisches Wissen zu verfügen. Außerdem wird ein inkrementeller Entwicklungsansatz vorgestellt welcher den Umgang mit späteren Änderungen erleichtert. Es wird eine Fallstudie präsentiert welche als Evaluationsgrundlage dient. Die Fallstudie beschäftigt sich mit Multimedia Services um Filme oder Live-Streams in einer gewünschten Sprache anzusehen.

To my parents and Verena.
From the bottom of my heart.

Contents

List of Tables

List of Figures

Glossary

BPEL Business Process Execution Language

CEP Complex Event Processing

DSL Domain-specific Language

ESB Enterprise Service Bus

GOF Gang of Four

GPL General Purpose Language

LOC Lines of Code

MDD Model-driven Development

MVNO Mobile Virtual Network Operator

POSA Pattern-Oriented Software Architecture

QOS Quality of Service

QUALA Quality of Service Language

SLA Service Level Agreement

SOA Service-oriented Architecture

SOAP Simple Object Access Protocol

SOC Service-oriented Computing

UDDI Universal Description, Discovery, and Integration

VBMF View-based Modelling Framework

WSDL Web Service Description Language

Previously Published Work

- The foundations of the thesis' case study (see Chapter 3) and the incremental development approach (see Chapter 6) were published recently in our following paper:

  > E. Oberortner, U. Zdun, S. Dustdar, A. Betkowska Cavalcante, and M. Tluczek. Supporting the Evolution of Model-driven Service-oriented Systems: A Case Study on QoS-aware Process-driven SOAs. In *IEEE International Conference on Service-Oriented Computing and Applications (SOCA)*, pages 14, 2010.

- The background information about patterns in distributed systems (see 4.1.2) and performance-related QOS properties are published at the Pattern Languages of Programs (PLoP) conference in 2010. The paper also covers the thesis' patterns for measuring the performance-related QoS properties (see Section 4.4.2) and the implementation of the patterns within the case study (see Section 4.6.3).

  > E. Oberortner, U. Zdun, and S. Dustdar. Patterns for Measuring Performance-Related QoS Properties in Distributed Systems, 2010. In *Proceedings of the 17th Pattern Languages of Programs (PLoP) Conference (PLoP)*, Reno, NV, October 2010.

- Background information on MDD and DSLs (see Section 5.1.3, the approach of tailoring a model-driven DSL to the stakeholders' expertise (see Section 5.2), and an early version of the QuaLa DSL (see Section 5.4) were published in the following paper:

  > E. Oberortner, U. Zdun, and S. Dustdar. Tailoring a model-driven Quality-of-Service DSL for various stakeholders. In *MISE'09: Proceedings of the 2009 ICSE Workshop on Modeling in Software Engineering*, pages 20–25, Washington, DC, USA, 2009. IEEE Computer Society.

- The final version of the QuaLa DSL is described in the following paper:

  > H. Tran, T. Holmes, E. Oberortner, E. Mulo, A. Betkowska Cavalcante, J. Serafinski, M. Tluczek, A. Birukou, F. Daniel, P.Silveira, U. Zdun, S. Dustdar. An End-to-End Framework for Business Compliance in Process-Driven SOAs. In *Proceedings of SYNASC 2010*, September 2010, IEEE Press.

- The explorative study of our model-driven DSL approach (see Section 5.3) and some background information about model-driven development (see Section 5.1.1) were published in the following paper:

  E. Oberortner, U. Zdun, and S. Dustdar. Domain-Specic Languages for Service-Oriented Architectures: An Explorative Study. In P. Mähönen, K. Pohl, and T. Priol, editors, *ServiceWave*, volume 5377 of *Lecture Notes in Computer Science*, pages 159–170. Springer, 2008.

- Our model-driven approach to specify a role-based page flow of web applications (see Section 5.5.1) is published in the following paper:

  E. Oberortner, M. Vasko, and S. Dustdar. Towards Modeling Role-Based Pageow Definitions within Web Applications. In Proceedings of the *4th International Workshop on Model-Driven Web Engineering (MDWE)*, volume 389 of CEUR Workshop Proceedings, pages 1–15, Toulouse, France, Sept. 2008.

- We have submitted the architectural decision model, its requirements, and pattern-based solutions (see Chapter 4) to the 2011 EuroPLoP conference.

  E. Oberortner, S. Sobernig, U. Zdun, R. Hanmer, S. Dustdar. An Pattern-based Architectural Decision Model to Design a QoS Monitoring Infrastructure in Service-oriented Systems. Submitted to the 16th European Conference on Pattern Languages of Programs (EuroPLoP), 2011, Irsee, Germany.

Acknowledgements

My first thank goes to my supervisors Professor Dr. Schahram Dustdar and Professor Dr. Uwe Zdun. Both guided me through my PhD studies, helped me whenever I had questions, and gave prompt feedback to me. Their guidance and great support helped me to build a professional research career. Thanks to their great mentoring, assistance, and patience.

My deepest thank goes to my parents, Christine and Ernst. You are here for me at every time, support me in every situation, and you'll stand behind me in whatever i do. Saying thanks to you is not enough.

From the bottom of my heart I want to thank my beloved girl, my dear, Verena. Thank you for loving me, being my best friend, and supporting me in every difficult moment. You make my life livable even more.

Many thanks to my colleagues and friends at the Distributed Systems Group (DSG) at the Vienna University of Technology. Mainly I want to thank Emmanuel Mulo, Huy Tran, and Ta'id Holmes. It was a great pleasure working and collaborating with you.

I want to thank all my friends, mainly Gerald Novak, Marcus Brandauer, and Helmut Faland. You provide me a lot of joy and fun beside work. Thanks to all colleagues of the KSV Wienstrom Attacki (http://www.attacki.at) and KSV Wienstrom Scorpions (http://www.ksvscorpions.at) hockey teams for having so much fun on and off the ice.

I say thanks to Benoit Langelier for proof-reading the thesis, explaining how to formulate the contributions better and more understandable. I am also grateful to the anonymous reviewers for numerous critical comments and insights that were extremely helpful for my work. Thanks to Andy Carlson, Stefan Sobernig, and Robert Hanmer for their constructive and supporting help during the shepherding process of the presented patterns to improve the quality of the patterns and the work itself.

This work was supported by the European Union FP7 project COMPAS (http://www.compas-ict.eu), grant no. 215175.

Chapter 1

Introduction

1.1 Problem Statement

In service-oriented systems, business activities are aligned with inner- and cross-organizationl IT services. Benefits are increased productivity, efficiency, and flexibility [137]. Service providers provide services to consumers that can invoke the services to automate their business activities. Contracts exist between service providers and service consumers that are called Service Level Agreement (SLA). An SLA is a contract that contains – among other things – agreements on performance-related Quality of Service (QOS) properties when the consumer accesses the providers' services over a network. SLAs assure that the consumers get the service they paid for and that the service provider fulfils the SLA guarantees. A current shortcoming is the lack of integration of negotiated SLAs into service-oriented systems [25, 88].

Service providers need to know what they can promise within the SLAs and what their IT infrastructure can deliver. Violating a negotiated SLA results in the payment of penalties to the service consumers or to external auditing institutions. Moreover, the reputation of the service provider becomes diminished from violating SLAs. On the other hand, the service consumers want to observe and validate that the server provider does not violate the guaranteed SLAs. From there, a monitoring infrastructure for observing the performance-related QOS agreements is vital [45, 47, 59].

Designing a QOS monitoring infrastructure is a challenging and comprehensive task. The QOS monitoring infrastructure must adhere to various business and technical requirements, such as the QOS monitoring should have a minimal performance overhead, or the services' implementation should not be modified. A service provider has different requirements on the QOS monitoring infrastructure then a service consumer. A service consumer must prevent SLA violations during the SLA's validity, whereas a service consumer wants to detect SLA violations after the SLA's validity. Performance-related QOS properties can be measured, evaluated, and stored in various ways. Resultant, to design an optimal

QOS monitoring infrastructure to fulfill the requirements, many architectural design decisions must be taken [77].

Monitoring performance-related QOS agreements, involves many stakeholders with different backgrounds, ranging from business to technical experts [80]. Business experts know how to formulate performance-related QOS agreements in the SLAs. Technical experts know how to measure, store, and evaluate the performance-related QOS agreements in the used technologies. To support the stakeholders, the requirements on the QOS domain must be stated clearly. For example, it must be known which performance-related QOS properties an SLA can contain and how the agreements should be specified. But, at early stages, the requirements are fuzzy and incomplete, stemming from the stakeholders' different interpretations of the QOS domain and background knowledge. Hence, in later stages requirement updates and extensions are inevitable [82].

1.2 A Justifying Scenario

In this section, we give an example to justify the importance of a QOS monitoring infrastructure. The scenario focuses on an online store, making it possible to order products online. In Figure 1.1, we present the example of a business process for handling online orders. The business process activities involved are realized by human and IT services alike.

In this simple process scenario, the provider and consumer roles alternate between the parties involved. The online store acts as service provider towards its online clients while the store itself consumes third parties' services. The following parties participate in the business process:

- A *service provider* offers services with a specific functionality to its customers. In our example, the service provider is the online store and offers services to its customers to order some products online.

- A *service consumer* accesses the offered services to request the services' functionality. To order some products online, the service consumers, i.e., online buyers, places an order by accessing the online store's web site, ordering the products in a desired quantity.

- *Third party providers* offer services to support the functionality of the service provider's offered services. For example, to process the consumer's order request, the online store has to reorder the requested products in case they are out of stock.

Consider an online buyer ordering a book at the online store. Assume that there is a binding agreement between the online store (as the service provider) and its clients (as the service consumers) regarding the maximum duration of order processing. This order processing time amounts to five working days and represents the maximum time in which the online store commits to dispatch the orders. However, it does not include the delivery time taken by the postal services or other intermediate

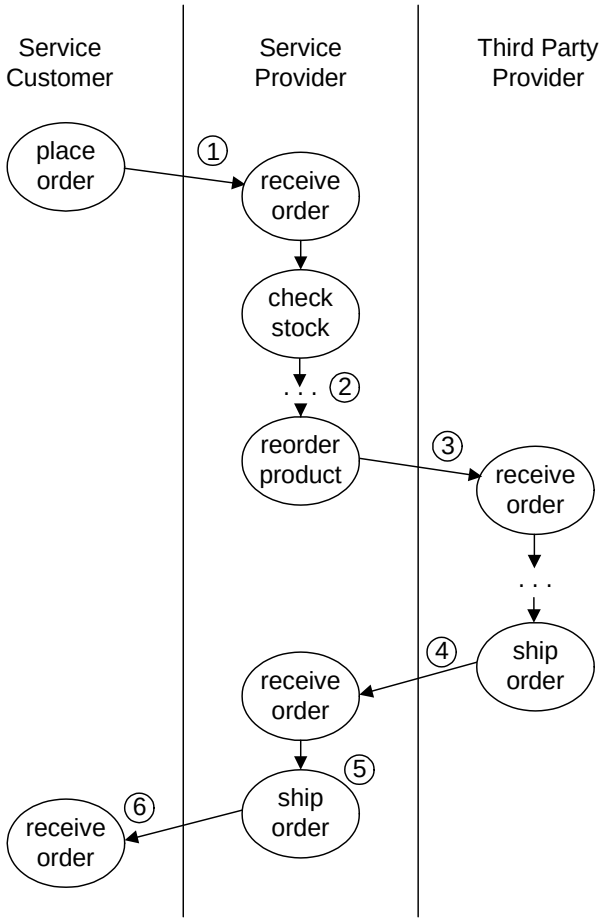


Figure 1.1: A justifying scenario

transporters used. In case of non-fulfilment, the customer receives the ordered product for free. Note that we do not consider that SLAs are negotiated between the online store and its third party provider. We also neglect any payment processes.

Under such obligations, the online store must minimize the risk of non-fulfillment. In particular, the online store must take precautionary measures to prevent SLA violations due to a wholesaling third party not delivering on time. This risk assessment requires some process monitoring capabilities. Equally, the client wants to verify the actual order processing time regularly during or once after the actual delivery, for instance as part of a package tracking system provided by the online store.

Designing a monitoring infrastructure meeting the requirements raised by the three parties is a particular challenge.

1.3 Research Questions

Research Question I:
How to design a QOS *monitoring infrastructure that fulfills the requirements?*

The in the SLA negotiated performance-related QOS properties must be monitored during or after the SLAs' validity. This research question concentrates on various design decisions that must be faced during the design process of a QOS monitoring infrastructure. We focus on design decisions about where and when to measure the performance-related QOS properties, where and when to evaluate the measurements, and where to store the measurements for a later evaluation.

Research Question II:
How to support the differently skilled stakeholders to specify the performance-related QOS *agreements?*

Stakeholders are differently skilled, ranging from business to technical background knowledge. Business experts know how the performance-related QOS properties are specified within the SLAs. Technical experts are experienced in the underlying technologies to monitor the performance-related QOS properties during the SLAs' validity. This research question focuses on the problem of including all stakeholders within the design process and to specify the SLAs' performance-related QOS properties.

Research Question III:
How to develop an appropriate stakeholder support, dealing with permanent changing requirements?

In early stages, the requirements on a QOS monitoring infrastructure are fuzzy and incomplete, stemming from different stakeholder expertise and interpretations of the QOS domain. After becoming more familiar with the domain concepts, the requirements of the QOS monitoring infrastructure evolve and change. The later the changes, the more complex and time-consuming the updates. This research questions focuses on approaching solutions to deal with changing requirements.

Research Question IV:
How to integrate a QOS *monitoring solution into an existing service-oriented system?*

Nowadays, enterprises start to utilize service-oriented distributed system to automate their business processes and to enhance cross-organizational transactions. Such systems are called process-driven SOAs [137]. To ensure an enterprise's internal policies, stemming from performance-related SLA negotiations, we want to research how to use the thesis' contributions to integrate a QOS monitoring infrastructure into an existing process-driven SOA.

1.4 Scientific Contributions

Contribution I:
An architectural decision model to design a QoS monitoring infrastructure

To the best of our knowledge, there exists no guidelines to design an appropriate QoS monitoring infrastructure. To answer *Research Question I*, we present a novel architectural design decision model that consists of relevant questions that arise through the decision making process. The model contains requirements on the QOS monitoring infrastructure and provides design solutions that extend and utilize well-established design patterns. In our model, we base the solutions on design patterns to monitor performance-related QOS properties, presented in the Gang of Four (GOF) book [35], the Pattern-Oriented Software Architecture (POSA) series [18, 19, 103], and the Remoting Patterns book [124]. The selection of the solutions depends on the QOS monitoring infrastructure's requirements. We evaluate the solutions against the challenging design problems and give advice in the decision making related to building QOS-aware service-oriented systems.

Contribution II:
Supporting the stakeholders with tailored domain-specific languages

After having designed a QOS monitoring infrastructure, utilizing the architectural design decision model (*Contribution I*), the differently skilled stakeholders must be supported to specify the performance-related QOS properties embedded in the SLAs. We present a novel approach that focuses on Domain-specific Language (DSL) to contribute to *Research Question II*. The DSLs are divided into multiple sub-languages at different abstraction levels. Each sub-language is tailored to the appropriate stakeholders' expertise. Our approach is evaluated by an explorative study of providing tailored languages within service-oriented architectures (SOA). We illustrate a developed model-driven DSL within the scope of an industrial case study for specifying a service's performance-related QOS compliance concerns and actions in case of violations. The DSL is separated into two sub-languages, tailored for business and technical experts.

Contribution III:
Incremental development of domain-specific languages

To support the stakeholders (*Contribution II*), the development of model-driven DSLs must deal with permanent changing requirements. To avoid complex and time-consuming updates in later development stages, we present an incremental development approach. Within the case study, we have researched (1) the applicability of the incremental approach, (2) the impact of requirement changes in later development stages, (3) possible drawbacks of using a non-incremental development approach, and (4) general recommendations for developing model-driven DSLs incrementally. We present the

findings during the development of the a model-driven DSL within the case study to contribute to *Research Question III*.

Contribution IV:
Applying the aforementioned contributions to extend an existing service-oriented system to QOS*-awareness*

To answer *Research Question IV* we use the aforementioned contributions to extend an existing service-oriented system to monitor the SLAs' performance-related QOS agreements. First, we utilize the architectural design decision model (*Contribution I*) to design an appropriate QOS monitoring infrastructure. To support the stakeholders (*Contribution II*), we integrate our developed model-driven DSL for specifying the SLAs' performance-related QOS compliance concerns. Based on the QOS specifications, the DSL's code generator generates executable code for measuring, storing, and evaluating the performance-related QOS properties. We demonstrate how we integrate QOS monitoring infrastructure into the existing service-oriented system.

1.5 Organization of the Thesis

In this section we give a brief overview of the thesis' structure, its chapters, and the chapters' contributions.

Chapter 2: Background
We explain the required background knowledge for a better understanding of the contributions in this chapter. We explain what web services and SOAs are, and give more detail information about SLAs and performance-related QOS properties.

Chapter 3: A Case Study
In this chapter we present a case study that builds the foundation to evaluate the thesis' contributions. The case study deals with advanced multimedia services, making it possible to watch movies or live streams in a favoured language. The services must comply to performance-related QOS agreements that are explained within the chapter.

Chapter 4: An Architectural Decisions Model to Design a QOS Monitoring Infrastructure
We present an architectural design decision model in this chapter that builds the first contribution of the thesis. The model consists of architectural design decisions that must be faced during the decision making process, such as where to measure, evaluate, or store the performance-related QOS properties. We list the model's requirements on a QOS monitoring infrastructure and present our model's architectural solutions to measure, evaluate, and store the performance-related QOS agreements in this chapter.

The solutions utilize and extend well-established design patterns. We present how we have utilized the model's proposed solutions in the scope of the case study.

Chapter 5: Supporting the Stakeholders to Specify QOS Compliance Concerns
In this chapter we present the thesis' third contributions, i.e., our approach to support the stakeholders with model-driven DSLs. We evaluate the approach with an explorative study over three experiments. The utilization of the approach is demonstrated on a developed DSL within the case study.

Chapter 6: Incremental Development of Model-driven DSLs
In Chapter 6 we introduce an incremental development approach to develop model-driven DSLs. We have researched the approach in the scope of the case study and present the findings during the development of the case study's DSL.

Chapter 7: Extending a Process-driven SOA to QOS-awareness
We take the thesis' first and second contribution to extend an existing process-driven SOA to monitor performance-related QOS agreements. We illustrate how to monitor QOS and how to support the stakeholders to specify the services' performance-related QOS compliance concerns.

Chapter 8: Conclusion
In this chapter we conclude the thesis by iterating the thesis' research questions and contributions. We also present potential future research in Chapter 8.

Chapter 2

Background

In this chapter we explain background information for a better understanding of the concepts and approaches presented in the thesis. We organize the chapter as follows: We start with a basic introduction to service-oriented distributed systems in Section 2.1, including web services, Service-oriented Architecture (SOA), and process-driven SOAs. In Section 2.2 we give basic background information on Service Level Agreement (SLA) and the performance-related Quality of Service (QOS) properties that are of interest in the thesis. We briefly summarize the chapter in Section 2.3.

2.1 Service-oriented Distributed Systems

In traditional distributed systems, a conventional middleware resides between interacting clients or applications and mediates their interaction. The middleware is centralized in an organization's distributed system and used by every client or application. Should the organization's clients or applications wish to interact with clients or applications of another organization, both organizations must agree on a common middleware [4].

Web services tackle this problem by using a program to invoke services that are located across the organizations' borders. A web service is a *procedure, method, or object with a stable, published interface*. Web services can be invoked by exchanging XML-based messages via Internet-based protocols [130]. Three XML-based standards have been proposed: (1) the Web Service Description Language (WSDL) [126] for describing the services' interfaces, (2) Universal Description, Discovery, and Integration (UDDI) [75] for advertising and discovering services, and (3) the Simple Object Access Protocol (SOAP) [125] for invoking services [45]. For the communication between services

Service-oriented Computing (SOC) is paradigm to utilize services as the basic constructs to support the development of compositions of distributed applications. In the field of SOC, an SOA is build to develop cross-organizational distributed systems [4, 89]. In an SOA, all functions and services, are defined using a description language and have invokeable, platform-independent interfaces that are

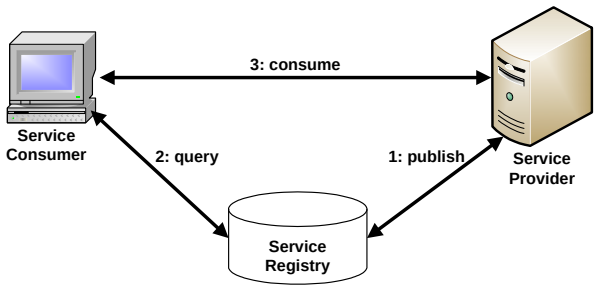


Figure 2.1: The SOA triangle

called to perform business processes.

We illustrate in Figure 2.1 the SOA's main components and the relationships between them. A *service provider* is an organization that offers accessible services to consumers. Service providers publish their services' information into a *service registry*, such as UDDI [75]. The service registry is a database that contains information of the accessible services in an XML-based format, such as WSDL [126]. A *service consumer* searches services in the service registry. After finding an appropriate service, the service consumer can invoke the service using a widely accepted standard, such as SOAP [125]. Some characteristics of services are:

- *Heterogeneity of Technologies*
  The technologies of the implemented service consumer's client and the service provider's service can differ, making it possible that, for example, for a .NET client to call a Java service.

- *Loosely coupled*
  Loosely coupled in the area of services means that service consumers and service providers do not have any knowledge about the others internal structure and context [4].

- *Location transparency*
  The service consumer and the service provider do not have any knowledge about the others location. The service consumer does not know at which location the invoked service resides. The service provider does not know from which location the service consumer is invoking the service.

SOAs are typically realized as layered architectures [39]. Based on a communication layer, which abstracts from platform and communication protocol details, a remoting layer provides the typical functionalities of distributed object frameworks, such as request handling, request adaptation, and invocation. Service clients invoke service providers using this infrastructure. In a *process-driven* SOA, a service composition layer is provided on top of a remoting layer. The composition layer provides

a process engine (or workflow engine) that orchestrates the services in the remoting layer to realize individual activities in a business process.

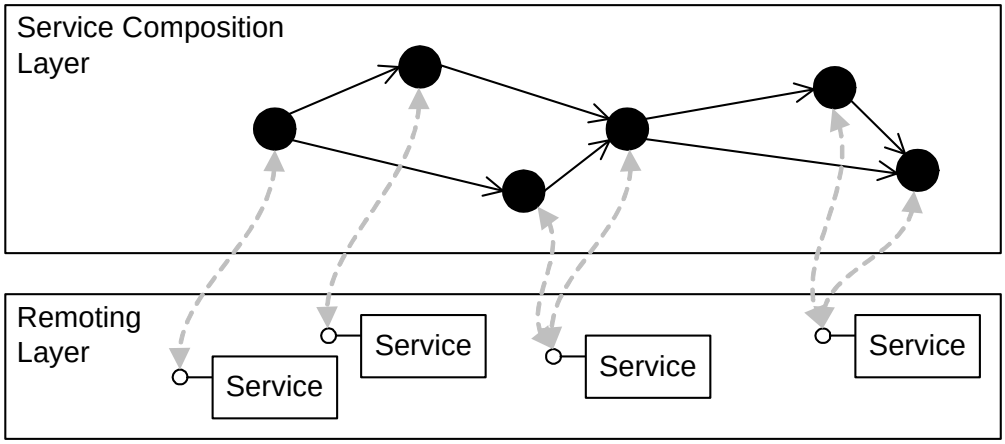


Figure 2.2: A process-driven SOA

We illustrate a the composition and remoting layers of a process-driven SOA in Figure 2.2. Services reside in the remoting layer and offer interfaces to describe their invokable operations. In the composition layer, the service invocations are orchestrated to perform business processes. The main goal of a process-driven SOA is to increase the productivity, efficiency, and flexibility of an organization via process management. This is achieved by aligning the high-level business processes with the applications supported by IT. Changes in business requirements are carried out as changes in the high-level business processes. The processes are implemented by linking their activities to existing or new IT-supported applications. Organizational flexibility can be achieved because explicit business process models are easier to change and evolve than hard-coded business processes. In the long run, the goal is to enable business process improvement through IT.

2.2 Service Level Agreements (SLA)

SLAs are contracts between service providers and service consumers which assure that service consumers get the service they paid for and that the service fulfils the SLAs requirements. In our work, we consider SLA clauses of agreements about the services' performance-related QoS properties (see Section 2.2.1). An SLA describes technical and nontechnical characteristics of a service, including the services' performance-related QoS properties [45, 56, 99].

Typically, SLAs are defined over a specific time period [34, 45, 56]. For a service provider it could result in serious financial consequences in case of violating the SLAs [81]. It is therefor important to monitor the negotiated SLAs' performance-related QoS properties and to enforce the services' quality during the SLA's validity [86]. A service consumer wants to know if the service provider delivered the

service quality as negotiated in the SLAs. This is mainly of importance after the SLA's validity.

2.2.1 Performance-related QoS Properties

A service's performance-related QOS attributes are non-functional properties of the service's performance [85]. Service consumers invoke services over the Internet, making it challenging to deliver the service's quality because of the Internet's dynamic and unpredictable nature [63].

Reported in the literature are many performance-related QOS properties that can be measured and monitored in a service-oriented system [86, 93, 98, 133]. Within the service consumer's network, clients invoke services that reside in the service provider's network and that are hosted on servers. A server can host multiple services. In Figure 2.3 we show the basics of some existing remoting middlewares, such as in web services frameworks like Apache CXF [115] or Apache Axis2 [114]. The invocation data, between the client and the service, flows in the middleware through so-called chains. A client and a server have an incoming and an outgoing chain – `IN Chain` and `OUT Chain` in Figure 2.3 – which are responsible for processing the incoming requests and the outgoing responses, respectively. Chains consist of multiple phases, making it possible to specify precisely where to hook INVOCATION INTERCEPTORS into the invocation path.

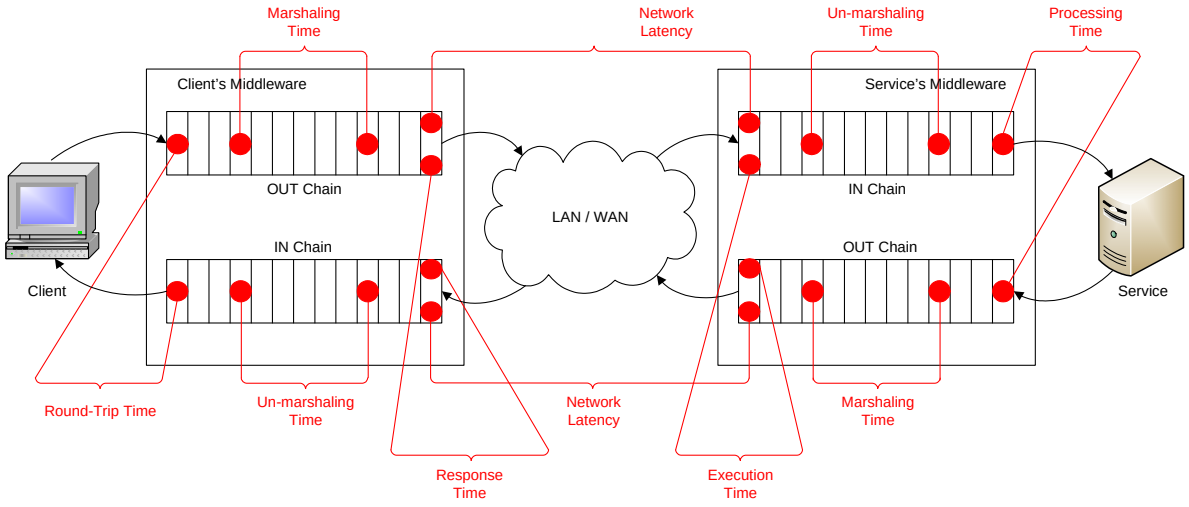


Figure 2.3: Measuring points of performance-related QOS concerns

In this work, we differentiate between negotiable, network-specific, and provider-relevant performance-related QoS properties. Negotiable QoS properties are agreed within the SLAs. Mostly, SLAs do not contain agreements about network-specific QoS properties, but, they are measurable and can be used to identify bottle-necks of long-running service invocations. Provider-relevant performance-related QOS properties give information about what the service provider's IT

infrastructure can deliver, such as how many clients can invoke the service simultaneously.

Negotiable performance-related QoS properties

- *Round-Trip Time*
  For a service consumer, it is important to know how long it takes to receive the requested data or results from the service. The elapsed time between the sending of the client's request and receiving the service's response is referred to the service's round-trip time.

- *Processing Time*
  On the server-side the processing time is the elapsed time for processing the client's incoming request. It does not take into account the performance-related QoS properties of processing the incoming requests and outgoing response in the underlying middleware.

- *Response Time*
  The response time is a client-side QoS property and measures the elapsed time between transmitting the marshaled invocation data to the server and the reception of the server's response. In the terminology of SLAs, the response time often refers to the elapsed time of responding to a problem in case the service is down.

- *Up-Time*
  In the literature, a service's up-time is often referred as the service's availability (e.g., [63, 85, 97]). However, using the term "availability" can lead to misunderstandings between a service provider and a service consumer [119]. For example, for the service consumer a service is available if it is accessible. But, for a service provider, a service is available if it is operating. To avoid misunderstandings, we define a service's up-time that the service is being up and running and returning correct results to the service consumers. The correctness of the results does not refer to the content of the results In comparison, Mani and Nagarajan [63] use the term "Accessibility".

Network-specific performance-related QoS properties

- *Marshaling Time*
  The invocation data must be marshaled for its transmission over the underlying network. At the client-side, the marshaling time measures the elapsed time of marshaling the outgoing invocation data of the service request. At the server-side, the marshaling time measures the elapsed time of marshaling the invocation data of the service's response.

- *Execution Time*
  The execution time is a server-side QOS property. It is a measure of the complete required time of a client's request, i.e., unmarshaling, processing, and marshaling.

- *Network Latency*
  The required time for transmitting the marshaled invocation data over the network is called network latency. It requires measuring points at the client- and the server-side. Network latency can be measured during the sending of the client's request and its reception at the server-side. Also, network latency is the elapsed time of transmitting the marshaled service's response from the service to the client over the network.

- *Un-marshaling Time*
  The marshaled invocation data must be un-marshaled to be process-able in the overlying layers. At the server-side, the un-marshaling time measures the elapsed time of un-marshaling the incoming invocation data of the service request. At the client-side, the un-marshaling time measures the elapsed time of un-marshaling the invocation data of the service's response.

Provider-relevant QoS properties

- *Throughput*
  The throughput is the number of successfully processed service requests within a given period of time.

- *Scalability*
  When the system is changing in size or in volume, a service must deliver its functionality without influencing the service's performance-related QOS properties quality attributes. Scalability is a performance-related QOS property that gives information about how an increasing number of service consumers impact the service's performance.

- *Robustness*
  A service's robustness is a measurement of the probability that a service can react properly to invalid, incomplete, or conflicting incoming requests. Rosenberg et al. [98] advice to measure the robustness by "tracking all the incorrect input messages and put it in relation with all valid responses".

2.3 Summary

In this chapter we gave some background information on web services, SOAs, process-driven SOAs, as well as SLAs and performance-related QOS properties in service-oriented systems. The concepts explained are helpful for a better understanding of the following chapters and the contributions of the thesis.

Chapter 3

A Case Study

In this chapter we present an industrial case study that we conducted within an European research project. The case study builds the basis for the contributions of this thesis as well as for the evaluation of the thesis' contributions.

The chapter is organized as follows: In Section 3.1 we describe the case study's scenario, exemplify it, and describe the case study's services. Section 3.2 concentrates on the services' Quality of Service (QOS) compliance concerns. We explain the case study's context and main development requirements in Section 3.3. The chapter concludes with a brief summary in Section 3.4.

3.1 The Case Study's Scenario

The case study's scenario focuses on advanced telecom services offered by Mobile Virtual Network Operator (MVNO). Such services combine value-added application capabilities with the Internet and Next Generation Mobile Telecommunication Network capabilities. All these capabilities are integrated by the MVNO's services to provide combinations of controls for calls and sessions, messaging features, presence, and location features, multimedia content streaming, or parental monitoring. An MVNO serves as a proxy between customers and the audio and video streaming providers. It offers services to processes media search requests and to provide favoured movie and audio content streaming, making it possible for the customers to watch, for example, live soccer matches with a selected audio commentary language.

The MVNO environment is particularly challenging, because the network infrastructure and many applications are owned and managed by different enterprises (i.e., the MVNO, the network providers, and third-party application providers).

3.1.1 An Example Scenario

For a better understanding of the case study's scenario, we present an example in this section. In Figure 3.1 we illustrate an example process of the MVNO case study.

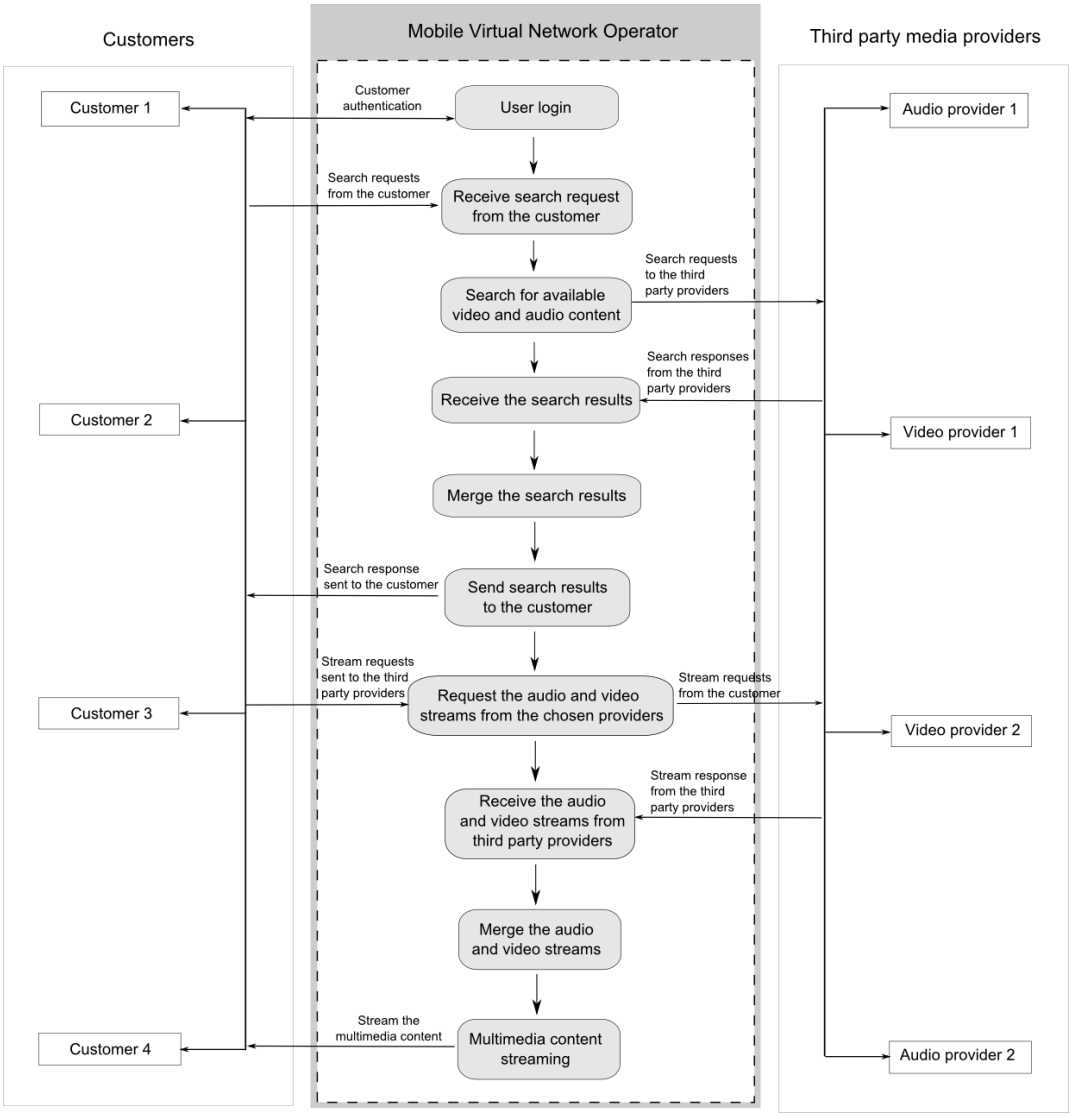


Figure 3.1: An example scenario of the MVNO case study

The MVNO is the service provider and offers services with on-demand audio and video streaming content to its customer. First, a service customer must login into the system to order to access the services that offer the MVNO's audio and video streaming features. After a successful authentication, service customers can search desired video streams in a favoured language by invoking the MVNO's search web service. Then, the MVNO invokes the web services of its audio and video providers to fulfill

the service customer's request. The MVNO receives the responses from the audio and video providers, assembles them, and returns a list of possible streaming endpoints to the customer. The customer starts the multimedia streaming by selecting one endpoint.

3.1.2 The Case Study's Services

In Table 3.1 we explain the offered services by the MVNO enterprise that the MVNO's customers can invoke.

Service	**Description**
Login	This service authenticates the customers to access the multimedia system
Search	This service offers the functionality of searching movies or live-streams in a favoured language
Stream	This service streams the selected movie or live-stream in the selected language to the customer

Table 3.1: The MVNO's offered services

The key features of the case study are that the services have to comply with particular QOS concerns. Within the scope of this case study, the service provider is required to fulfill various performance-related QOS compliance concerns. We list the QOS compliance concerns in the next section.

3.2 The Case Study's QoS Compliance Concerns

QoS Compliance Concerns	**Description**
UP-Time	The probability that the service S is running and answering queries. The probability can be computed based on a time interval `[i..j]`.
Processing Time	The maximum needed time for processing one client's requests.
Delivery Rate	The calculated percentage of choices whose streams can be delivered. The rate can be computed based on a time interval `[i..j]`
Minimal Frame Rate	The required number of delivered frames per second for streaming multimedia content.

Table 3.2: QOS compliance concerns

It is crucial for the MVNO to check and avoid any potential violations with regard to the services offered to the customers, as well as to detect any performance drops in the third party media providers'

services. The terms and conditions of the offered services (see Table 3.1) are regulated by appropriate Service Level Agreements (SLAs) negotiated between the MVNO and the customer as well as between the audio and video providers and the MVNO enterprise. Thus, there are many QOS compliance concerns associated with the MVNO process and accompanying services, which have to be compliant with negotiated agreements. The MVNO's SLAs consist of various QOS requirements of the services. In Table 3.2 we list the required QOS compliance concerns within the case study. The QoS compliance concerns are associated with the listed MVNO services in Table 3.2.

The MVNO has to assure the services' quality. It is a non-trivial task as the MVNO's service quality usually depends on the service quality from third parties. All the services need to be up and running within a specified time interval, i.e., answering the customer's requests. The `Search` service needs to process the customers' queries in a negotiated time frame, i.e., the services' processing time. The `Stream` service needs to transmit the chosen video with a minimal required frame rate and has to meet a specified delivery rate.

3.3 The Case Study's Requirements

Within the case study, one requirement was to comply to the SLAs' negotiated QoS concerns using Model-driven Development (MDD) techniques. To fulfil this wide requirement of ensuring QOS compliance during the service-oriented systems's runtime, we had to design a QOS monitoring infrastructure first. We had to investigate a **simple and novel model** for designing a QOS monitoring infrastructure. Based on the model, we had to generate the source code of the QOS monitoring infrastructure automatically. Hence, it was important to identify the business and technical requirements in the simple and novel models.

To support the various differently skilled stakeholders within the case study, we had to investigate a **simple and novel language** for describing the case study's QOS compliance concerns. The case study's stakeholder expertise was ranging from business experts of the QOS domain to technical experts of web service frameworks. Hence, we had to develop a language based on the model to support the differently skilled stakeholders. The language had to offer functionalities for describing the QOS compliance concerns, to define particular actions to avoid violations of the QOS compliance concerns, as well as for describing the technological artifacts for monitoring QOS within the underlying used web service framework.

A final and important requirement of the case study was to follow an **iterative approach**. Within the iterative approach we had to refine the earlier work, as new progress was made.

3.4 Summary

In Chapter 3 we have explained an industrial case study that was conducted within an three-year European research project. The case study focuses on telecommunication services that have to fulfil QOS compliance concerns. We listed the case study's services, presented an example, listed the required QOS compliance concerns and explained the case study's main requirements. We use the case study for describing and evaluating the main contributions of this thesis.

Chapter 4

An Architectural Decisions Model to Design a QoS Monitoring Infrastructure

Designing a monitoring infrastructure is a challenging and comprehensive task. Many architectural design decisions must be taken about measuring, evaluating, and storing the performance-related QoS agreements [77]. To give some examples, performance monitoring can be realized at different network communication layers, either at the client-side, at the server-side, in intermediary components, or any combination of the latter.

In this chapter we present an architectural design decision model (*Contribution I*) that identifies relevant design decisions arising throughout the decision making process. The model aligns the design decisions to possible design solutions. The solutions, in turn, are based upon established design patterns in their solution space. The model guides you in selecting solutions according to the business and technical requirements imposed on your QoS monitoring infrastructure. Our model's design decisions, requirements, and solutions come from a thorough literature review of QoS monitoring frameworks, such as presented in [10, 15, 38, 48, 58, 68, 96, 98, 100, 139].

The presented architectural design decisions and solutions focus on preventing and detecting SLA violations. We document design practices and patterns of monitoring performance-related QoS properties, such as round-trip time, network latency, or processing time [86, 93, 98, 133]. We give advice in the decision making process for designing QoS-aware distributed systems. The background of this work are established patterns, presented in the Gang of Four (GOF) book [35], the Pattern-Oriented Software Architecture (POSA) series [18, 19, 103], and the Remoting Patterns book [124].

The chapter is organized as follows: In Section 4.1 we give background information on patterns itself and patterns in distributed systems. Section 4.2 explains the main components and features of a QoS monitoring infrastructure that are of interest. Then, in Section 4.3 we explain the requirements on a QoS monitoring infrastructure that have discovered within the case study and a thorough literature

review. The architectural design decision model is presented in 4.4, including several design decisions, requirements, and solutions. The relationships between the design decisions, influenced by the requirements, is illustrated in 4.5. In Section 4.6 we evaluate the architectural design decision model in the scope of the case study. A discussion of using Model-driven Development (MDD) to generate the architectural design solutions is given in Section 4.7. We summarize and conclude the chapter briefly with Section 4.8.

4.1 Background

In this section we explain required background knowledge for a better understanding of the chapter's contributions. First, we describe what patterns are and of which parts they consist. Then, we describe well-established patterns in distributed systems that build the foundation of the solutions proposed within the architectural design decision model.

4.1.1 Patterns

The Gang-of-Four [35] bases their defintion of a pattern on Christopher Alexander's definition [3]:

"Each pattern describes a problem which occurs over and over again in our environment. A pattern describes the core solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice."

The Hillside Group [22], the home of design patterns and the host of various pattern conferences, defines a design pattern as follows:

"A design pattern is a well-established design solution to a problem in a particular context"

Resultant from both definitions, each pattern consists of a *context*, a *problem*, and a *solution*. Every pattern has its *forces*, but, every pattern brings *consequences* as well. The well-established solution of a pattern is proven by the pattern's *known uses*.

- The pattern's *context* is the scope of the pattern's application area.
- The pattern's *problem* is the recurring design problem within the pattern's context. The pattern's problem states when to apply the pattern. The problem statement can contain various pre-conditions that must be met before the pattern's problem arises.
- The pattern's *solution* is a description of how to apply the pattern to solve the problem within the given context. The solution describes elements to make up the design, their relationships, responsibilities, and collaborations.

- The pattern's *forces* are the resultant strengths of applying the pattern for solving the problem. Forces describe the benefits of applying the pattern.
- The pattern's *consequences* are the trade-offs of applying the pattern for solving the problem. Consequences can also result in new arising problems.
- The pattern's *known uses* describe were the pattern is applied in the literature or in existing systems. The known uses are proofs of pattern's solution.

4.1.2 Patterns in Distributed Systems

Now, we introduce the patterns within distributed systems. The patterns described hereafter build the basis of our defined patterns. In Figure 4.1 we illustrate the typical activities within a distributed system when a client invokes some server's remote object.

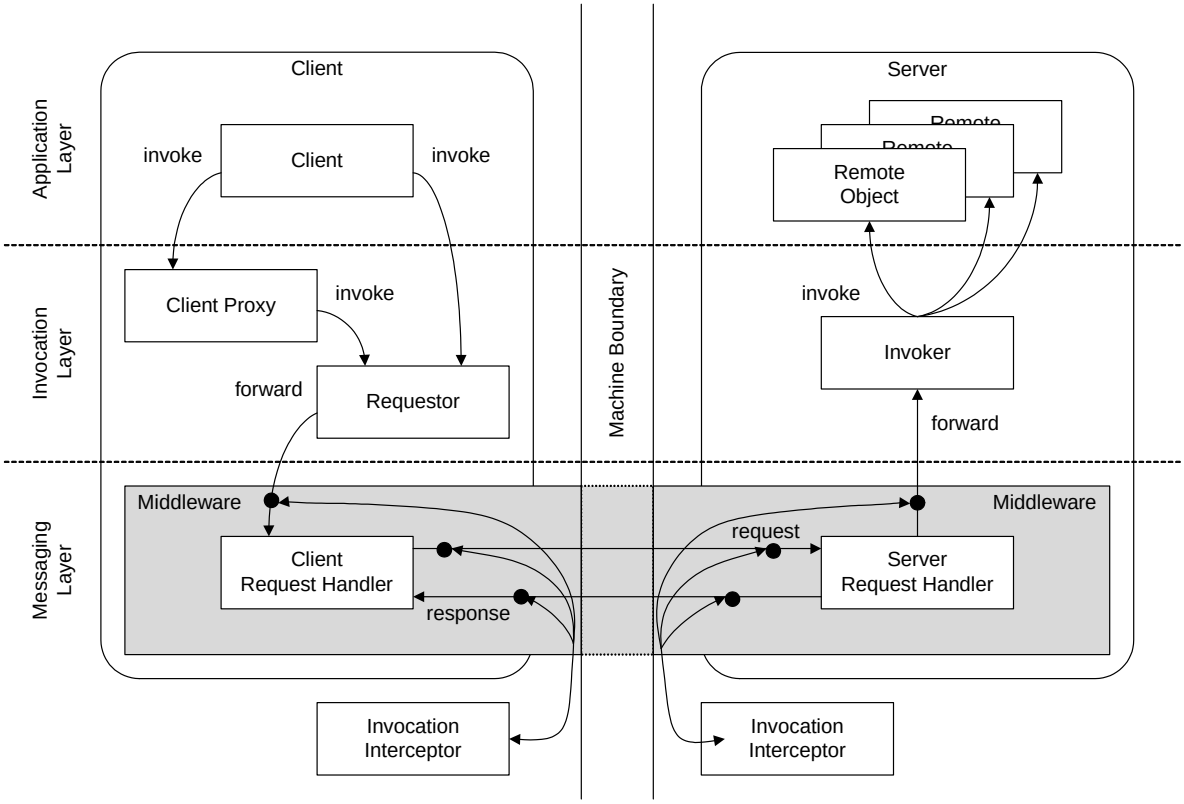


Figure 4.1: An overview of existing patterns in distributed systems

In distributed systems, a middleware manages the communication between the client and the server, hiding the heterogenity of the underlying platforms and providing transparency of the dis-

tributed communications. The middleware can access the network services offered by the operating system for accessing and transmitting requests to the server's remote objects over the network [124].

For accessing the client's middleware, the REQUESTOR pattern can be used [124]. The REQUESTOR invokes the remote object's operation using the underlying middleware. Also, the client's application can access the middleware following the CLIENT PROXY pattern [124] to provide a good separation of concerns and to attach additional information to the client's requests. The CLIENT PROXY invokes the middleware using the REQUESTOR pattern. The implementation of the client's middleware can follow the CLIENT REQUEST HANDLER pattern [124], to send the requests over the network to the server and to handle the server's response.

The implementation of the server's middleware can follow the SERVER REQUEST HANDLER pattern [124]. A SERVER REQUEST HANDLER receives the incoming requests, performs additional processing, and forwards the requests to the INVOKER of the remote objects. The INVOKER [124] receives the requests from the SERVER REQUEST HANDLER, can perform additional processing again, and dispatches the request to the corresponding remote object. After the remote object processed the incoming request it sends the response back to the INVOKER, which performs some additional processing, and forwards the response to the SERVER REQUEST HANDLER. The SERVER REQUEST HANDLER can perform again some additional processing and forwards the response to the requestor.

The INVOCATION INTERCEPTOR pattern [124], which is based on the INTERCEPTOR pattern [103], provides hooks in the invocation path to perform additionally required actions, such as logging or securing the invocation data. Mostly, the client's or server's middleware provides functionalities for placing INVOCATION INTERCEPTORS into the invocation path. Hence, an INVOCATION INTERCEPTOR can process and manipulate the available invocation data, which depends on the INVOCATION INTERCEPTOR's place in the invocation path. The middleware can provide the feature of attaching and changing an INVOCATION INTERCEPTOR dynamically during the runtime of the system, such as by using an API or configuration files. As a consequence, the INVOCATION INTERCEPTOR implies a higher complexity of the middleware's implementation. An INVOCATION INTERCEPTOR can attach the context-specific information to the INVOCATION CONTEXT [124] of the invocation data. In this paper, we assume the usage of the INVOCATION CONTEXT pattern for storing the performance-related QoS measurements during remote object invocations.

Client and server interactions can take place within a local area network (LAN) or over a wide area network (WAN), such as the Internet. If a client wants to invoke a remote object that is not located in the same LAN, the client request must be sent over a WAN to the corresponding remote object's LAN. In this case, inside the LAN a proxy server can be used, whose implementation follows the well-known PROXY pattern. Client and server can make use of the different PROXY patterns, such as such as CLIENT PROXY, VIRTUAL PROXY, and FIREWALL PROXY [19].

Figure 4.2 illustrates the usage of the PROXY pattern for implementing a web proxy. In this sce-

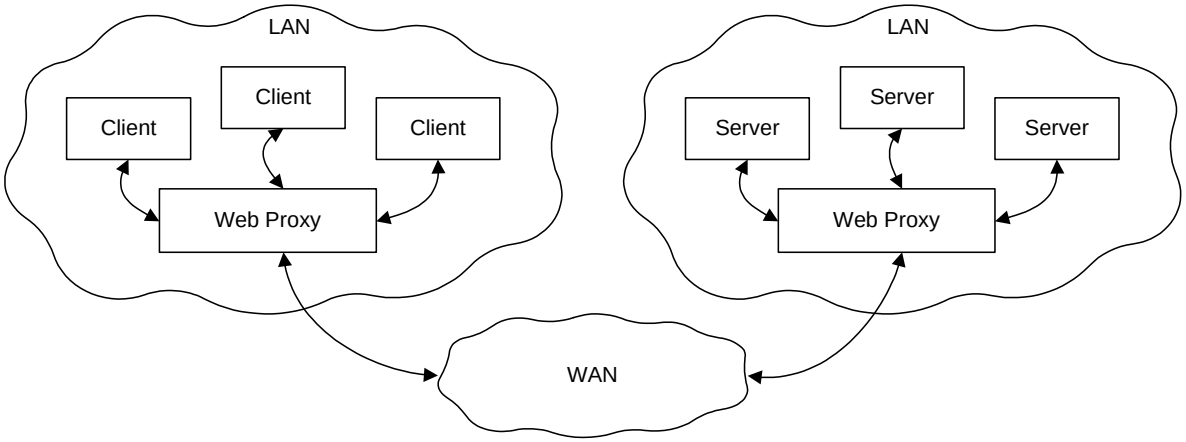


Figure 4.2: Using the WEB PROXY pattern

nario, every component – client, server, and web proxy – features some middleware that manages the network access. For accessing a remote object over a WAN, the client-side WEB PROXY receives the requests from the clients within the LAN. It applies additional processing to the client's request, marshals it, and sends it into the WAN. A server-side WEB PROXY receives requests over a WAN, unmarshals them, applies additional processing, and forwards it to the appropriate remote object in the same LAN. After the remote object's processing, the server-side WEB PROXY receives the response, marshals it, applies additional processing, and sends it back to the client-side requestor. The client-side WEB PROXY receives the server-side response, applies additional processing and forwards the response to the appropriate client.

4.2 Features of a QoS Monitoring Infrastructure

Infrastructures for quality-of-service monitoring are characterized by distinguishing features, with feature denoting a unit of functionality being of interest to the technical stakeholders of a QoS monitoring infrastructure. When evaluating and adopting a particular infrastructure design, a certain feature configuration is decided upon. The feature configurations obtainable are covered by our architectural design decision model. Figure 4.3 depicts commonalities and variations of QoS monitoring infrastructures in terms of a feature diagram, using the Extended Eisenecker-Czarnecki Notation [23]. As illustrated, there are three mandatory dimensions found in all performance monitoring infrastructures: MEASURING, EVALUATION, and STORAGE. In addition, some systems provide a REPORTING feature as an extension point.

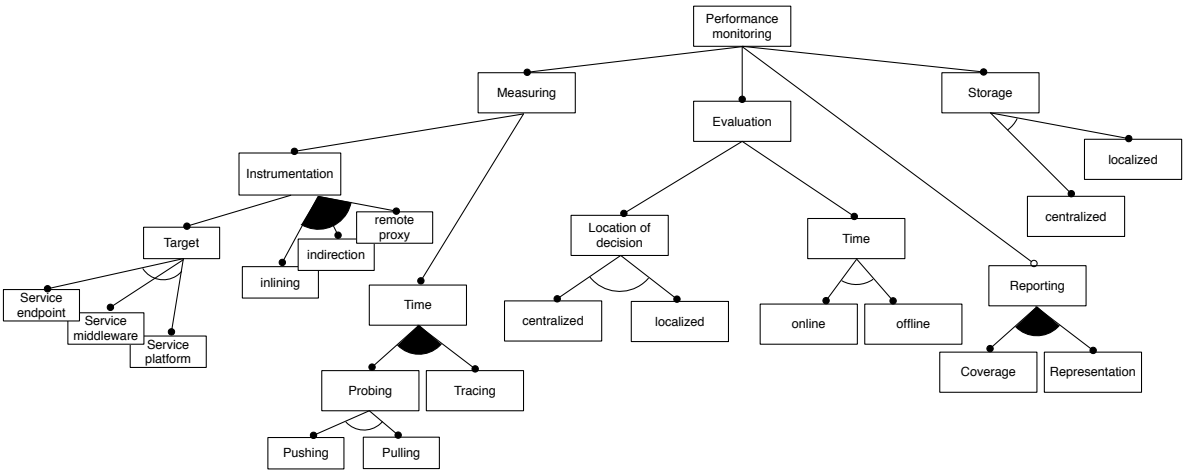


Figure 4.3: Features of a QoS monitoring infrastructure

MEASURING

There are multiple variants of measuring performance-related QoS properties in a service-oriented system. Most importantly, different strategies of instrumenting the system components for runtime and execution monitoring at various spots are available. System components can either be instrumented at the service endpoints (e.g., the client and service applications), at the level of the service middleware (e.g., a middleware framework such as Apache CXF or a WS process engine such as Apache ODE), or at the level of the service platforms, i.e. the execution environments of both the endpoint applications and the middleware frameworks (e.g., language engines such as a Java virtual machine). We can also classify the instrumentation location as either local or central. If measuring is limited to the service endpoints (and their middleware as well as platforms), we refer to *local* measuring points [63]. Service intermediaries such as business-process engines offer *central* measuring points.

As for instrumentation techniques, the following can be identified: inlining, indirection, and proxying. While some of these techniques are entirely independent of the kind of instrumentation target, certain techniques are only applied to specific targets. By inlining, we mean to implement measuring points by introducing dedicated measuring code into the client or service implementations directly. Alternatively, forms of indirection can be adopted. Variants of the COMPONENT WRAPPER pattern can be used to redirect instruction calls to some sort of measuring wrapper component by means of delegation, before forwarding the call to the actual receiver. At the level of language systems, forms of interception filters (e.g., AspectJ join points or command traces) can be used. Another level is instrumenting the language engine as such (e.g., the bytecode execution in a Java virtual machine such as method entries and method exits). Indirection at the level of the service middleware can be achieved by adopting an extension mechanism offered by middleware frameworks. For instance, INVOCATION INTERCEPTORS [124] offer predefined extension points along the path of invocation processing.

Looking at the service interactions, indirection can also be achieved by deploying service-level proxying within the service consumers' or service providers' networks. In such a setting, a REMOTE PROXY service responsible for measuring the QoS properties [124] trades service invocations on behalf of the actual service implementations.

As for the timing of measurement, measurements can either be piggybacked onto actual service invocations (*Tracing*) and/or a monitoring system allows to create mock-up invocations to perform the measurements without interfering with actual invocations (*Probing*). We refer to such invocations as *probes*. Probes are either generated and emitted on demand (*Pushing*), e.g., at regular intervals following a specified probing strategy, or triggered by certain system-wide events (*Pulling*).

EVALUATION

When designing a monitoring system, it must be decided on *when* (*Time*) and on *where* to evaluate performance-related QoS measurements (*Location of decsision*). As for the timing, SLA performance evaluation can either happen during the service (and therefore SLA) performance (*online*) or after the delivery of the service, i.e., after an SLA's duraction of validity. While offline evaluation satisfies the requirements emerging from SLA accounting and reporting, online evaluation enables scenarios of preventing SLA violations as part of the SLA management.

Another important variation in monitoring systems results from organising the evaluation feature in a *centralized* or in a *localized* manner. A centralized evaluation is performed by a central evaluation component, responsible for all clients and services in a service-oriented system. For instance, a business-process execution engine may be extended to perform the role of the evaluation component. Adopting a centralized evaluation has important implications. For instance, centralized evaluations can be performed faster because the performance-related QoS measurements must not be collected from each client or service. However, the clients and/or services have to submit the performance-related QoS measurements over the network to the centralized evaluation component.

Localized evaluation re-locates the responsibility of performing evaluations at each of the service endpoints, i.e., both service clients and service providers. While localizing evaluations avoids introducing a single point of failure, the evaluation overhead potentially affects the actual activities performed by clients and providers in a negative manner. A particular performance overhead is incurred if predictive SLA monitoring is performed and if multiple clients and services are become subject to monitoring. Also, evaluating SLA performance based on aggregated measurements from a system-wide (global) perspective is hindered.

STORAGE

The monitoring data can be stored locally or centrally. Storing the measurements locally implies that the evaluation becomes more complex in case the SLAs are defined for multiple clients or services.

Storing the QoS measurements centrally facilitates the operation of a central evaluation component, however, the time-to-response of the monitoring system in case of SLA violations is degraded because the clients and the services must store the their data into a centralized storage over the network.

REPORTING *(optional)*
Feature-complete and production-grade QoS monitoring systems offer a *Reporting* feature for presenting QoS evaluation results to the stakeholders, for instance, to the finance department for billing, to the engineers for diagnosing and planning, or directly to the service consumers [119]. A possible solution to report the QoS monitoring results is a web-based dashboard, as described in [105]. While do not fully cover issues pertaining to such a reporting feature in the scope of this paper, we review selected technical aspects, especially the choice of *Representation* (e.g., processable report formats, UI-based reporting, notification schemes) and *Coverage* (i.e., the range of reported details and the level of granularity). Many of the architectural design decisions documented in this paper directly affect the design decision process for reporting and violation management components.

4.3 Requirements on a QoS monitoring infrastructure

In this section, we explain the criteria driving the decision-find process and the various requirements imposed on a QoS monitoring infrastructure. Both, criteria and requirements, influence the architectural design decision and the selection of an appropriate solution. In our model, we differentiate in our model between decision criteria, system-specific, and implementation-specific requirements. Criteria are characteristics that must be known a-priori to making any design decisions, such as whether services are provided or whether the provided services invoke services of some third party providers. System-specific requirements concentrate on the general requirements on the QoS monitoring infrastructure and its architecture. At this level, technical details regarding the implementation of the QoS monitoring infrastructure are omitted. For example, system-specific requirements are scalability or reusability. Implementation-specific requirements focus on realizing the components forming the QoS monitoring infrastructure. For instance, a given scenario might require access to the clients' or services' implementations.

In Figure 4.4, we illustrate how the requirements influence themselves. For example, requiring a QoS monitoring infrastructure that has a minimal performance overhead induces to design a scalable QoS monitoring infrastructure. Understanding the interrelatedness of requirements helps to comprehend the relationships between the architectural design decisions. In the following, we elaborate on the decision criteria, system-specific, and implementation-specific requirements, as well as their influences.

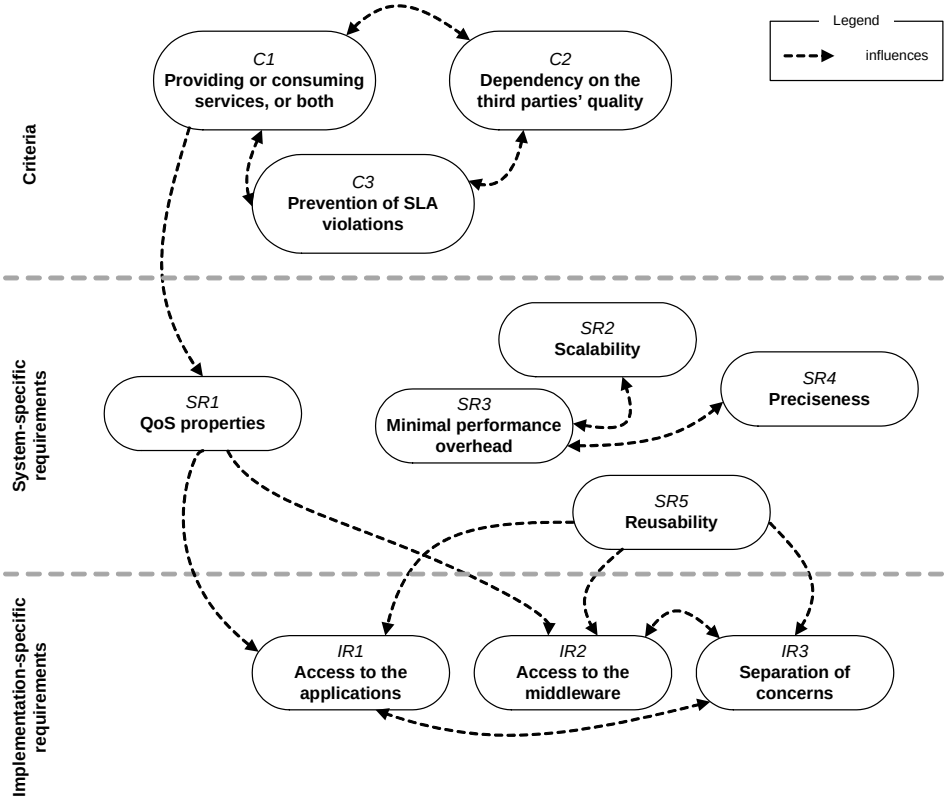


Figure 4.4: Influences between the criteria and requirements

4.3.1 Decision criteria

- C_1 – **Providing or consuming services**
  This criterion considers whether the decision-taking party plans to provide or to consume services; or even both. While in a service-oriented system, a provider and consumer roles can be strictly separated, a service provider can also act as a consumer towards third party services.

  The criterion is related to the decision whether it becomes necessary to either detect or prevent SLA violations (C_3). For a service provider, it is desirable to prevent SLA violations during the SLA's validity in order to avoid financial consequences and a diminished reputation. In contrast, a service consumer wants to detect potential SLA violations under a ruling SLA. Detecting and reporting violations is also a use case when the performance quality delivered by a service provider is directly dependent on third party providers. With this, the criteria on providing or consuming services also is affected by the criterion C_2.

- C_2 – **Dependency on the third parties' quality**
  In service-oriented systems, service providers often invoke third party services to accomplish their services' functionality. As a result and as illustrated in the motivating example (see Section 1.2), the services' quality so become dependent on the quality of some third parties' services. In order to avoid SLA violations, an appropriate QoS monitoring solution must be designed to take appropriate actions well-timed in case the performance of the third parties' services degrades.

  Third party dependencies bear the risk of SLA inversions and generally limit a service providers capacity to commit to a high-performance SLA. Provided that there are no adequate monitoring facilities and the SLA details are not carefully crafted (e.g., by excluding features directly coupled to third party performance from the SLA), a provider's SLA can only pass on whatever the respective third-party SLAs offer, degraded by the provider's non-fulfillment probability. Regarding the risk of SLA inversion, a monitoring infrastructure assists at detecting the non-fulfillment by third-party providers.

  If relying on third party services, a service provider takes the role of a service consumer. With this, this criterion leads to C_1 and, as a consequence, to C_3.

- C_3 – **Prevention of SLA violations**
  Prior to entering the decision making process, it must be decided if the QoS monitoring infrastructure should prevent or just detect SLA violations. This criterion results from criteria C_1 and C_2. For a service consumer it is maybe enough just to detect SLA violations. For example, in the motivating scenario, a detection of SLA violations for the service consumer is sufficient. But, for the service provider, only a detection of SLA violations is not satisfactory. For service providers it is desirable to prevent SLA violations in order to avoid financial consequences. This criterion results from criteria C_1. In contrast to detecting violations, preventing SLA violations has the benefit for the service-providing parties to effectively avoid any SLA violations. However, developing a preventive QoS monitoring solution is a complex design and development task. Note that, in our model, preventing SLA violations implies the capacity to detect them.

4.3.2 System-specific Requirements

System-specific requirements are requirements on the QoS monitoring infrastructure independent of the implementation. In our model, we consider the following system-specific requirements:

- SR_1 – **QoS properties**
  To measure the performance-related QoS properties, it is necessary to know which of the service performance indicators are negotiated in the underlying SLA. Typically, SLAs do not cover all measurable performance-related QoS properties. For example, for a service consumer the

service provider's message processing time (at the level of communication middleware) is not of interest. Rather, a service consumer is more concerned about the services' *round-trip time* or *time-to-response*.

Nevertheless, from the perspective of the service provider, it is necessary to measure the network-specific performance-related QoS properties as well in order to detect bottlenecks in long running service invocations.

After having decided whether to adopt a provider-side and/or consumer-side QoS monitoring solution (C_1), the selection of performance-related QoS properties to gather and to measure is next. Once the performance-related QoS properties and the measure instruments are decided upon, it becomes clear if and which kind of implementation-level access is required. Implementation-level access refers to either the provider- and/or client-side service implementations (IR_1) or even the provider- and client-side middleware implementations (IR_2); or even both.

- SR_2 – **Scalability**
  SLAs are contracts between one service provider and one service consumer. But, a service providers can have same SLAs negotiated with multiple service consumers. Service consumers itself can have various SLAs negotiated with different service providers. Hence, many SLAs must be monitored and tracked. Providing many SLA-aware services to many consumers implies that the consumers can invoke the service in parallel, requiring to monitor the performance-related QoS agreements of each service invocation. As a result, the QoS monitoring infrastructure should scale to a variable number of service clients and services provided. Scalability involves both up- and down-scaling. If the number of SLA-governed services and clients to monitor increases, the monitoring infrastructure must adapt and must guarantee availability. A decreasing number, however, should result in freeing system resources dedicated to monitoring tasks. The latter is particularly important when SLA monitoring is realised as a third-party service.

  The property of scalability, in particular up-scaling, is directly affected by the performance overhead incurred by monitoring invocations (SR_3). A highly scalable monitoring system implies a minimal performance overhead.

- SR_3 – **Minimal performance overhead**
  A further requirement is that the QoS monitoring solution does not introduce critical performance overhead into to distributed system. The monitoring of service execution introduces an INDIRECTION LAYER [11] into the distributed system because the implementations of the client and service applications must be instrumented to gather data related to executing remote invocations (e.g., by intercepting method invocations, message delivery, marshalling, etc. to gather

execution timings) and related to network I/O (e.g., latency). It is not desirable that the execution performance of the overall system degrades due to monitoring the performance-related QoS properties. The requirement on minimal performance overhead is strong coupled with the scalability requirement (SR_2): the lower the performance overhead, the more scalable the QoS monitoring system.

The overhead affects the scalability of a monitoring system (SR_2). The higher the overhead, the more imprecise are the performance-related QoS measurements (IR_4). This again results in imprecise evaluation results. High performance overhead can imply SLA violations. For example, in case a centralized evaluation component becomes overloaded it can influence the systems' performance, resulting that the processing of some clients' requests lasts longer as expected.

- SR_4 – **Preciseness**
  The preciseness criterion relates to the rigor and validity of the performance-related QoS measurements and the evaluation results. Imprecise measurements cause imprecise evaluation results and, as a consequence, false positives and false negatives in detecting SLA violations. Monitoring tasks such as measuring, evaluating, and storing should not distort the actual measurements. Most importantly, preciseness follows from minimising the indirection ovehead (SR_3).

- SR_5 – **Reusability**
  The QoS monitoring solution is required to be reusable in the heterogeneous software landscape which constitutes a service-oriented system. By reusability, we refer to the ability to deploy QoS monitoring for potentially diverse clients and services. This diversity results from various implementation platforms and middleware frameworks used.

  As a consequence, there is a major tension between reusability and the need to access and to instrument the service and the middleware implementations (IR_1, IR_2). A reusable monitoring system must respect a separation of concerns (IR_3), in particular by separating those monitoring concerns (storing, evaluation) from those which require platform- and implementation-specific adaptation (sensoring).

4.3.3 Implementation-specific Requirements

Implementation-specific requirements focus on the implementation of the QoS monitoring infrastructure's components. We identified the following implementation-specific requirements:

- IR_1 – **Access to the service and client applications**
  Monitoring performance-related QoS properties of service invocations often requires access to

the client's or service's implementation, in particular to apply certain measurement strategies. For example, to measure the *round-trip time* of a service invocation in the client, measuring points can be placed directly into the client's implementation. To measure the *processing time*, measuring points can be placed directly into the implementation of a service.

This requirement conflicts with a separation of concerns (IR_3) and has the potential to decrease the reusability (SR_5) of a monitoring system.

- IR_2 – **Access to the middleware implementation**
  For monitoring network-specific performance properties, such as the marshalling time, access to the middleware is required. The middleware must be adapted to measure the required network-specific performance-related QoS properties. Middleware frameworks offer different strategies for extending and intercepting the processing of invocations (e.g., INVOCATION INTERCEPTORS [124]).

  Before the kind of adaptation and any modification of the middleware framework can be decided upon, it must be clarified which kind of measurement probes are required (SR_1). Only then, it can be decided at which interception points certain processing steps are to be metered. Measuring the performance-related QoS properties by accessing the middleware improves over the separation of concerns (IR_3) because the measuring logic is decoupled from the services' or clients' implementations.

- IR_3 – **Separation of concerns**
  A monitoring solution must exhibit an overall state of separation of concerns. Multiple criteria contribute to this objective. First, a monitoring system must not modify the clients' or services' implementations in order to monitor the performance-related QoS agreements (IR_1). With this, there is a certain level of transparency because the monitoring solution is decoupled from the clients' and services' implementation. Monitoring solutions which realise their measurement sensors at the level of the middleware contribute to concern separation (IR_2). Separating concerns directly affects the system's reusability (SR_5) implementation-specific requirements.

4.4 Architectural Design Decision Model for Designing a QoS Monitoring Infrastructure

In this section, we describe our model of architectural design decisions for designing an appropriate QoS monitoring infrastructure. We present the requirements on a QoS monitoring infrastructure, architectural design decisions, and options. Requirements reflect an organization's business and technical requirements, such as a prevention of SLA violations is necessary. Architectural design decisions are questions that arise during the design process, such as where to measure to performance-related QoS

properties in the clients or services. Options provide solutions for an architectural design decision, dependent on the requirements.

We describe for each architectural design decisions the requirements and proposed solutions. The proposed solutions are based on patterns [35] that are well-established solutions to a problem in a certain context. We describe for each pattern its forces and consequences.

4.4.1 Design Decision: WHICH SLA PARTY NEEDS QOS MONITORING?

First, it must be decided if a service provider or a service consumer wants to introduce a QoS monitoring solution. In our model, this architectural design decision is the first of the decision making process.

We illustrate in Figure 4.5 the model's solutions for this design decision that is influenced by the requirement if services are provided or consumed. Our model provides three different architectural decision options — SERVICE PROVIDER QOS MONITORING, SERVICE CONSUMER QOS MONITORING, and COMBINED QOS MONITORING.

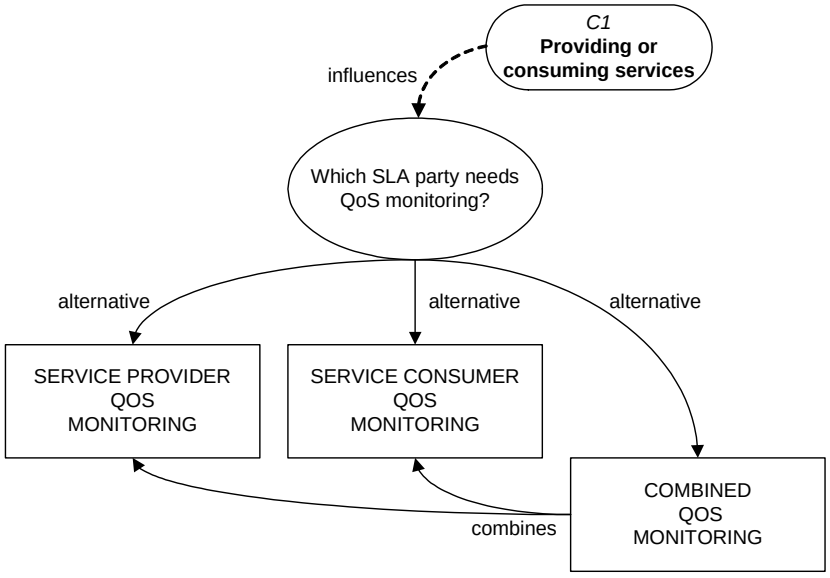


Figure 4.5: WHICH SLA PARTY NEEDS QOS MONITORING?

Solution: SERVICE PROVIDER QOS MONITORING

Integrate a QoS monitoring infrastructure into the service provider's network.

❖ ❖ ❖

In case of providing services, our model proposes a SERVICE PROVIDER QOS MONITORING solution. A SERVICE PROVIDER QOS MONITORING solution makes it possible to measure server-side performance-related QoS properties. Client-side performance-related QoS properties can not be measured.

Known Uses:

- Windows Performance Counters (WPC) [73] of the the Windows Communication Foundation (WCF) [72] can be utilized to perform server-side QoS monitoring. WPCs are part of the .NET framework [70].
- Mani and Nagarajan [63] explain the measuring of performance-related QoS properties within a client's implementation.

Solution: CLIENT-SIDE QOS MONITORING

Integrate a QoS monitoring infrastructure into the service consumer's network.

❖ ❖ ❖

In case of consuming services, our model proposes a SERVICE CONSUMER QOS MONITORING solution. A SERVICE CONSUMER QOS MONITORING solution makes it possible to measure client-side performance-related QoS properties. Server-side performance-related QoS properties can not be measured.

Known Uses:

- Rosenberg [96] developed a SERVICE PROVIDER QOS MONITORING solution, called QUATSCH. The performance-related QoS properties are measured during probe service requests.

Solution: COMBINED QOS MONITORING

Integrate a common QoS monitoring infrastructure into the service consumer's and service provider's network. Measure the performance-related QoS properties in both networks and combine both measurements to evaluate the performance-related agreements.

❖ ❖ ❖

In case service provider and service consumer agree on a common QoS monitoring infrastructure, a COMBINED QOS MONITORING solution is proposed. As illustrated in Figure 4.5, a COMBINED QOS MONITORING solution combines the SERVICE PROVIDER QOS MONITORING and SERVICE CONSUMER QOS MONITORING solutions. This solution makes it possible to measure client- and server-side performance-related QoS properties.

Known Uses:

- Michlmayr et al. [67] present a combined monitoring solution, requiring access to the clients' and services' implementation.
- Sahai et al. [100] introduce an SLA monitoring engine with two monitoring components. One in the service provider's network and one in the service consumer's network.

4.4.2 Design Decision: WHERE SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

This architectural design decision focuses on how to instrument the clients' and the services' implementations to measure the performance-related QoS properties of service invocations. This can be done in various ways and layers of the network communication, such as in the application layer, the network layer, or by extending some used middleware.

In Figure 4.6 we illustrate how the requirements influence this design decision and which design solutions our model offers. The model's solutions are patterns that extend and utilize existing well-established design patterns, such as the WRAPPER pattern, the INTERCEPTOR pattern, the INVOCATION INTERCEPTOR pattern, or the PROXY pattern [35, 103, 124].

Measuring the performance-related QoS properties should deliver precise measurements, produce a minimal performance overhead, and should not decrease the system's scalability. The implementation of the measuring logic should provide separation of concerns in order to be reusable. Dependent on which performance-related QoS properties should be measured, access to the clients' or services' implementation or to the middleware's implementation is required.

Pattern: QOS INLINE

An SLA contains negotiated performance-related QoS properties where only the elapsed time of a remote object invocation is relevant to the client, i.e., the round-trip time. For the server it is relevant

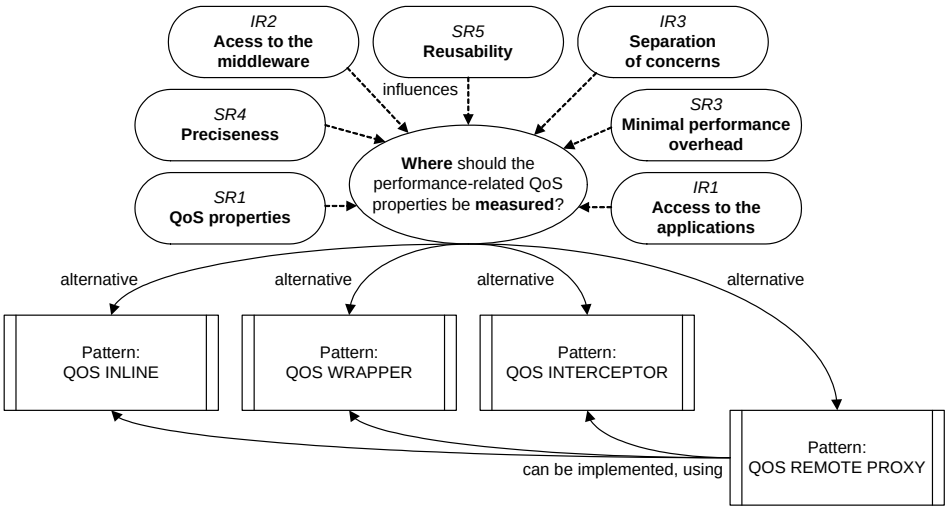


Figure 4.6: WHERE SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

to measure the elapsed time of processing a client's requests, i.e., the processing time. The server may be interested to find some possible bottle-necks within the remote object's behaviour as well.

❖ ❖ ❖

How can the client's and the remote object's implementation be instrumented for measuring performance-related QoS properties?

Consider a typical scenario of measuring performance-related QoS properties in a service-oriented system. The client invokes some service via an underlying middleware. The middleware transmits the client's request to the service over a network. The service's middleware receives the request, the service processes the request, and returns the response back to the client. Now, the client's and the service's implementation have to be instrumented to measure the SLA's performance-related QoS properties.

Therefore,
Instrument the client's and the service's implementation with local measuring points and place them directly into their implementation.

Figure 4.7 shows the QOS INLINE pattern. The client invokes the service via a middleware and wants to measure the elapsed time of the service invocation. The client's implementation can be in-

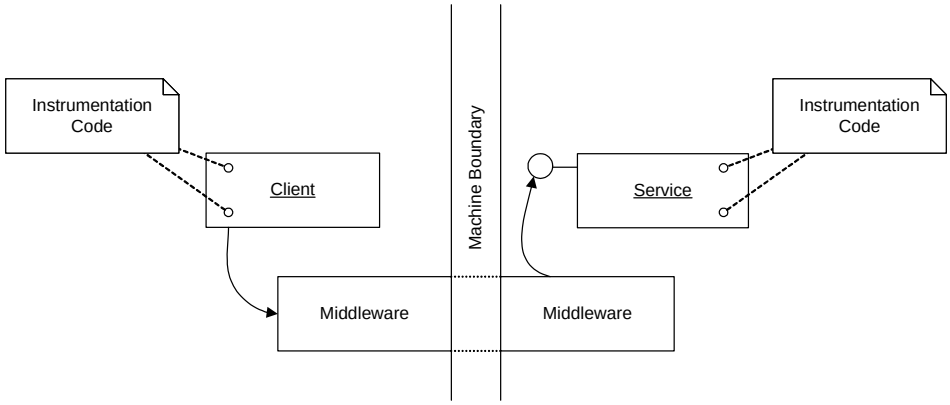


Figure 4.7: The QOS INLINE pattern

strumented for measuring the round-trip time. On the server-side, the service receives the client's request, processes it, and measures the processing time. The service's implementation can be instrumented directly with local measuring points.

On the client-side, the round-trip time can be measured precisely by calculating the elapsed time between sending the service request and receiving the response. The QOS INLINE pattern does not affect the measurements of other performance-related QoS measurements. The client-side implementation of the QOS INLINE pattern affects the client's behaviour only slightly.

On the server-side, the QOS INLINE pattern can measure the processing time precisely without influencing other performance-related QoS measurements. Multiple measurement points can be placed at arbitratry places in the service's implementation, making it possible to find, for example, bottlenecks within the processing of the client's request. Dependent on the number of measuring points, QOS INLINE pattern does not have significant affect on the service's performance.

❖ ❖ ❖

The QOS INLINE pattern does not provide a good separation of concerns because the measuring points are placed into the implementation directly. Also, the QOS INLINE pattern is not a reusable solution because existing clients and services must be instrumented and redeployed individually.

A general consequence of the QOS INLINE pattern is that not many performance-related QoS properties can be measured. At the client-side, it is easy to measure the round-trip time, but, difficult to measure performance-related QoS properties that have to be measured in some underlying network layers, such as the network latency. It is easy to measure the processing time at the server-side, and the round-trip time at the client side. But on both sides it is difficult to measure performance-related QoS properties that have to be measured in some underlying layers, such as the network latency. Assuming a small number of measuring points, separate tools, such as packet sniffers, can be utilized to measure

the performance-related QoS properties that are not measurable with the QOS INLINE pattern.

Every source code can be extended with time measurements using the QOS INLINE pattern. The QOS INLINE pattern can not be applied in service-oriented systems only, also in local function calls or object method invocations. Using the QOS INLINE pattern is advisable if the QoS measurements are relevant in the client's or service's application layer.

Known Uses:

- Mani and Nagarajan [63] explain QoS in service-oriented systems by using the QOS INLINE pattern to measure the elapsed time of a service invocation, i.e., the round-trip time.

Pattern: QOS WRAPPER

The negotiated SLAs between client and server include performance-related QoS properties with respect to the elapsed times of service invocations. The client and services must be instrumented for measuring the performance-related QoS agreements. The client's and the service's implementation should be instrumented with a reusable solution that provides separation of concerns.

❖ ❖ ❖

Which solution is reusable and provides a good separation of concerns for instrumenting the client's and the service's for measuring performance-related QoS properties?

As proposed by the QOS INLINE pattern, measuring performance-related QoS properties during service invocations can be done by placing measuring points into the client's or service's implementation directly. But, this solution does not provide separation of concerns and reusability. It is not possible to attach the measuring of the performance-related QoS properties to existing clients and services without redeployment. For improvement, the performance-related QoS properties have to be measured separated from the client's and service's implementation.

Therefore,
Instrument the client's and service's implementations with local QOS WRAPPERS that are responsible for measuring the performance-related QoS properties. Let a client invoke a service using a client-side QOS WRAPPER. Extend a service with a server-side QOS WRAPPER that receives the client's requests.

Figure 4.8 illustrates the QOS WRAPPER pattern. The client invokes a service using a client-side QOS WRAPPER that offers the client the service's operations, takes over the service invocation, and

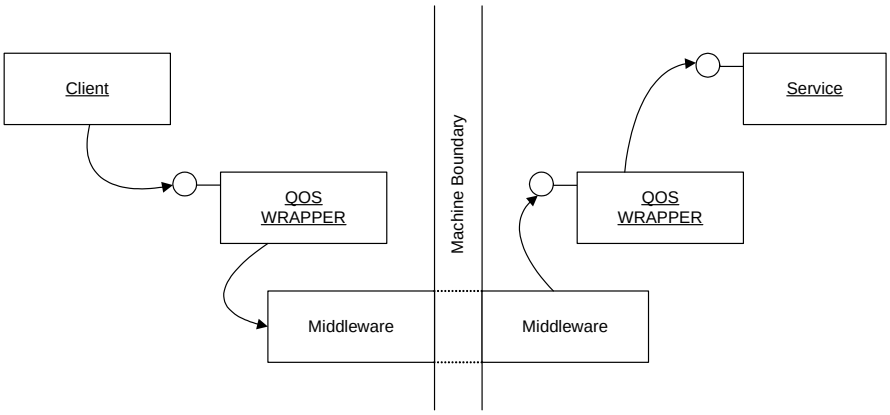


Figure 4.8: The QOS WRAPPER pattern

measures the performance-related QoS properties. At the server-side, the QOS WRAPPER processes the incoming requests for the service, measures the server-side performance-related QoS properties separated from the service's implementation, and returns back the service's response to the requesting client.

Every client and service can be instrumented with a local QOS WRAPPER, providing a uniform measuring of the performance-related QoS properties and a reusable solution. A QOS WRAPPER provides separation of concerns because it measures the performance-related QoS properties separated from the client's or the service's implementation.

❖ ❖ ❖

On the client-side, the service invocations are insignificantly lengthened because the client does not invoke the service not directly, but via the QOS WRAPPER. A client-side QOS WRAPPER provides precise QoS measurements. A server-side QOS WRAPPER can insignificantly lengthen the service invocations as well, but, it measures the QoS properties precisely.

The client's QOS WRAPPER can measure the round-trip time and the server's QOS WRAPPER the processing time. The QOS WRAPPER pattern is not able to measure network-specific performance-related QoS properties. But, separate tools, such as packet sniffers, can be utilized to measure network-specific performance-related QoS properties.

The client-side QOS WRAPPER can be implemented following the CLIENT PROXY pattern [19], whereas the server-side QOS WRAPPER can be implemented following the INVOKER [124] pattern.

Known Uses:

- Afek et al. [2] implemented a framework for QoS-aware remote object invocations over an

ATM network. The authors extended the Java RMI interface by providing an API to the clients. Following the QOS WRAPPER pattern, the client-side API ensures QoS by providing a good separation of concerns. A server-side QOS WRAPPER server acquires and arranges the service with the desired QoS.

- Loyall et al. [62] introduce Quality Objects (QuO) that are responsible for checking contractually agreed QoS properties. A QuO is a QOS WRAPPER because it is located at the client's or service's machine, but, is separated from the client's or service's implementation.
- Wohlstadter et al. [129] build a QOS WRAPPER that wraps the Apache Axis middleware for measuring QoS.
- The Application Resource Measurement (ARM) API [101] is a QOS WRAPPER to measure performance-related QoS properties.
- Rosenberg et al. [98] utilize a QOS WRAPPER in order to measure the services' performance-related QoS properties.

Pattern: QOS INTERCEPTOR

Clients and services must be instrumented to performance-related QoS properties with a reusable, precise, from the implementation separated solution. Access to the middleware is provided to measure negotiable and network-specific performance-related QoS properties in order to detect, for example, bottle-necks in long-running service invocations.

How can the middleware be instrumented to measure performance-related QoS properties of service invocations?

In service-oriented systems, the client's middleware transmits the invocation data of the service request to the service over a network. The service's middleware is responsible for receiving incoming data and to transmit the service's response to the client. The client's middleware processes the incoming data and forwards it to the client's application. Let's consider that access to clients' and the services' underlying middleware is provided. The middleware must be instrumented to measure negotiable and network-specific performance-related QoS properties, providing reusability, precise QoS measurements, and separation of concerns.

Therefore,

Hook QOS INTERCEPTORS into the middleware that intercept the message flow between the client and the service. Let the QOS INTERCEPTORS measure the performance-related QoS properties of service invocations.

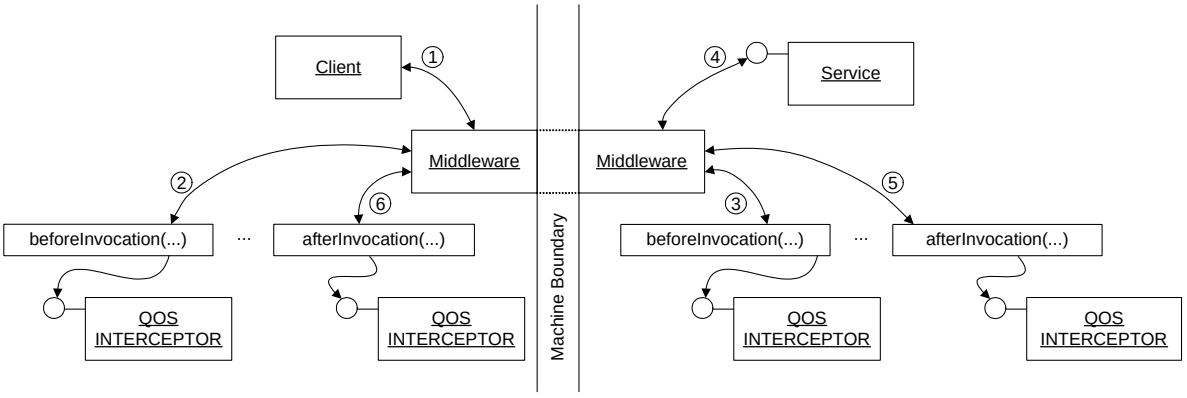


Figure 4.9: The QOS INTERCEPTOR pattern

Figure 4.9 demonstrates the QOS INTERCEPTOR pattern that utilizes the INVOCATION INTERCEPTOR pattern [124]. A QOS INTERCEPTOR can be utilized on the client- and the server-side. Multiple QOS INTERCEPTORS can be placed in the invocation path, where each of them is responsible to measure different performance-related QoS properties, making it is possible to find, for example, bottle-necks of long-running service invocations.

Many middleware frameworks, such as Apache CXF [115] or .NET Remoting provide possibilities in the middleware to attach a QOS INTERCEPTOR into the invocation path dynamically, using APIs or configuration files. But, the complexity of the middleware's implementation increases by providing hooks or interfaces to attach and change QOS INTERCEPTORS in the invocation path dynamically.

A QOS INTERCEPTOR delivers precise measurements of network-specific performance-related QoS properties. The QOS INTERCEPTOR has the benefit that the client's and remote object's implementations do not have to be instrumented for measuring the performance-related QoS properties. The client's and remote object's middleware are instrumented to hook QOS INTERCEPTORS into the invocation path. A QOS INTERCEPTOR provides a good separation of concerns because the measuring is separated from the client's and remote object's implementation. Because a QOS INTERCEPTOR is hooked in the client's or remote object's local middleware, a precise measuring of almost all performance-related QoS properties can be achieved. In addition, a QOS INTERCEPTOR is reusable because existing QOS INTERCEPTORS can be attached dynamically into the middleware of existing clients and remote objects.

A QOS INTERCEPTOR does not measure the elapsed time of transferring the invocation data from

❖ ❖ ❖

the application layer to the middleware as well as the required time of transferring the invocation data from the middleware to the application layer. Hence, the measurements of negotiable performance-related QoS properties are slightly different in comparison to using the QOS INLINE pattern. Placing multiple QOS INTERCEPTORS into the invocation path can impact the preciseness of the QoS measurements. For example at the server-side, a QOS INTERCEPTOR that measures the measures the processing time can influence the measured execution time (see Figure 2.3).

Known Uses:

- The OpenORB project [118] supports QOS INTERCEPTORS.
- The .NET Remoting framework [71] introduces the *RealProxy*, that is a QOS INTERCEPTOR to intercept remote object invocations.
- The Apache web service frameworks Axis [113], Axis2 [114], and Apache CXF [115] provide the features to use QOS INTERCEPTORS to intercept the messages exchanged between clients and services for measuring performance-related QoS properties.
- The QoS CORBA Component Model (QOSCCM) [84] uses the QOS INTERCEPTOR pattern to easily adapt an application for measuring performance-related QoS properties.
- The VRESCo runtime environment [68] measures the performance-related QoS properties using QOS INTERCEPTORS.
- Li et al. [60] use QOS INTERCEPTORS to intercept the messages between clients and services for measuring the performance-related QoS properties.

Pattern: QOS REMOTE PROXY

In distributed systems, the client and the remote object do not have to be necessarily located in the same local area network (LAN). In this case, the client invokes the remote object via a wide area network (WAN), such as the Internet.

❖ ❖ ❖

How to introduce a good separated, reusable, and uniform infrastructure for measuring the performance-related QoS properties in the case when client and remote objects are not located in the same LAN?

In many cases, the server hosts the remote object and is not located in the client's LAN. Hence, the client has to access the remote object via a WAN. Client and server want to measure performance-related QoS properties. The desired solution should be uniform for each client and remote object, enhancing the deployment of new clients and remote objects. Also, a good separated and reusable QoS measurement infrastructure is desired.

Therefore,

Implement and setup a QOS REMOTE PROXY in the client's and remote object's LAN that takes over the responsibility of measuring the performance-related QoS properties. In the client's LAN, configure each client to invoke the remote objects via the LAN's QOS REMOTE PROXY. In the server's LAN, make each remote object only be accessible via a QOS REMOTE PROXY.

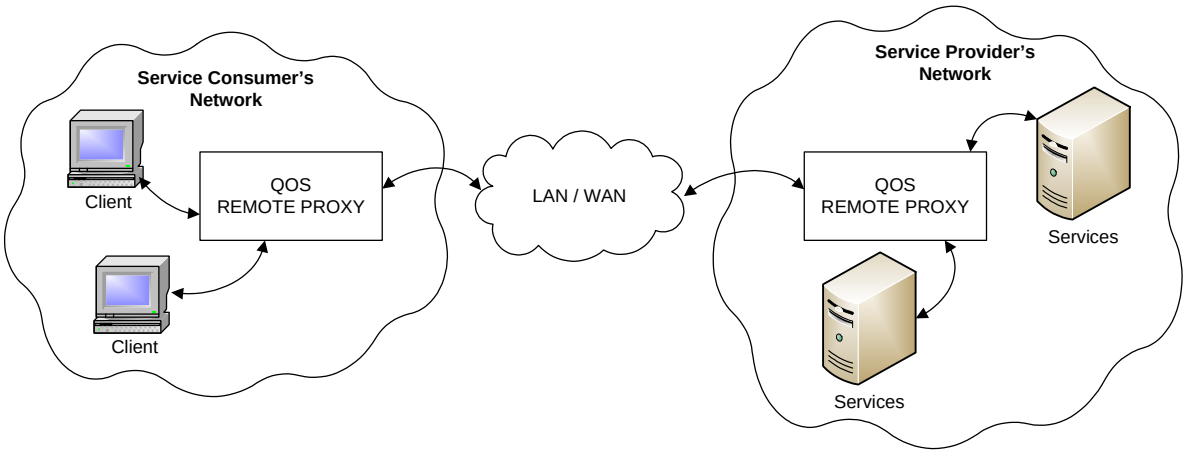


Figure 4.10: The QOS REMOTE PROXY pattern

Figure 4.10 shows an infrastructure where the client and the remote object are not located in the same LAN. As shown, the QOS REMOTE PROXY pattern can be applied in both LANs. The client's QOS REMOTE PROXY receives the client's request, performs the required QoS measurements, and forwards the request to the remote object's LAN. A server-side QOS REMOTE PROXY receives the client's requests (directly or via the client's QOS REMOTE PROXY), performs the required QoS measurements, and forwards the request to the appropriate remote object. After the remote object processed the request, it sends the response back to the server-side QOS REMOTE PROXY that measures the required performance-related QoS properties and forwards the response to the requestor. The client-side QOS REMOTE PROXY receives the response (from the remote object directly or from the server-sid QOS REMOTE PROXY), performs QoS measuring, and forwards the response to the appropriate client.

In the client's and the server's LAN, a QOS REMOTE PROXY provides a good separation of concerns

because the measuring of the performance-related QoS properties is separated. Also, there is no impact on the client's and server's performance. In addition a QOS REMOTE PROXY is a reusable solution. Each new client can be configured to invoke the remote object via the client's LAN QOS REMOTE PROXY. Also, it is possible to configure each remote object that is only accessible via the server's LAN QOS REMOTE PROXY.

❖ ❖ ❖

At minimum one extra hop in the client's and server's LAN is needed because of accessing the QOS REMOTE PROXY instead of accessing the WAN or the remote object directly. Hence, the measurements of the performance-related QoS properties at the QOS REMOTE PROXY differ from the client's and remote object's local QoS measurements. In case the client and the server are measuring the negotiated performance-related QoS properties independently, both can fake the QoS measurements.

A client-side QOS REMOTE PROXY can affect the client's performance slightly. But, a QOS REMOTE PROXY can impact the performance of the client's LAN because each client has to invoke the remote object via the QOS REMOTE PROXY. On the server-side, a QOS REMOTE PROXY does not affect the performance of the remote object directly, but, it can have an impact on the server's LAN. A QOS REMOTE PROXY inside the server's LAN can be implemented as a load-balancer, gateway, reverse proxy, dispatcher, as well as a firewall following the appropriate patterns [19].

The QOS REMOTE PROXY does not necessarily require that the client and the remote object are located in different LANs. In a case where client and remote object are located in the same LAN, the setup of one QOS REMOTE PROXY inside the LAN is adequate.

Known Uses:

- Wang et al. [127] introduce a QoS-Adaptation proxy that receives the clients' requests, performs the QoS measurements, and forwards the clients' requests to their destinations. The clients' applications remain unchanged while the proxy performs the necessary adaptations and QoS measurements.
- The Corba IIOP specifications [83] introduce the VisiBroker [17] environment that uses the QOS REMOTE PROXY pattern for measuring the performance-related QoS properties.
- The Apache TCPMon [117] tool can be instrumented to serve as a proxy between the clients and the server's remote objects. An implementation of the QOS REMOTE PROXY is to extend this tool for measuring performance-related QoS properties.
- Sahai et al. [100] introduce a QOS REMOTE PROXY for monitoring SLAs in web service-oriented distributed systems.

- Badidi et al. [13] present WS-QoSM, a QoS monitoring solution that measures the QoS properties following the QOS REMOTE PROXY pattern.

- The Cisco IOS IP SLA [21] follows the QOS PROXY pattern that has the responsibility of measuring the performance-related QoS properties.

4.4.3 Design Decision: WHEN SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

A service's performance-related QoS properties are measured within the service invocation. This architectural design decision focuses on the time and frequency of the service invocations. In Figure 4.11 we illustrate the requirements' influences of this design decision.

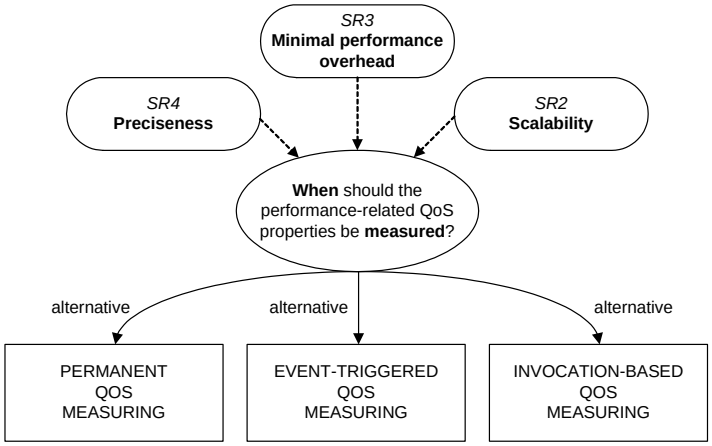


Figure 4.11: WHEN SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

In our model we propose four different solutions for the architectural design decision about the measurement time.

Solution: PERMANENT QOS MEASURING

Send periodically, in pre-defined time intervals, probe requests to the service to measure the performance-related QoS properties permanently.

To get a permanent information about the performance-related QoS compliance concerns, the service consumer must adapt the client's measuring solution to send periodically probe requests to the services. During the probe requests, the performance-related QoS measurements can be measured. The service provider must invoke the services internally in periodic intervals to get a permanent infor-

mation about the services' performance-related QoS properties. The service provider must develop a component that invokes the services and measure the performance-related QoS properties.

One possible solution is to develop a centralized component in the service consumers or service providers network that invokes the services periodically. For example, a QOS REMOTE PROXY can be extended to invoke the services periodically to measure the services' performance-related QoS properties permanently.

Invoking the services frequently, i.e., setting a short time interval, a precise information about the services' performance-related QoS properties can be gathered. A short time interval can produce performance overhead, resulting in a low scalability. Setting a long time interval, the preciseness can be diminished, but, the performance overhead is minimal and the scalability enhances.

Solution: EVENT-TRIGGERED QOS MEASURING

Send probe requests to service to measure the performance-related QoS properties in case certain events occur in the system.

At the client and server side, an event listener is executed when certain events occur, such as user requests or messages from running applications that depend on the performance-related QoS properties. At the client side, send a probe request to the service if a certain event occurs. At the server side, invoke the service if a certain event occurs and measure the performance-related QoS properties within the invocation.

If events occur rarely, the performance overhead is minimal and the scalability increases. But, the preciseness of the performance-related QoS properties decreases. Occur events frequently, the measurements of the performance-related QoS properties becomes more precise. But, the scalability decreases because of the performance overhead.

Solution: INVOCATION-BASED QOS MEASURING

Measure the performance-related QoS properties only in real service invocations.

All performance-related QoS properties are measured within service invocations. The previous solutions (PERMANENT QOS MEASURING and EVENT-TRIGGERED QOS MEASURING) measure the performance-related QoS properties in probe requests. The INVOCATION-BASED QOS MEASURING focuses on measuring the performance-related QoS properties in real service invocations.

In case service invocations happen often, the performance overhead can increase, resulting in a lower scalability. But, the measurements of the performance-related QoS properties becomes more precise. Seldom service invocations result in a minimal performance overhead, dependent on the selected solutions of the other design decisions'. The scalability enhances, but, the preciseness can be diminished of seldom service invocations.

For selecting the INVOCATION-BASED QOS MEASURING solution, the service provider must not

develop a component that sends probe requests to the services in order to measure the services' performance-related QoS properties.

4.4.4 Design Decision: WHEN SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

The next architectural decision focuses on the evaluation of the performance-related QoS measurements. In our terminology, evaluating means to check the performance-related QoS measurements regarding the SLAs in order to detect or prevent SLA violations.

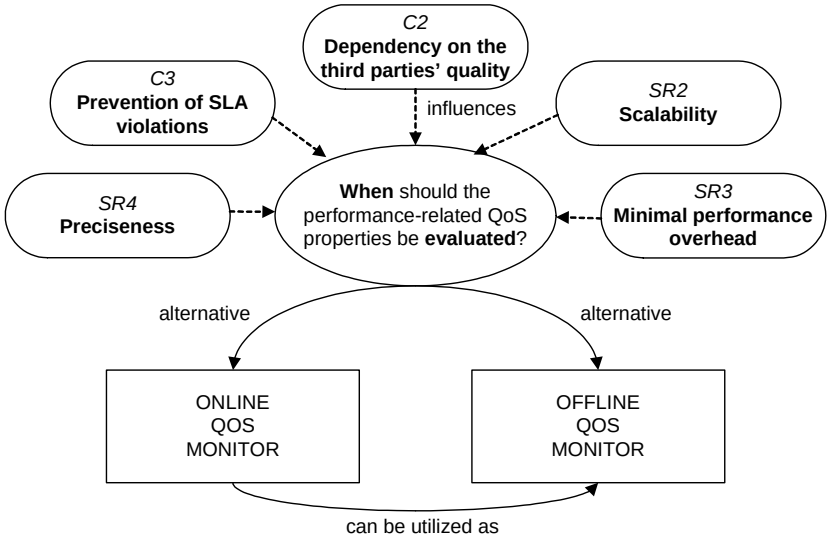


Figure 4.12: WHEN SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

In Figure 4.12 we illustrate the design decisions requirements and the proposed solutions. The evaluation solution should deliver precise results in order to detect or prevent SLA violations. In case the services' performance depends on some third parties' services, the evaluation solution should alert performance drops well-timed. But, the evaluation solution should have minimal performance overhead in a high scalable system. An ONLINE QOS MONITOR can be used as an OFFLINE QOS MONITOR.

In the following, we present our model's solutions for this architectural design decision. The presented solutions are derivations of the QOS OBSERVER pattern [124].We explain the solutions' forces and consequences regarding the requirements.

Solution: ONLINE QOS MONITOR

Evaluate the performance-related QoS measurements with regard to the negotiated SLAs during the SLA's validity.

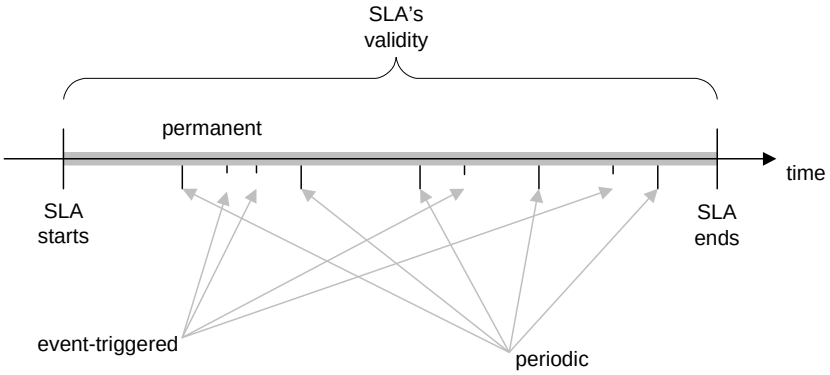


Figure 4.13: ONLINE QOS MONITOR

SLAs are contracts that are typically negotiated over a certain period of time. An ONLINE QOS MONITOR evaluates the performance-related QoS measurements within the SLAs' validity. In Figure 4.13 we sketch the the ONLINE QOS MONITOR solution for a better understanding.

❖ ❖ ❖

A **permanent** ONLINE QOS MONITOR must evaluate the performance-related QoS properties after they are measured immediately. Because of the permanent knowledge about the current compliance state performance losses can be detected, making it possible to detect SLA violations before they occurred. But, the permanent evaluation can impact the systems performance.

An **event-triggered** ONLINE QOS MONITOR evaluates the performance-related QoS measurements in case certain events occur, such as user requests or system events. Dependent on the events' frequency, SLA violations can be avoided to take appropriate actions. In case the events' frequency is low, it is possible to violate SLAs. Between the occurrence of two events, the performance-related QoS measurements have to be stored somewhere. After the occurrence of an event, the stored measurements must be involved of the evaluation. Also dependent on the events' frequency, an event-triggered ONLINE QOS MONITOR can imply a performance overhead.

A **periodic** ONLINE QOS MONITOR evaluates the measured performance-related QoS properties in pre-defined time intervals. Dependent on the intervals' length, SLA violations can occur or can be prevented. A perodic ONLINE QOS MONITOR can impact the system's performance if the time interval is set to low. Within the time interval, the performance-related QoS measurements must be stored and after the elapsed time period included into the evaluation.

In case of deciding in favour of an event-triggered or periodic ONLINE QOS MONITOR the architectural design decision WHERE SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES? (see Section 4.4.6) must be answered too.

Solution: OFFLINE QOS MONITOR

Store the performance-related QoS measurements during the SLA's validity. Evaluate the stored measurements after the SLA's validity

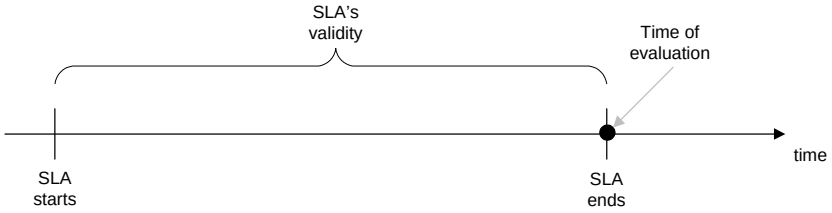


Figure 4.14: OFFLINE QOS MONITOR

In Figure 4.14 we illustrate on a time line when the OFFLINE QOS MONITOR evaluates the performance-related QoS measurements. As shown, the evaluation takes place after the SLA's validity.

❖ ❖ ❖

The OFFLINE QOS MONITOR has a minimal performance overhead because the performance-related QoS measurements just must be stored after they have been measured. After the SLA's validity the stored measurements are evaluated and possible SLA violations are detected. Because of a minimal performance overhead the scalability increases. A OFFLINE QOS MONITOR can deliver precise results in case the performance-related QoS properties were measured precisely.

As a consequence, the OFFLINE QOS MONITOR is not an adequate solution to prevent SLA violations. It is also difficult the detect any performance drops in case the services' quality depends on third party services. Hence, a OFFLINE QOS MONITOR is not advisable for service providers. But, it is a convenient solution for a service consumer to detect SLA violations after the SLA's validity.

In case of deciding for a OFFLINE QOS MONITOR the architectural design decision WHERE SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES? (see Section 4.4.6) must be answered because the performance-related QoS measurements must be stored during the SLA's validity.

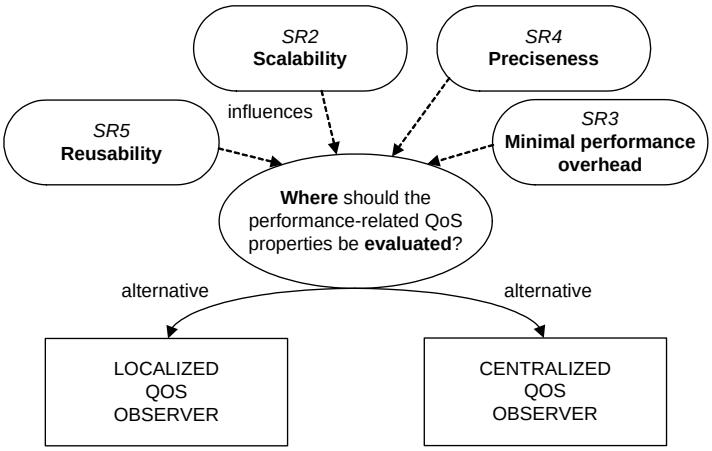


Figure 4.15: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

4.4.5 Design Decision: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

This design decision concentrates on the location where the evaluation of the performance-related QoS measurements should take place. In Figure 4.15 we show how requirements influence this design decision.

The evaluation solution should be reusable, making it possible that multiple performance-related QoS measurements can be evaluated regarding the negotiated SLAs. It is required that the SLA evaluation solution has a minimal performance overhead and that the system's scalability does not decrease. The evaluation solution should provide precise evaluation results and should not influence the measurements of other performance-related QoS properties.

In our model, we propose two architectural design solutions for evaluating the performance-related QoS measurements. Both are strategies of the QOS OBSERVER pattern [124].

Solution: LOCALIZED QOS OBSERVER

Evaluate the performance-related QoS measurements locally at each client or service.

In Figure 4.16 we sketch the LOCALIZED QOS OBSERVER solution that is based on the QOS OBSERVER pattern [124]. The LOCALIZED QOS OBSERVER resides within each client or service and is responsible for evaluating the performance-related measurements. The measuring solution passes the QoS measurements to the LOCALIZED QOS OBSERVER, making an immediate evaluation possible.

A LOCALIZED QOS OBSERVER is a scalable solution with a minimal performance overhead. Dependent on the implementation, a LOCALIZED QOS OBSERVER is reusable. In case of implementing

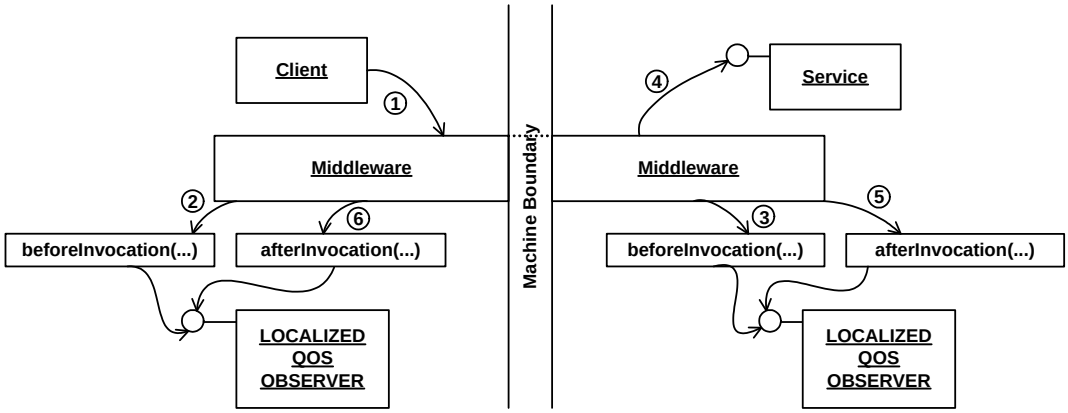


Figure 4.16: LOCALIZED QOS OBSERVER

❖ ❖ ❖

a WRAPPER, the LOCALIZED QOS OBSERVER is reusable. In contrast, implementing the LOCALIZED QOS OBSERVER within the services' or clients' implementation is not reusable.

A LOCALIZED QOS OBSERVER can influence other performance-related QoS measurements in case the measurements are evaluated or stored immediately. For example, a server-side LOCALIZED QOS OBSERVER that evaluates immediately a service's processing time can influence the measured round-trip time at the client-side.

Solution: CENTRALIZED QOS OBSERVER

Submit the performance-related QoS measurements from each client or service to a CENTRALIZED QOS OBSERVER that is responsible for the evaluation of the measurements.

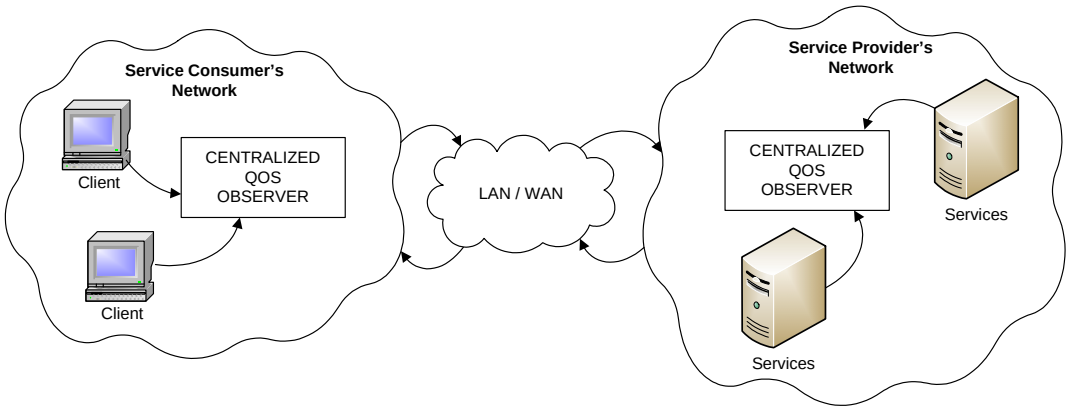


Figure 4.17: CENTRALIZED QOS OBSERVER

In Figure 4.17 we illustrate the architecture of a CENTRALIZED QOS OBSERVER. The clients send the performance-related QoS measurements to a CENTRALIZED QOS OBSERVER that is placed within the service consumer's network. At the server side, the services submit the performance-related QoS measurements to a server-side CENTRALIZED QOS OBSERVER to evaluate the measurements.

❖ ❖ ❖

A CENTRALIZED QOS OBSERVER is a reusable solution to evaluate the performance-related QoS measurements. The clients' and the services' measuring solution must be configured or implemented to submit the measurements to the CENTRALIZED QOS OBSERVER.

Sending the performance-related QoS measurements to the CENTRALIZED QOS OBSERVER over the network can impact the systems' performance. In a high scalable system, a CENTRALIZED QOS OBSERVER can be a bottle-neck of the QoS monitoring infrastructure. At the server-side, the performance-related QoS properties are measured and submitted to the CENTRALIZED QOS OBSERVER within the service provider's network. The sending of the measurements over the network can influence the client-side measurements, resulting in imprecise performance-related QoS measurements and evaluation results.

Known Uses:

- Sahai et al. [100] introduce an SLA violation engine, a CENTRALIZED QOS OBSERVER.
- Badidi et al. [13] present a CENTRALIZED QOS OBSERVER within the WS-QoSM architecture.
- The CISCO IOS IP SLAs [21] provide a CENTRALIZED QOS OBSERVER to evaluate the performance-related QoS measurements.
- Li et al. [60] use a CENTRALIZED QOS OBSERVER for evaluation.
- Michlmayer et al. [67] designed an event-driven CENTRALIZED QOS OBSERVER for detecting SLA violations.
- The EVEREST+ framework [61] includes a CENTRALIZED QOS OBSERVER to predict SLA violations.

4.4.6 Design Decision: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE STORED?

The architectural design decision about where to store the performance-related QoS measurements is in close relationship with the aforementioned design decision where to evaluate the performance-related QoS measurements (see Section 4.4.5).

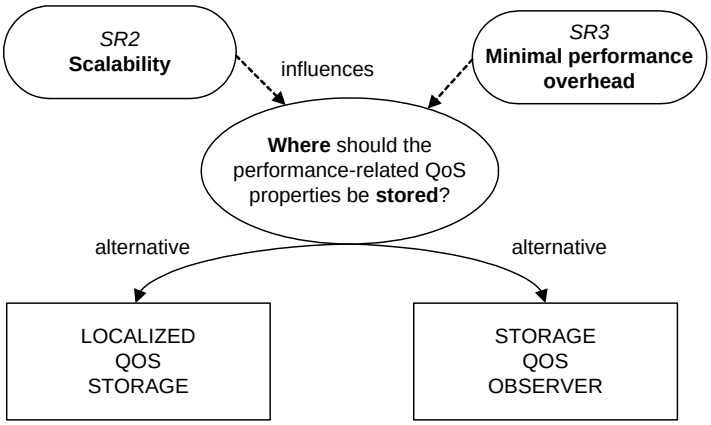


Figure 4.18: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE STORED?

In Figure 4.18 we present how the requirements influence this architectural design decision. Storing the performance-related QoS measurements should have minimal performance overhead and should not influence the system's scalability.

In our model, we provide two possible solutions for storing the performance-related QoS measurements.

Solution: LOCALIZED QOS STORAGE

Store the performance-related QoS measurements locally at each client or the services.

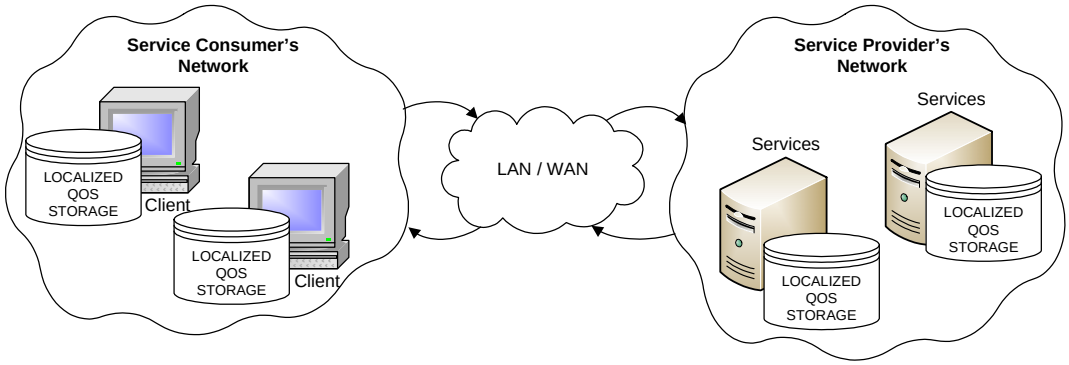


Figure 4.19: LOCALIZED QOS STORAGE

In Figure 4.19 we illustrate the architecture of a LOCALIZED QOS STORAGE. A LOCALIZED QOS STORAGE stores the performance-related QoS measurements locally at the client or the service, such as in a log file.

❖ ❖ ❖

The solution does not impact the performance, because the performance-related QoS measurements must not be transmitted over the network to be stored. In addition, the scalability of a LOCALIZED QOS STORAGE increases.

In case the SLAs include multiple clients or services, the evaluation of the stored measurements can become more time consuming and complex. A CENTRALIZED QOS OBSERVER has to collect from each client or service the measurements for evaluation. In case of choosing a LOCALIZED QOS OBSERVER, the LOCALIZED QOS STORAGE is a fast and simple storing solution.

Solution: CENTRALIZED QOS STORAGE

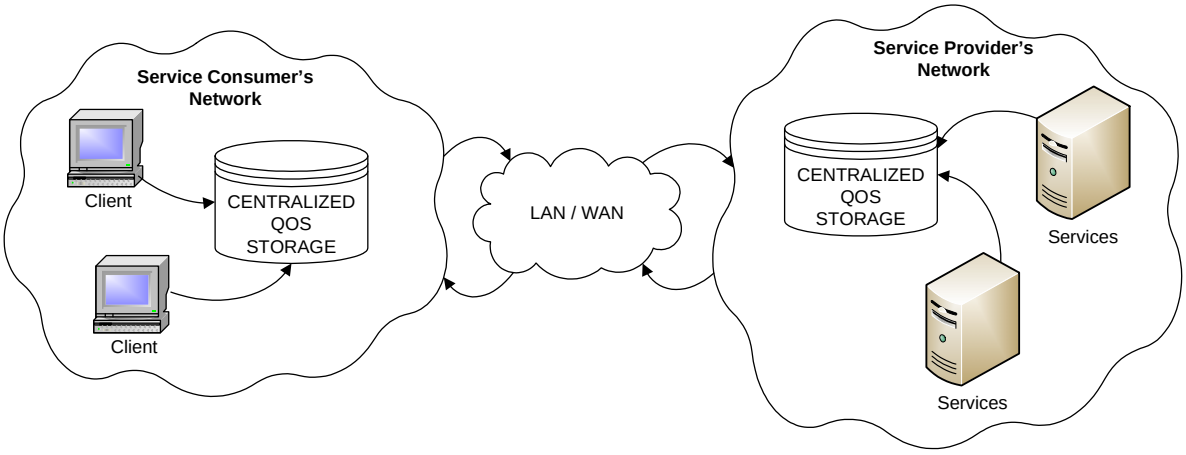


Figure 4.20: CENTRALIZED QOS STORAGE

In Figure 4.20 we illustrate the CENTRALIZED QOS STORAGE solution. A CENTRALIZED QOS STORAGE stores the performance-related QoS measurements in a centralized storage, such as in a database. In this case, the clients and services have to submit the performance-related QoS properties over the network in order to store them in the CENTRALIZED QOS STORAGE.

❖ ❖ ❖

In case the SLAs include multiple clients or services, a CENTRALIZED QOS OBSERVER can evaluate the stored measurements easily because they must not be collected from each client or service. If choosing a LOCALIZED QOS OBSERVER, then the client or service have to query and fetch the stored measurements over the network in order to evaluate them. A CENTRALIZED QOS OBSERVER is reusable for all clients or services within the network.

Sending the measurements over the network to the CENTRALIZED QOS STORAGE can result in a performance overhead. Also, the scalability can decrease.

Known Uses:

- Sahai et al. [100] build a high performance database that stores the QoS measurements.
- Li et al. [60] store the performance-related QoS measurements following the CENTRALIZED QOS STORAGE solution.
- Rosenberg et al. [98] use a CENTRALIZED QOS STORAGE to store evaluation results.

4.5 Relationships between the Architectural Design Decisions

Requirements influence architectural design decisions, resulting in commonalities of the architectural design decisions. In our model, we provide solutions for the design decisions the have forces and consequences dependent on the business and technical requirements. In this section we discuss the influences between the requirements, architectural design decisions, and solutions of our model.

In our model, we provide various requirements on a QoS monitoring infrastructure. One requirement can influence multiple architectural design decisions. Discovering the requirements of each architectural design decision helps to identify dependencies between the architectural design decisions.

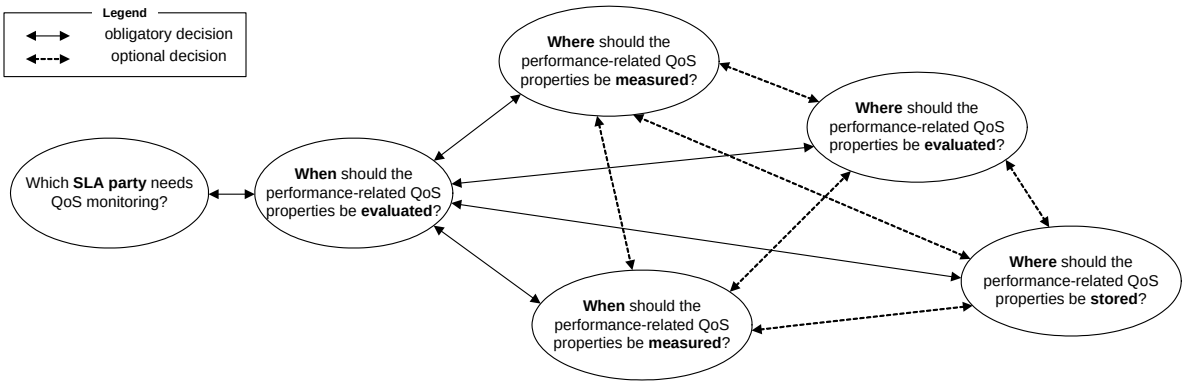


Figure 4.21: Influences between the architectural design decisions

In Figure 4.21 we illustrate how the architectural design decisions depend on the requirements on the QoS monitoring infrastructure. In the upper part of the figure we demonstrate a flow through the decision making process. Continuous lines between two design decisions mean that both design decisions must be taken, whereas dotted lines depict optional design decisions. In the bottom of the Figure, we show how the requirements influence the selection of a solution for each architectural design decision.

First, a design solution for the design decision WHICH SLA PARTY REQUIRES QOS MONITORING? must be taken. Depend on the requirements (*providing or consuming services*), a service provider or a service consumer wants a QoS monitoring infrastructure, or a combined QoS monitoring solution is required. After the designer knows the requirements and enters them into our model, our model proposes an appropriate solution. The design decision WHEN SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE EVALUATED? has additional requirements, such as scalability, minimal performance overhead, or preciseness. To propose an appropriate solutions, our model needs to know the requirements.

Our model stores the already entered requirements and proposes solutions automatically. For example, if a scalable evaluation solution with a minimal performance overhead is required at any taken design decision, our model also proposes scalable solutions with a minimal performance overhead for the subsequent decision. After entering more and more requirements, our architectural design decision model can propose multiple solutions, making it possible that not every design decision must be taken.

It would be possible to enter all the requirements at the beginning of the decision making process and that the model proposes the solutions for measuring, storing, and evaluating the performance-related QoS measurements. We have decided in favour of an interactive decision making process, entering the requirements iterative during the decision making process. This brings the benefit that the designers can go some steps back or forward within the decision making process, making it possible that the model proposes optimal solutions.

4.6 Evaluation of the Model in the Case Study

In this section we present how we evaluate the presented architectural design decision model in the scope of the case study (see Chapter 3). We first list the requirements on the case study's QoS monitoring infrastructure, followed by the model's proposed architectural solutions. We have implemented the measuring solutions in the case study and visualize runtime measurements of the services' performance-related QoS properties.

4.6.1 The Case Study's QoS Monitoring Requirements

The MVNO provides services to service consumers to stream multimedia content. The service consumers and the MVNO negotiate SLAs regarding the multimedia services' performance-related QoS properties. The MVNO as a service provider wants to introduce a QoS monitoring infrastructure, where the services' performance quality depends on the performance quality of the third parties' services. As a service provider, the MVNO has to prevent SLA violations in order to avoid financial consequences and a diminished reputation.

Because the MVNO provides services to the service consumers, access to the services' implementation is given. It was allowed to choose a web service framework, but, We were not allowed to modify the services' implementation to perform QoS monitoring. Therefore, we had to design a transparent QoS monitoring infrastructure. Because the MVNO provides multiple services to its consumers, it was desired to design a resuable QoS monitoring infrastructure that has a minimal performance overhead. The QoS monitoring infrastructure must be scalable in case more and more consumers use the MVNO's features of streaming multimedia content in a favoured language.

The MVNO is *providing services* (C_1) to the service consumers, wants to *prevent* (C_3) SLA violations, and the performance of the MVNO services *depend on the third parties' performance* (C_2). We had to design a *scalable* (SR_2) QoS monitoring infrastructure with a *minimal performance overhead* (SR_3). It is required to provide *separation of concerns* (IR_3) and *reusabliy* (SR_5).

4.6.2 The Case Study's Solutions

In the case study, we have used the architectural design decision model to design a QoS monitoring infrastructure that fulfills the afore-mentioned requirements. We illustrate the proposed solutions in Figure 4.22.

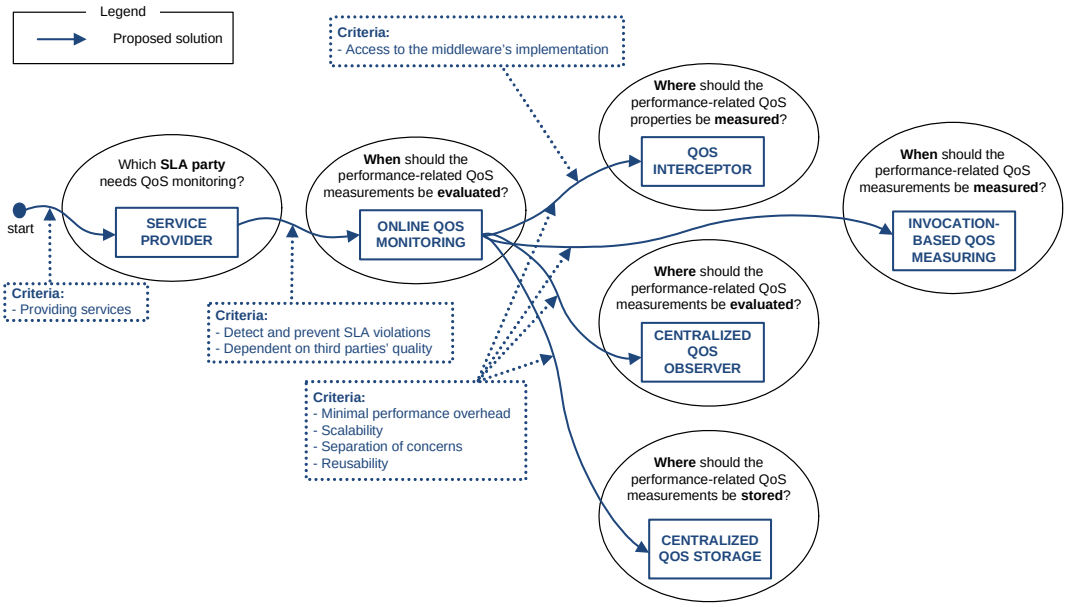


Figure 4.22: Proposed solutions of our architectural design decision model

The model proposed to develop a SERVICE PROVIDER QOS MONITORING solution because the MVNO provides services to its consumers. To prevent SLA violations the services performance-related QoS properties must be evaluated during the validity of the SLAs. Our model proposed to

develop a ONLINE QOS MONITORING solution. With a ONLINE QOS MONITORING solution any performance drops of the third parties' services can be detected, making it possible to take appropriate actions to avoid SLA violations to the service consumers.

Because of the scalability, minimal performance overhead, separation of concerns, and reusability requirements, our model was able to propose architectural design solutions to measure, evaluate, store performance-related QoS properties. In the case study, we have decided in favour of the Apache CXF web service framework [115] because it provides convenient solutions to intercept the incoming messages to measure the services' performance-related QoS properties. Our model proposed to follow the QOS INTERCEPTOR pattern. To avoid undesired performance drops of the services, our model proposed an INVOCATION-BASED QOS MEASURING solution. Hence, the services' performance-related QoS properties are measured for each incoming request.

Our model proposed to use a CENTRALIZED QOS OBSERVER solution to evaluate the performance-related QoS measurements. The QOS INTERCEPTORS must be extended to submit the measurements to the CENTRALIZED QOS OBSERVER over the network. As a trade-off, the performance overhead can increase in case the MVNO plans to offer more services to its consumers instead of only three. To store the QoS measurements, our model proposes a CENTRALIZED QOS STORAGE. It is possible to deploy the CENTRALIZED QOS OBSERVER and CENTRALIZED QOS STORAGE on the same node in the service provider's network, resulting in a convenient ONLINE QOS MONITORING solution.

4.6.3 Implementation of the Measuring Solutions within the Case Study

This section exemplifies the presented patterns for measuring performance-related QoS properties within a service-oriented system. We exemplify the patterns on a web service that offers the functionality to login into a remote system. The service's `login` operation receives a username and a password from the client and checks if the client is authorized to enter. We have implemented the clients and services using the Apache CXF web service framework [115]. In the following, we present the client-side implementation of the presented patterns.

Pattern: QOS INLINE

Figure 4.23 shows a code excerpt of a client that invokes a web service and measures the round-trip time following the QOS INLINE pattern. We used the Apache CXF's feature of implementing a dynamic client where we do not have to use the `wsdl2java` tool for generating the web service's stub explicitly.

The client offers a `callLoginService` method to invoke the web service's `Login` operation. First, we have to instantiate the `JaxWsDynamicClientFactory`, following the FACTORY pattern [35]. Then, the client is created by using the previously instantiated FACTORY. The client puts two QoS measuring points around the actual web service invocation – `client.invoke(...)` – to measure

LoginServiceClient + QOS INLINE

```
public class LoginServiceClient {

        public void callLoginService() {
                JaxWsDynamicClientFactory dcf =
                        JaxWsDynamicClientFactory.newInstance();
                Client client = dcf.createClient("login.wsdl");

                try {
                        /* measure current time */
                        long tBeforeInvocation = System.nanoTime();

                        /* call the web service */
                        client.invoke("login", new Object[]{"client","password"});

                        /* measure the round trip time */
                        long tRoundTrip = System.nanoTime() - tBeforeInvocation;
                } catch (Exception e) {
                        e.printStackTrace();
                }
        }

}
```

Figure 4.23: Measuring the round-trip time following the QOS INLINE pattern

the round-trip time of the web service invocation.

Pattern: QOS WRAPPER

In Figure 4.24 we illustrates a web service client that measures the round-trip of the web service invocation following the QOS WRAPPER pattern. Instead of placing measuring points for the round-trip time in the client's implementation directly, the client invokes the web service via a local QOS WRAPPER. The implemented QOS WRAPPER offers the same interface to the client as the remote object. In this example, the QOS WRAPPER takes over the responsibility of measuring of the round-trip time of a web service invocation.

LoginServiceClient

```
public class LoginServiceClient {
   public void callLoginService() {
      /* invoke the Login Web service */
      new QoSWrapper.login(
            "client","password");
   }
}
```

QOS WRAPPER

```
public class QoSWrapper {
   private Client loginClient;
   public  QoSWrapper() {
      /* initialize WS stubs */
      JaxWsDynamicClientFactory dcf =
            JaxWsDynamicClientFactory.newInstance();
      this.loginClient = dcf.createClient("login.wsdl");
   }

   public void login(String sUsername, String sPassword) {
      /* measure current time */
      long tBeforeInvocation = System.nanoTime();
      /* call the requested service */
      loginClient.invoke("login",
            new Object[]{sUsername,sPassword});
      /* measure time difference */
      long tRoundTrip = System.nanoTime() - tBeforeInvocation;
   }
}
```

Figure 4.24: Measuring the round-trip time following the QOS WRAPPER pattern

Instead of invoking the web service directly, the client calls the `invoke` method of the `QoSWrapper`. Within the `invoke` method, the QOS WRAPPER measure the elapsed time of the web service invocation, i.e., the round-trip time.

Pattern: QOS INTERCEPTOR

The QOS INTERCEPTOR pattern can be implemented easily using the Apache Axis, Apache CXF web services framework or in object-oriented RPC middlewares, such as CORBA, .NET Remoting, and Windows Communication Foundation.

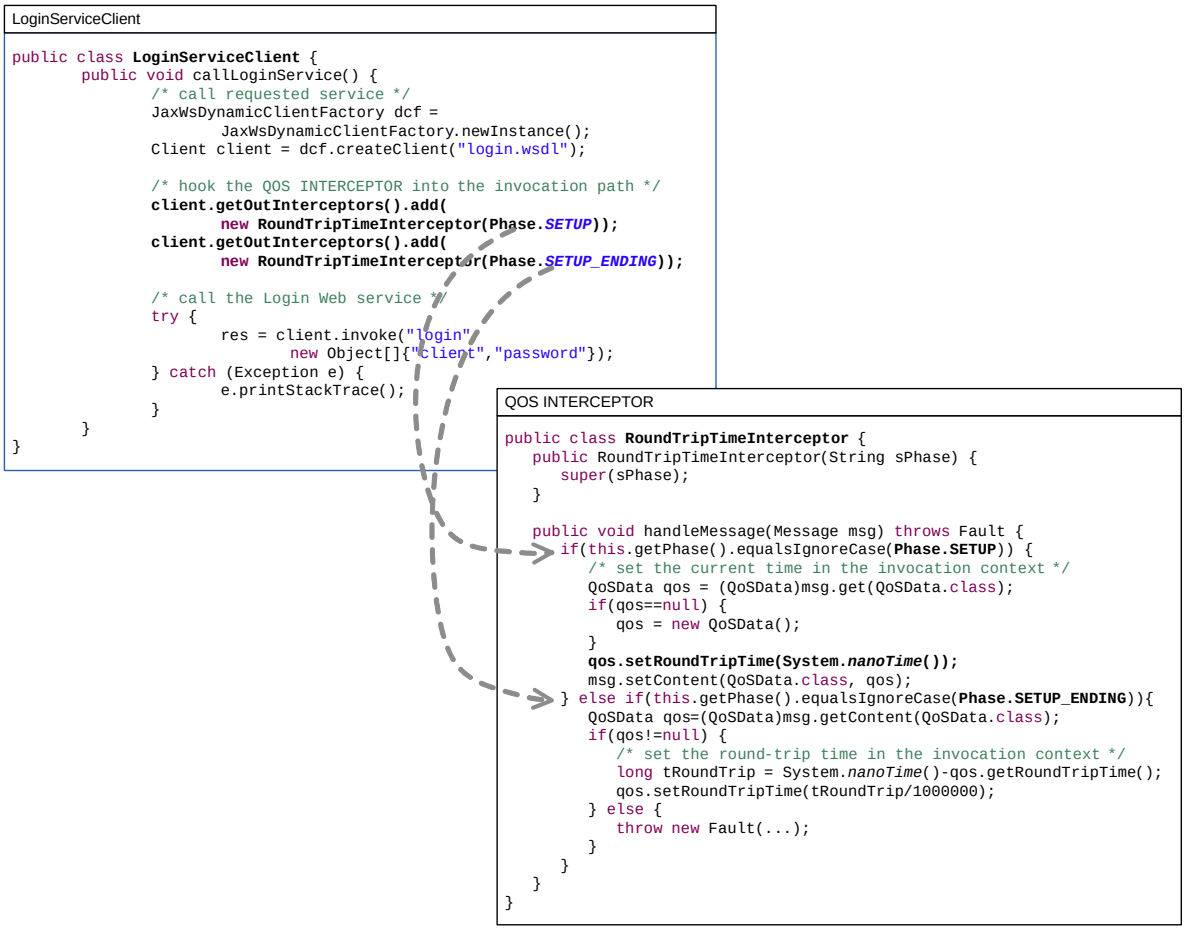


Figure 4.25: Measuring the round-trip time following the QOS INTERCEPTOR pattern

Figure 4.25 shows an excerpt of the client's implementation and the implemented QOS INTERCEPTOR for measuring the round-trip time of a web service invocation. First, the client initializes the generated stubs of the web service, creates objects of the interceptors, and defines where to place them into the invocation path. In our example, the `RoundTripTimeInterceptor` measures the round-trip

time between the `SETUP` and `SETUP_ENDING` phases of the client's `OUT` chain. The Apache CXF web service framework provides facilities for attaching the interceptors to the invocation path by calling the `getOutInterceptors().add()` method.

The `handleMessage` method of the `RoundTripTimeInterceptor` contains the business logic of the QOS INTERCEPTOR. In the `SETUP` phase, the interceptor puts the current time into the INVOCATION CONTEXT – `QoSData` – of the message. In the `SETUP_ENDING` phase, the interceptor calculates the time difference – the round-trip time – and puts it again into the INVOCATION CONTEXT.

Pattern: QOS REMOTE PROXY

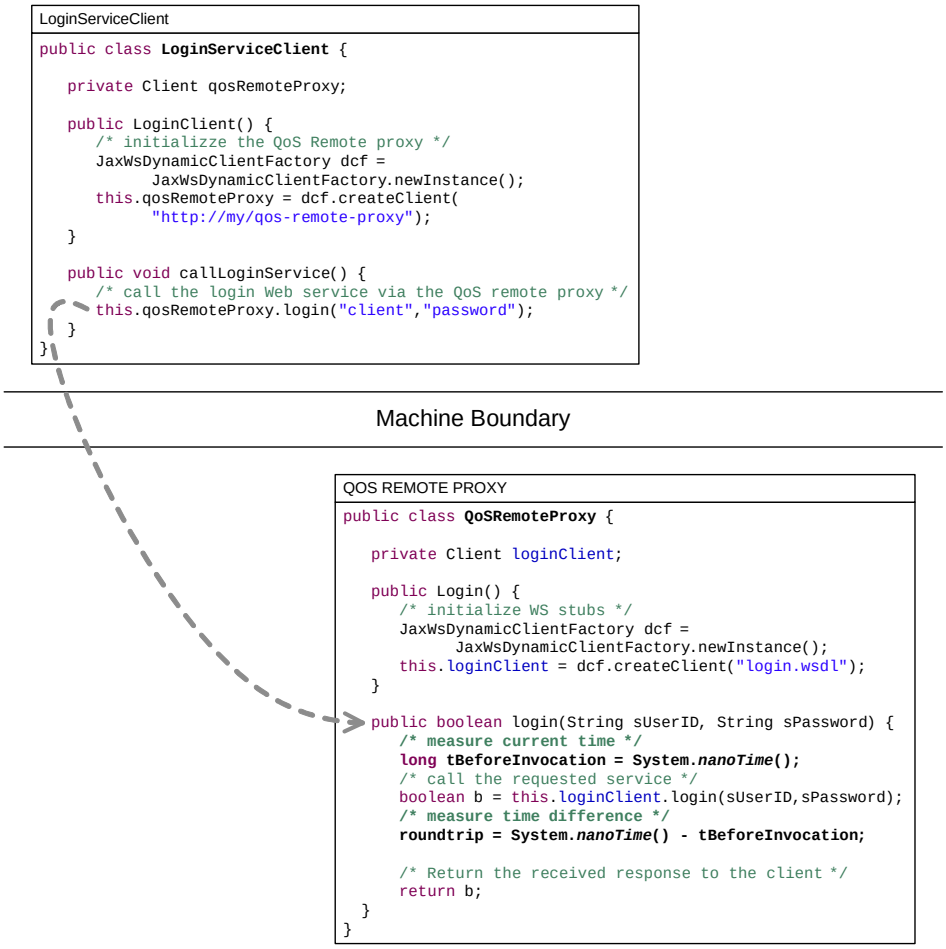


Figure 4.26: Measuring the round-trip time following the QOS REMOTE PROXY pattern

The QOS REMOTE PROXY offers interfaces to the clients to invoke remote objects and takes over the responsibility of measuring the performance-related QoS properties. In comparison to the previously

shown QOS WRAPPER example, the client does invoke the web service via the QOS REMOTE PROXY over the LAN and not directly.

We illustrate our Apache CXF implementation of a QOS REMOTE PROXY in Figure 4.26. The client invokes the `login` method of the QOS REMOTE PROXY instead of calling the web service's `login` operation directly. As illustrated, the QOS REMOTE PROXY performs the measuring of the performance-related QoS properties. In our example, the implemented QOS REMOTE PROXY measures the round-trip time of the web service invocation.

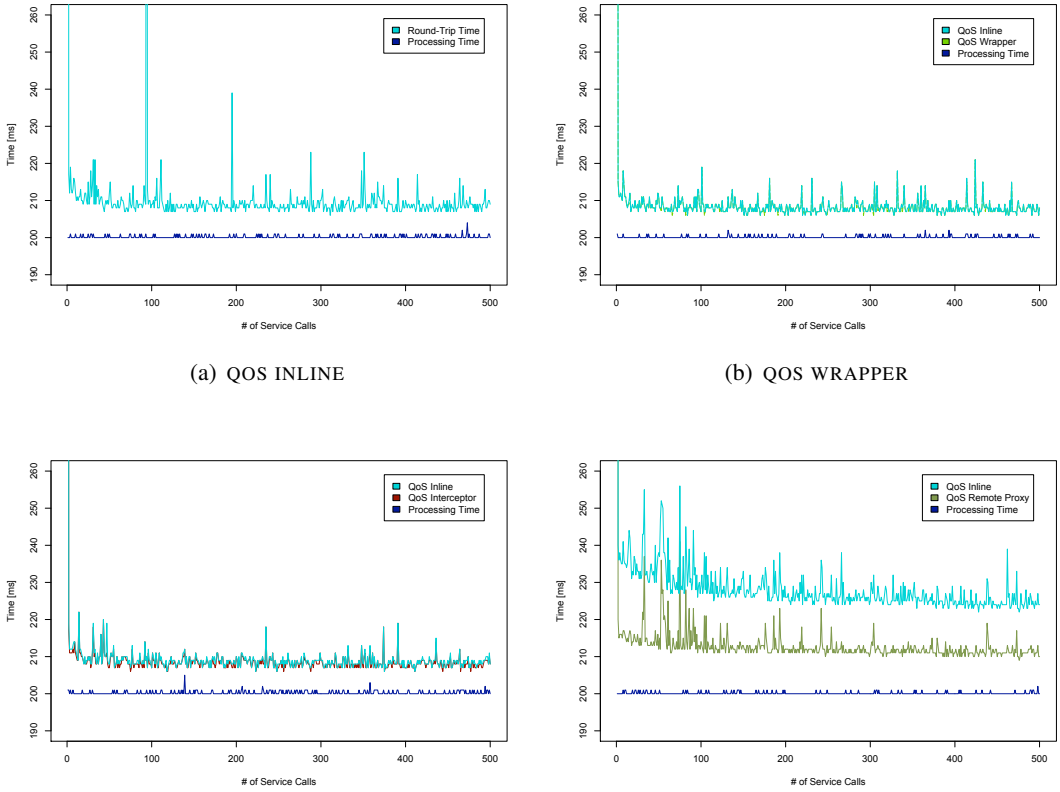
4.6.4 QoS Measurements during the Runtime

To evaluate the presented pattern implementations, the client invokes the web service 500 times every second and we measured the round-trip times in the client's QoS components. In the web service implementation we simulated a behaviour which lasts 200 milliseconds, i.e., the processing time of the web service is 200 milliseconds. All measurements – the round-trip time in the client's components and the processing time in the web service – are written into a local log file. Hence, all patterns – QOS INLINE in the client, the QOS WRAPPER, the QOS INTERCEPTOR, and the QOS REMOTE PROXY – were extended with a logging functionality.

The client was implemented in Java, running on a Mac with an Intel 2.4 GHz Core 2 processor and 2 GB of RAM. The web service was implemented using the Apache CXF web service framework and was running on a server having an Intel Xeon CPU with 3 GHz and 14.1 GB of RAM. The server's operating system was Ubuntu Linux version 10.04. The QOS REMOTE PROXY was running also on a server having an Intel Xeon CPU with 3.20 GHz and 10 GB of RAM. The QOS REMOTE PROXY's operating systems was again Ubuntu Linux version 10.04.

Figures 4.27(a), 4.27(b), 4.27(c), and 4.27(d) compare the QoS measurements, following the QOS INLINE, QOS WRAPPER, QOS INTERCEPTOR, and QOS REMOTE PROXY patterns, respectively. The x-axis indicates the number of the web service invocations and the y-axis the measured QoS properties, i.e., the round-trip time on the client-side and the processing time on the server side. In the implementation of the QOS WRAPPER, QOS INTERCEPTOR, and QOS REMOTE PROXY pattern we were also implementing the QOS INLINE pattern to see the differences between measuring the round-trip times within the client's source code or within from the client separated components.

- The CXF implementation of the QOS INLINE pattern (Figure 4.27(a)) shows that the first invocation of a web service is time-consuming. This arises because the time for generating and initializing the stubs for the web service invocations as well as the dynamic loading of the generated stubs is included in the measurement. Figure 4.27(a) illustrates in a good manner how long it takes that the result of the web service invocation is available at the client. In the QOS INLINE pattern, the time difference between the two measurements only reflect the network latency, resultant from possible network delays or jitters. It can not be discovered if time consuming web



(a) QOS INLINE

(b) QOS WRAPPER

(c) QOS INTERCEPTOR

(d) QOS REMOTE PROXY

Figure 4.27: CXF implementation of the measuring patterns

service invocations can result from other bottle-necks, such as marshaling and unmarshaling the request or the response.

- Figure 4.27(b) compares the QOS WRAPPER pattern with the QOS INLINE pattern, both implemented in the Apache CXF web service framework. As illustrated, the measurements of the round-trip time are mostly the same, meaning that the QOS WRAPPER implementation does not produce much overhead. In contrast, the QOS WRAPPER implementation provides a good separation of concerns because it does not modify the client's source code for measuring performance-related QoS properties.

- Figure 4.27(c) compares the CXF implementation of the QOS INTERCEPTOR pattern with the CXF implementation of the QOS INLINE pattern. Similar to the previous comparison, the QOS INTERCEPTOR implementation does not produce much overhead, resulting in almost equal measurements of the round-trip time. The implementation of the QOS INTERCEPTOR gives the ad-

ditional advantage that many performance-related QoS properties can be measured, such as the marshaling or unmarschaling times. Furthermore, the interceptors can be attached to the web service invocations dynamically.

- Figure 4.27(d) compares the QOS REMOTE PROXY pattern against the QOS INLINE pattern, both implemented in the Apache CXF web service framework. The measured round-trip times at the client implemented by following the QOS INLINE pattern are almost double the measured round-trip times at the CXF implementation of the QOS REMOTE PROXY. This arises from the additional hop in the LAN from the client to the QOS REMOTE PROXY.

4.7 Discussion

4.7.1 Aspect-oriented Implementation of the Measuring Patterns

A possible way to implement some of the presented patterns and to provide a good separation of concerns, is to follow the aspect-oriented programming (AOP) paradigm. An aspect is a construct that contains the separated concern's implementation and a description of how to weave it into the code [53, 54].

To improve the separation of concerns within the QOS INLINE pattern, its implementation can follow the AOP paradigm. Implementing an aspect-oriented QOS INLINE solution results in a QOS WRAPPER. The aspects of measuring performance-related QoS properties are separated from the client's or remote object's implementation, resulting in a good separation of concerns. Furthermore, the measuring aspects can be reused and attached to new deployed clients and remote objects.

The QOS INTERCEPTOR pattern can be implemented following the AOP paradigm. Such a solution is interesting if the middleware does not provide hooks for placing a QOS INTERCEPTOR into the invocation path.

In the case where the QOS REMOTE PROXY has additional responsibilities to measuring performance-related QoS properties, its implementation can follow the AOP paradigm. Hence, it is possible to separate the QOS REMOTE PROXY'S QoS measuring from its business logic.

4.7.2 Model-driven Generation of the Measuring Patterns

It is possible to generate the presented patterns and their components for measuring the performance-related QoS properties automatically. In general, all reusable parts can be generated automatically.

Following the QOS INLINE pattern, it is difficult to generate the measuring points into existing clients or remote objects. Only clients and remote objects that have to be newly deployed can be generated automatically including the measuring points. The client's or the remote object's imple-

mentation has to be developed manually. Following the AOP paradigm, it is possible to generate the required aspects for measuring the performance-related QoS properties automatically.

A QOS WRAPPER can be generated automatically and the generic parts of the client's and remote object's implementations for accessing the client or remote object via the QOS WRAPPER.

QOS INTERCEPTORS can be generated and attached to the client's and remote object's middleware automatically for measuring the performance-related QoS properties. Existing clients and remote objects can be extended easily.

It is possible to generate a QOS REMOTE PROXY automatically. New clients can be generated and configured to access the remote objects only via the generated QOS REMOTE PROXY. Also, it is possible to generate the remote objects automatically and to configure them that they are only accessible via a QOS REMOTE PROXY. Existing clients and services must be re-configured or re-deployed.

4.8 Summary

In this chapter we have presented an architectural design decisions model, guiding designers through the decision making process of a QoS monitoring infrastructure. In the scope of our work, a QoS monitoring infrastructure has to measure, evaluate, and store performance-related QoS properties, agreed within SLAs. Reporting of the evaluation and eventual SLA violations is however out of scope.

The architectural design decision model covers design decisions, requirements, and proposes design solutions. We have discovered the requirements and architectural design decisions in a thorough literature review and within the scope of the case study (see Chapter 3). The model's architectural design solutions extend and utilized well-established design patterns, such as the WRAPPER pattern [35], the INTERCEPTOR pattern, or the QOS OBSERVER pattern [124].

We have evaluated the model in the scope of the case study and presented the proposed solutions for the case study. We have also implemented the presented patterns for measuring the performance-related QoS properties in the case study and demonstrated some runtime QoS measurements. A discussion on using AOP or MDD to enhance the development of the QoS monitoring infrastructure's components is given. The models architectural design decisions, requirements, and solutions are summarized in the thesis' Appendix A.

Chapter 5

Supporting the Stakeholders to Specify QoS Compliance Concerns

Nowadays, many languages for specifying the performance-related QoS compliance concerns of distributed and service-oriented system exist, such as described in [40, 48, 56]. But, to the best of our knowledge, no language exists to specify the performance-related QoS agreements supporting technical and non-technical stakeholders. In this chapter, we present our approach of utilizing Domain-specific Language (DSL) that are developed following the Model-driven Development (MDD) paradigm. Our approach tailors the model-driven DSLs for the stakeholders, dependent on their domain and technical knowledge.

This chapter is organized as follows: Section 5.1 explains some needed background information for a better understanding of our approach. In Section 5.2 we illustrate our approach to support the differently skilled stakeholders. Section 5.3 presents a performed explorative study of our approach to develop model-driven DSLs for Service-oriented Architectures (SOAs). Then, in Section 5.4 we present a model-driven DSL that we have developed within the scope of the industrial case study presented in Chapter 3. In Section 5.5 we explain developed model-driven DSLs that also follow our approach. Section 5.6 lists some lessons that we have learned during the development of the various model-driven DSLs. We list related works in 5.7. Section 5.8 summarizes and concludes this chapter.

5.1 Background

5.1.1 Model-driven Development (MDD)

MDD is a paradigm for developing software by providing a separation of the software's functionality and the software's underlying technology. Models are used for designing systems, understanding them better, specifying required functionalities, and creating documentation. Usual development approaches

separate the models and the code by using, for example, models as documentation of the code. In MDD, the models' stakeholder do not see the source code because models replace the source code. Models are transformed by using code generators or transformation rules to executable source code. Then, the generated source code can be debugged, tested, and extended by manually written code by the programmers [50, 102].

To get a better understanding of MDD, we first explain the MDD's terminology. A *Domain*, also refered to application domain, is a bounded region of interests or knowledge, such as banking, healthcare, or telecommunication. An *Architecture* describes the artifacts of a system and the rules for the interaction between the artifacts using some connectors. A *Model* describes or specifies the domain's elements and its relationships. A model is an abstract representation of structure, functionality, and behaviour of a system. A model's *Semantics* describe the elements of a model and its meanings. A *Model Transformation* maps a model to another model of the same system or transforms the model into executable source code. A *Modeling language* is an interface for the models' stakeholders, making it possible that the stakeholders can specify model instances.

Mainly, MDD focuses on [108]:

- *Increasing the speed of development*
  Executable code can be achieved in a fast way by applying model transformations
- *Better maintenance of software*
  Bugs within the generated code can be abolished by simply changing the transformation rules. This results in a better avoidance of redundancy and improved maintenance facilities.
- *Higher degree of reusing software*
  Once defined architectures, modeling languages and transformations can be reused for the development of other software systems.
- *Better manageability of complexity by abstraction*
  The efforts of programming should be eliminated through modeling languages.
- *Raising the level of abstraction*
  Because models describe systems and their required functionalites, the technological details are hidden from the models' stakeholders. The code generators transform the models into executable source code.
- *Interoperability and portability*

To raise the level of abstraction, MDD should be domain-specific. The modeling language and the model transformations need to be domain-specific [50]. In the following we describe the artifacts of

model-driven domain-specific languages.

5.1.2 Domain-specific Languages (DSL)

A domain-specific language (DSL) is a small language that is particularly expressive in a designated domain. In the literature, many similar definitions of DSLs exists (see [30, 49, 65, 111]. However, all definitions have some communalities:

- A DSL is tailored for a designated *domain*
  A DSL contains language constructs that are similar or equivalent to the domain's artifacts and their relationship for specifying concrete domain problems [65, 79]. In comparison, a General Purpose Language (GPL), such as Java, C, or Perl, is designed to solve problems of arbitrary domains.

- A DSL is particularly *expressive*
  The goal of a DSL is to be more expressive, to better tackle complexity, and to make modeling easier and more convenient [50]. However, successful development of a DSL requires the involvement of domain and technical experts, including the design of the notation and the evaluation of the expressive power of the language.

- A DSL is a *small language*
  Instead of dealing with generality, like GPLs, a DSL offers only a limited number of artifacts of the designated domain [65].

- A DSL describes knowledge via a graphical or textual *syntax*
  A DSL's syntax is the notation that the DSL offers to its users for specifying concrete domain problems.

Types of DSLs

DSLs can be built in various styles. To get a better understanding of our work, we briefly describe some types of DSLs. A DSL can be either *embedded* or *external* [30, 111]. The difference between them lies in their concrete syntax.

- An *embedded* DSL is an extension of the used language workbench and has the same concrete syntax as the language workbench. An embedded DSL can directly access all features of the host language including libraries, frameworks, or other platform-specific components [111]. The language workbench's features, such as editors, debuggers, or compilers are immediately available and can directly be used within the embedded DSL. Examples of embedded DSLs are described in [33], [42], or [74].

- An *external* DSL offers its users a concrete syntax that is different from the language workbench's syntax. Hence, external DSLs come with the advantage that DSL designers may define any possible syntax, be it textual or graphical, without considering the syntactical particularities of a given host language. This said, an *external* DSL requires the development of a parser for reading the specifications and a mapping for mapping the parsed elements onto the DSL's language model. Furthermore, an external DSL is not bound to a certain host language or platform but can be mapped to different target platforms via transformations. In an external DSL, only the language elements exposed by the concrete syntax are available to the DSL user. Hence, it is impossible to use the features of the language workbench directly (as it is for embedded DSLs). Examples of frameworks for building external textual DSLs are Frag [135, 136], the Eclipse' Xtext framework [28], or the Microsoft's modeling platform "OSLO" [128]. Examples of external graphical DSLs are listed in [50].

5.1.3 Model-driven DSLs

Model-driven DSLs can help multiple stakeholders, with different background and expertise, to express relations and behaviors of a domain with familiar notations. The goal is that each stakeholder — maybe with the help of other stakeholders — can easily understand, validate, and even develop parts of the solution needed. For instance, domain experts do not have to deal with technological aspects, such as programming APIs or service interface descriptions. Domain experts can assist the technical experts that they can map not well-known domain problems to an appropriate technological model. This leads to an intense collaboration between the different stakeholders and lowers the possibility of misunderstandings.

We illustrate in Figure 5.1 a model-driven DSL's major artifacts (see also [108, 138]):

- A model-driven DSL is defined by using the terms of a *meta-model*. The constructs of the meta-model are used to define the DSL's language models or its abstract syntax.
- A model-driven DSL's central artifact is its *language model* or *abstract syntax* which defines the domain's artifacts of interest and their relationships. The *language model* defines the elements of the domain and their relations without considering their notations. Each abstract syntax can be pictured by multiple concrete syntaxes [12, 108].
- The *concrete syntax* describes the representation and notation of the domain elements and their relations in a suitable form for the DSL users and stakeholders. Hence, the DSL's concrete syntax is important from a stakeholder's perspective.
- A *model instance* is a specification of a concrete problem of the domain that was defined by using the DSL's concrete syntax. Abstract and concrete syntax enable the different stakeholders

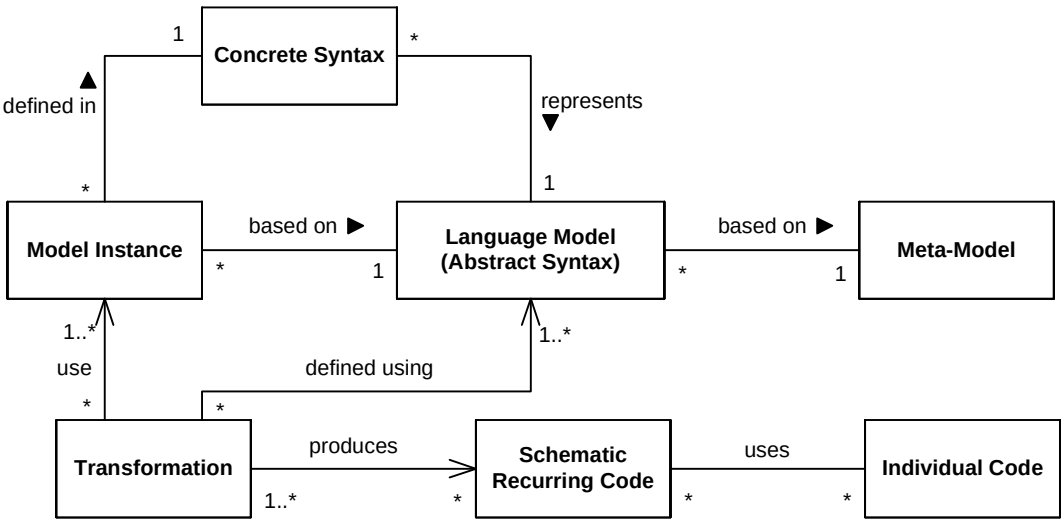


Figure 5.1: A model-driven DSL's major artifacts

to define model instances with a familiar notation. Also, we can say that a model instance is a DSL program.

- The ultimate goal of the *transformations*, which are defined on the model, is to transform the model instances into executable languages, such as programming languages or web service frameworks. There are different kinds of transformations, such as model-to-model or model-to-code transformations. In addition, there are different ways to specify transformations, such as transformation rules, imperative transformations, or template-based transformations, exist. The transformations generate all those parts of the (executable) code which are schematic and recurring, and hence can be automated.

5.2 Our Model-driven DSL Approach to Support the Stakeholders

To offer expressive and convenient languages for the different stakeholders, our approach provides a horizontal separation of model-driven DSLs into multiple sub-languages, where each sub-language is tailored to the appropriate stakeholders. We illustrate our approach of separating model-driven DSLs – from now on just called DSL – into two sub-languages at different levels of abstraction in Figure 5.2.

In this approach, we distinguish between high-level and low-level artifacts. Due to the diverse backgrounds and knowledges of the different stakeholders, it makes sense to present to each group of stakeholders only the models they need for their work, and omit other details, as proposed in [91]. We separated the artifacts into high- and low-level ones to achieve better understandability for the different stakeholders. High-level artifacts are relevant for non-technical stakeholders and represent

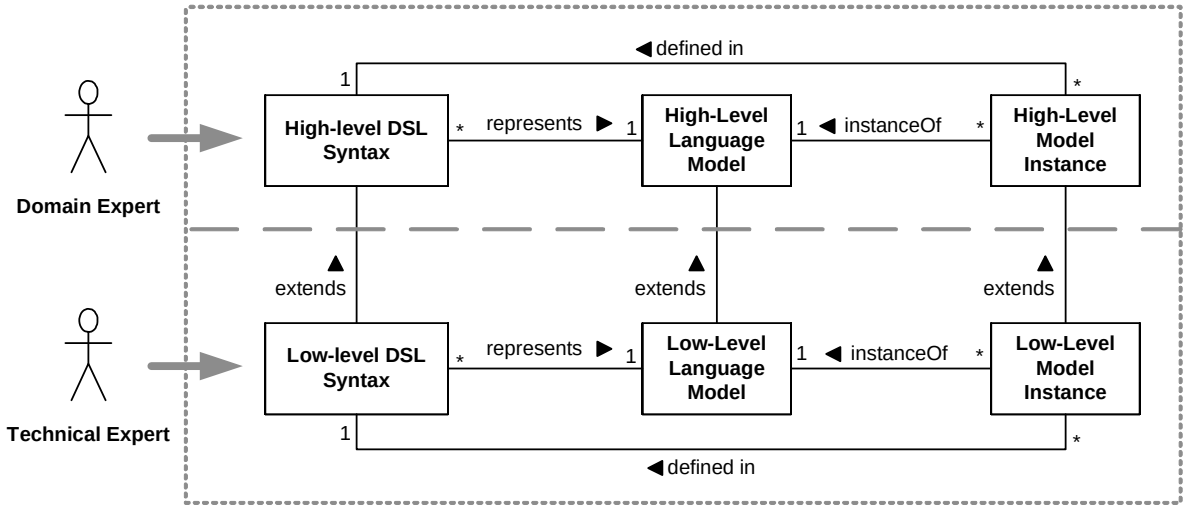


Figure 5.2: Separating a model-driven DSL into high- and low-level DSLs

the domain's artifacts that are of interest as well as their the domain's artifacts relationships. Low-level technical artifacts are relevant for technical stakeholders and represent the technology's artifacts that are needed for mapping the high-level artifacts onto the technological ones.

We design and tailor a high-level DSLs to support the domain experts, making it possible for domain experts to work with a language in which the domain artifacts are depicted in or close to the domain's artifacts. For instance, in the banking domain terms like account, bond, fund, or stock order are used in the high-level DSL.

Technical experts can express the additionally needed technical aspects with a low-level DSL where the terminologies and notations are close or equal to the artifacts of the underlying technology or platform. Technical experts utilize the low-level DSL to specify the technical details that are missing in the high-level DSLs. These details are needed by the model-driven code generator to turn the model instances, expressed in the DSLs, into an executable code (see Figure 5.1). For instance, in the process-driven SOA domain, relevant low-level concerns are service, service deployment, process variable, or database connection.

High-level and low-level DSLs represent appropriate language models. Low-level language models extend the high-level language models or vice versa, e.g., by using inheritance. Language models can have multiple DSL syntaxes. In our approach, we base the syntax of the high-level and low-level languages on its language models. Furthermore, language models can have multiple language model instances, which are defined using the DSL's syntax. High-level DSL syntaxes, language models, and model instances extend low-level DSL syntaxes, language models, and model instances respectively.

The DSLs are used to define model instances of the high-level and low-level language models. Each model instance represents concrete solutions of a particular problem of the domain. After the definition

of high-level and low-level model instances, schematic recurring code can be generated automatically, as illustrated in Figure 5.1.

Following our approach does not mean that only a separation into two levels, such as high-level and low-level, is possible. It is also possible to provide multiple different levels of abstractions where each level of abstraction is tailored to the designated stakeholders. The number of different levels of abstractions depends on the problem domain, as well as on the number of the different type of stakeholders.

5.3 An Explorative Study: DSLs for SOAs

Many DSLs for specific aspects of SOAs have been designed (see for instance [37, 64]). But, to the best of our knowledge, no study provides evidence for specific aspects and claims associated to SOA DSLs. Hence, this research field is clearly an explorative nature. For this reason, we have decided to use an explorative, qualitative research method to get insights and evidences in this study, following a similar approach to constructing a grounded theory [110].

In our case, the initial analysis has been performed by developing some DSLs in various projects (we also considered those reported in [36, 134]), as well as a thorough literature review and discussions with experienced and novice DSL developers. There are many ways to implement a DSL, such as using MDD or extending a dynamic language (see [31] for details). We have decided in favor of model-driven DSLs because, in our experience, the explicit support for language models is useful for representing the various domain concerns to the stakeholders, especially of a process-driven SOA.

5.3.1 The Study's Claims of Investigation

After the initial investigation phase, we decided to conduct an in-depth study of specific claims associated to model-driven DSLs using a controlled series of three prototyping experiments. In each experiment, we have developed a number of MDD-based DSL prototypes, as well as a model-driven infrastructure to generate a running process-driven SOA from the models expressed in the DSLs. The experiments deal with process-driven SOAs, as well as an extension of process-driven SOAs with Web UIs. In our experiments we focused on the design decisions made and on the design trade-offs that have been considered. At first we will to describe the experiments in detail and afterwards the main results. In the scope of this study, we tried to provide evidence or counter-evidence for the claims.

All three prototyping experiments have been conducted in a project that has run for twelve months and included four developers. Two developers worked with approximately 50% of their time for the full project duration, one contributed 20% of his time for the full duration, and one contributed approximately 50% of his time for five months. The project not only included DSL development, but also development of other artifacts, such as models and transformations, needed to obtain a running

prototype solution.

Claim I

Developing model-driven DSLs follows a systematic development approach [37, 107].

Claim II

A process-driven SOA encompasses multiple concerns, such as orchestration of business processes, information in processes, collaboration between processes and services, data, transactions, human-computer interaction, service deployment, and many more. To express these concerns, it is claimed that using model-driven DSLs reduces the complexity of the overall system, compared to a system developed without DSL and MDD support [5].

Claim III

Using model-driven DSLs for expressing SOA concerns enables developers and other stakeholders to work at a higher level of abstraction compared to using technical interfaces, such as programming APIs, executable process models expressed in BPEL code, or service interface descriptions such as WSDL (see [123]). Hence, model-driven DSLs can be tailored by providing constructs that are common to the domain the different stakeholders work in [8]. This enhances the readability and understandability of each DSL for the different stakeholders. Nevertheless, the different levels of abstractions imply the definition of integration points or transformation rules between the constructs of the DSLs from the different layers.

Claim IV

Due to the different levels of abstraction, it is claimed that language models should provide clear extension points for integrating new concerns [109].

5.3.2 Study Details

In our study, we performed three controlled experiments, in which a number of model-driven DSL prototypes have been developed:

- **Basic concerns**
  In this experiment we realized a number of DSLs for expressing a process-driven SOA's basic concerns, such as flow, information, and collaboration.

- **Extensional concerns**
  This experiment focused on extending process-driven SOAs with additional DSLs for supporting long-running transactions and human participation.

- **External concerns**
  Within this experiment, we realized a DSL for expressing non-process-driven SOA concerns, such as extensions of process-driven SOAs with Web applications, especially Web UIs.

Step-by-step we analyzed the various claims by reviewing and analyzing the design decisions made in our project. Within each experiment, we compared the different DSLs and their artifacts (such as DSL syntax, language models, transformations, and extension points) and used the results as input for our study. Also, the inputs led to refactoring of the DSLs in order to improve them. In addition, with each additional experiment stage, we compared the DSLs between the stages. That is, we followed a constant comparison method, as advocated by grounded theory approach [110], throughout our study. For comparison, we used different methods, such as expert reviews of our DSLs and models, student experiments with the models, and the application of the DSLs and models in industrial case studies.

In the first experiment, the language models were designed together and at the same time. The extension points were specifically designed to integrate the language models. The organization of the language models is shown in Figure 5.3(1). A Core language model provides the extension points for modeling the basic concerns of process-driven SOAs, such as collaboration, controlflow, and information. During the second experiment, the extension points were used to introduce extensional concerns for which the extension points in the basic models had not originally been designed for. The language model structure of the second experiment is shown in Figure 5.3(2). In the third experiment, we investigated in how far external extensions, i.e., non-process-driven SOA concerns, can be integrated with the existing language models for process-driven SOAs. In particular, we integrated Web UIs with the process-driven SOA models. The organization of the Web UI's language models is depicted in Figure 5.3(3).

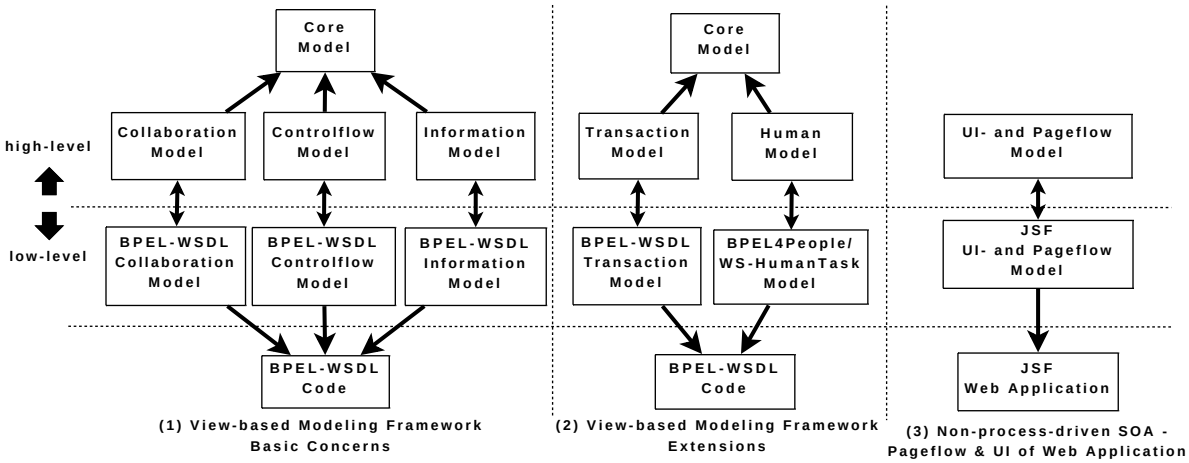


Figure 5.3: Experiments Overview

Process-driven SOA Basic Concern Language Models

The first experiment concentrates on basic concerns of process-driven SOAs, as well as following our model-driven DSL approach by providing high- and low-level DSLs for the different stakeholders [8]. The View-based Modeling Framework (VbMF) [121, 122] is a model-driven framework for reducing the development complexity in process-driven SOAs, as well as for improving the models' interoperability and reusability. It provides multiple language models, high-level and low-level ones, each responsible for a different concern of process-driven SOAs, such as flow, collaboration, or information. We illustrate the connection between the high-level and low-level language models in Figure 5.3(1).

In this experiment, we used a systematic top-down development approach as follows. First, high-level language models were designed. A central core language model provides extension points for defining new language models for the appropriate concerns. Furthermore, it provides extension points for various language models for basic and extensional concerns. The following language models extend the core language model for modeling basic concerns of process-driven SOAs:

- The **controlflow** language model offers constructs for modeling controlflows of business processes, which consist of many activities and control structures. Activities are process tasks, such as service invocations or data handling. The execution order of activities is described through control structures, such as conditional switches.

- To compose the functionality provided by services or other processes, the **collaboration** language model is used. This language model extends the core language model to represent interactions between a business process and its partners.

- The **information** language model represents the flow of data objects inside the business process. Furthermore, it provides a representation of message objects traveling back and forth between the process and the external world.

For each high-level language model, except the core language model, the low-level language models were designed as an extension of the high-level language models. Both the high-level and low-level language models are close to the concepts of BPEL and WSDL. Finally, the DSL syntaxes were developed. The high-level DSL syntaxes are based on the constructs of the high-level language models, whereas low-level DSL syntaxes are based on the constructs of the low-level language models. Hence, domain experts can – with the help of technical experts – use the high-level DSLs for modeling domain concerns, and technical experts can model technical concerns with the low-level DSLs.

Process-driven SOA Extensions

In contrast to the first experiment, which analyzed the basic concerns of process-driven SOAs, this experiment uses the introduced extension points of the core language model for integrating extensional concerns, such as an process-driven SOA's transaction and human interaction concerns. The goal of this experiment is to figure out if a systematic top-down development approach, as used in the first experiment, can be applied for extensional concerns of process-driven SOAs. We show the structure of the high- and low-level language models for both experiments in Figure 5.3(2).

To extend VbMF for long-running transactions, transactional concerns were integrated into the VbMF through a newly defined language model [121, 122]. In the same way as the controlflow, collaboration, and information language models were created, the first step was to design a high-level **transaction** language model which extends the core language model. Afterwards, a low-level transaction language model was designed which extends the high-level transaction language model. Like the low-level language models of the first experiment, the low-level transaction language model is based on BPEL and WSDL concepts too. Finally, the high-level and low-level DSLs' syntaxes were developed to support the modeling of transactions, based on the constructs of the appropriate language model.

A second extension of VbMF is the support of human interactions in process-driven SOA [41]. Again, a high-level **human** language model was designed which extends the core language model. Human aspects are assigned to processes and activities. A low-level human language model extends the high-level human language model, and it is based on concepts of BPEL4People [43] and WS-HumanTask [1]. Finally, the high- and low-level DSLs' syntaxes were implemented, based on the appropriate language models, to support the modeling of human tasks for SOA-based business processes.

Non-Process-Driven SOA Extensions: Web User Interfaces

The third experiment followed again a systematic top-down development approach, as adopted in the first two experiments. The language model hierarchy is depicted in Figure 5.3(3). The goal of this experiment is to figure out, if the systematic development approach can also be applied to extensions of process-driven SOAs with non-process-driven SOA concerns. The experiment deals with the modeling of web UIs for web pages, as well as process-oriented modeling of the pageflow through Java-like `IF-ELSE` statements. Web UIs contain the input and output components which are displayed to the user on the web pages. The pageflow provides the basis for selecting the subsequent web page that should be displayed to the user, dependent on the current page and the user interactions, such as which link or button the user presses.

First, the high-level language model is introduced for modeling the pageflow and the UIs of the Web pages. A low-level language model for modeling the pageflow is introduced which is based on

the pageflow definition of the Java Server Faces (JSF) [112] web application technology. The DSLs were implemented to provide suitable modeling of the pageflow and the UIs. The developed DSLs provide constructs that are very similar to the language model. In this experiment, there was no need for a mapping between the constructs of the DSL and the constructs of the language model.

5.3.3 Study Results

The experiments provided some useful insights into design decisions required during the design of model-driven DSLs for process-driven SOAs:

- *There exists a design decision regarding the relation between the DSL's concrete syntax and the DSL's language model*
  We observed that in all three experiments the relationship between the names used in the DSL syntaxes and the names of the constructs defined in the language models was a concern. In all three experiments, we decided that the DSL syntaxes provide constructs that are named equivalently to the constructs in the language model. If the DSL syntax constructs are not named equivalently to the language model constructs, a more complex mapping between DSL and language model constructs is required, which means that extra efforts are required to develop this mapping. The mapping might also make the relationships between syntax constructs and models harder to understand. However, with a different naming in models and syntaxes, the syntax and modeling elements can be tailored more easily.

- *Low-level language models are extensions of high-level language models*
  In all three experiments, the low-level language models are extensions of the high-level language models. Hence, a relationship exists between them. A design decision must be made, in which order and dependency the high-level and low-level models are designed. The high-level language models can be designed first, followed by the low-level language models. Hence, domain concerns can be expressed close to their domain notions, such as compliance concerns in business processes. Another possible design approach is to derive the high-level language models from the low-level language models, which are based on technical concerns, such as constructs similar to BPEL (as done in our basic models). In this case, emphasis must be put on the high-level design of technical concerns, in order to make them understandable to domain experts, too. This is often not easy. Yet another approach is to design high- and low-level language models and DSLs in parallel. The main problem lies in the huge differences between the offered constructs of the languages. Examples are languages like the Business Process Modeling Notation (BPMN) and BPEL. This approach requires a mapping between the often incompatible high-level and low-level language models, with possible inconsistencies. A part of this design decision is the development order of the high- and low-level language models and DSL syntaxes.

If possible, the design of the high-level DSL syntax and language models should be performed together with the domain experts.

- *There is a trade-off between the extension points and the language models' complexity*
  In the first two experiments, which deal with basic and extensional concerns of process-driven SOAs, multiple language models where used. Multiple language models reduce the complexity by separation of concerns. This leads to providing tailored views for the different stakeholders. The main challenge of splitting lies in finding appropriate extension points to merge models. Poor extension points can lead to inconsistencies between the models. In addition, merging through extension points is more complex than using modeling abstractions, such as associations. In the third experiment, one language model is used for modeling the pageflow and UIs of Web applications. Having only one language model does not provide a good separation of concerns for the development team and other stakeholders, but, on the other hand, there is no need for providing suitably designed extension and integration points, as well as possibly complex merging algorithms for the integration of multiple models. The design decision is whether it makes sense to split one language model into multiple models or not, and if splitting is chosen, where to split. Trade-offs for this design decision regard the number of concerns, development teams, and stakeholders.

Evidences for the claims:

- It is possible to follow a systematic top-down development approach, such as the one described in our three experiments in Section 5.3.2. In our case, this is not only valid for process-driven SOAs but also for non-process-driven SOA concerns, such as in our case Web applications.
- The systematic development approach used for the basic concerns of process-driven SOAs, such as controlflow, collaboration, or information of process-driven SOAs, can be followed for modeling extensional concerns, such as the transactional or human concerns in our experiments.
- Through a separation in high- and low-level DSLs, it is possible to support different stakeholders with different background and knowledge, i.e., domain experts and technical experts.
- Model-driven DSLs can enhance the understandability and readability for the individual stakeholders of a process-driven SOA. Furthermore, model-driven DSLs can reduce the complexity of process-driven SOAs.

Counter-evidences and design trade-offs:

- It is possible that the integration of high- and low-level concerns lead to DSL language design issues, such as redundancy in languages, inconsistencies, and which language should be chosen for overlapping concerns.
- Detailed separations of one language model into multiple ones can result in loose coupling of the different language models. Thus, the result is: the more detailed the separation, the more complex the model integration points for merging the different application models. Possible ways to achieve model integration are name-based matching, ontology-based matching, or inheritance. Hence, there is a trade-off between the complexity of the integration points and the degree of separation of concerns achieved in the language models.
- We observed another trade-off between model integration point design for the different stakeholders and the understandability, as well as the readability. The more complex the integration points are, the less understandable and readable the DSLs and/or their language models become in many cases. Hence, enhancing understandability and readability for one type of stakeholders increases the complexity of integrating models for other stakeholders. That is, the complexity for stakeholders, who need to integrate and understand all models at once, can rise even though the complexity for individual stakeholders decreases.

5.4 QuaLa: A Model-driven DSL for Specifying QoS Compliance Concerns

In this section, we present a model-driven DSL, named Quality of Service Language (QUALA). QUALA was developed within the scope of the industrial case study, presented in Chapter 3. QUALA follows our approach of developing model-driven DSLs to support the various stakeholders (see Section 5.2. The purpose of QUALA is to enable the case study's stakeholders to specify the case study's web services' QoS compliance concerns that are defined within SLAs. Furthermore, actions can be defined which should be performed if the SLA's QoS negotiations get violated. QUALA provides the facility of specifying QoS compliance concern rules, making it possible to describe the QoS compliance concerns to perform predictive QoS monitoring.

Within the case study, we divided QUALA into two DSLs: The first one, the high-level QUALA, is tailored for domain experts, whereas the second one, the low-level QUALA, is tailored for technical experts. The low-level QUALA extends the high-level one with the additionally needed technical artifacts. Merging both DSLs results in a complete description of the case study's QoS-aware web services, making it possible to generate the web services and the QoS monitoring infrastructure automatically.

With the high-level QUALA, domain experts are able to model which performance-related QoS properties have to be measured for a specific web service to fulfill the contractually agreed SLAs, as well the actions that should be performed in case of SLA violations. The high-level QUALA provides expressive notations that are named similar to the terminology of the QoS and the SLA domains. An example of specifying the given requirements is: If the *ProcessingTime* of *Service X* is *longer than 10 seconds*, then send an *e-mail* to the administrator of the service provider.

Technical experts work with the low-level QUALA that is tailored for specifying how to measure case study's performance-related QoS properties in the used web service framework, as well as how to perform the specified actions. Similar to the high-level QUALA, we name the constructs and expressions of the low-level QUALA equivalent to the particular technology's artifacts.

5.4.1 The high-level QuaLa

Within the case study, we formulated the requirements on the high-level QUALA as follows: it should be possible to specify SLAs that contain the web services' QoS compliance concerns. To be able to perform predictive QoS monitoring, it should be possible to define rules as combinations of QoS compliance concerns using logical operators, such as AND or OR. Furthermore, it should be possible to specify actions that have to be performed in case a rule gets violated.

The high-level QuaLa's language model

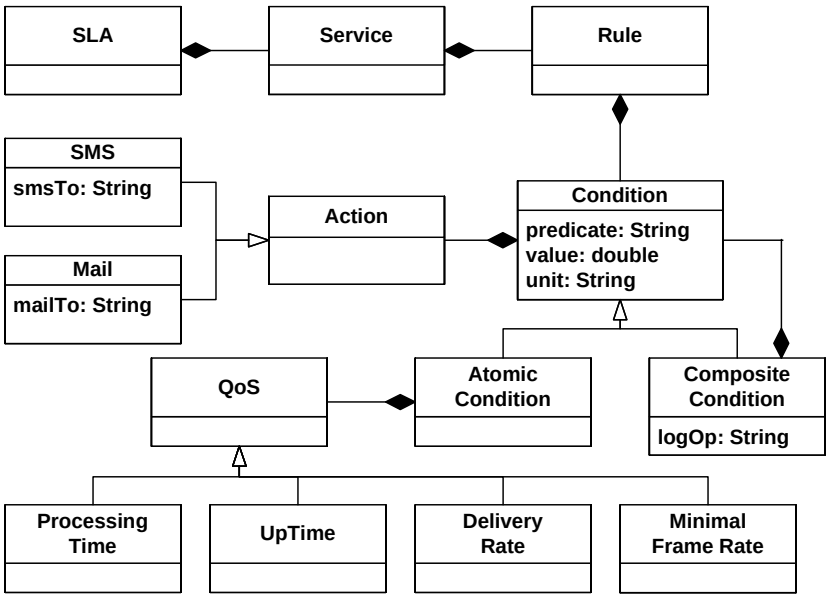


Figure 5.4: The high-level QUALA's language model

To fulfill the high-level QUALA's requirements, we designed a language model that we present in Figure 5.4. In the high-level QUALA's language model, `SLAs` consist of `Services` that are connected to `Rules`. A rule consists of multiple `Conditions`. Conditions are of type `AtomicConditions` or `CompositeConditions`. A composite condition consists of multiple conditions, atomic or composite ones. Atomic conditions are linked to the `QoS` properties. Each condition can be connected to `Actions` that should be performed.

Comparing the language model and the requirements, we can define SLAs with rules of QoS compliance concerns and actions in case of SLA violations.

The high-level QuaLa's Concrete Syntax

```
sla-specification = sla-name '{' [service-name '{' [qos-constraint]* '}']* '}'
qos-constraint = rule '=>' action [',']?
rule = condition [logical-operator ['(']? condition [')']?]+
condition = qos-property operator predicate
qos-property = 'UpTime' | 'ProcessingTime' |
               'DeliveryRate' | 'MinimalFrameRate'
operator = '<' | '<=' | '>' | '>='
predicate = number unit
unit = '%' | 'd' | 'h' | 'm' | 's' | 'fps'
logical-operator = 'AND' | 'OR'
action = mail-action | sms-action
mail-action = 'mailto' '"' mail-address '"'
sms-action = 'smsto' '"' phone-number '"'
```

Figure 5.5: The high-level QUALA's concrete syntax

In Figure 5.5 we present the high-level QUALA's concrete syntax using EBNF [90]. The high-level QUALA is an external DSL [30, 111] and has a textual block-oriented concrete syntax. An `sla-specification` starts with the SLA's name followed by a block (delimited by { and }) of services and their QoS constraints. The specification of a service's QoS compliance concerns starts with the service's name followed by a block (again, delimited by { and }) of `qos-constraints`. A QoS constraints consists of a `rule`, an arrow (`=>`), and an to performing `action`. Rules are separated by a colon (`,`). A rule is an optional combination of multiple `conditions` that are connected by a `logical-operator`.

For a better understanding of the high-level QUALA's concrete syntax we present an example of using the high-level QUALA within the case study in Section 5.4.4.

5.4.2 The low-level QuaLa

The expressions of the low-level QUALA depend on the used underlying technologies used for hosting the web services. We decided to use the open-source Apache CXF web service framework [115] in our prototype. The technical artifacts of the Apache CXF web service framework are: The communication

between the service customer's client and the service provider's services is based on message-flows. Each message-flow consists of a number of phases, where each phase can contain interceptors to measure the performance-related QoS properties. For instance, to measure the web services' processing time, we can hook interceptors into phases before and after the web services' processing.

The low-level QuaLa's language model

The low-level QUALA's language model extends the high-level QUALA's one by using inheritance, to enrich and extend the high-level language model with the additionally needed technical artifacts, such as how the processing time is measured within the particular web service framework. The low-level QUALA's language model contains all necessary technological artifacts for extending the high-level specifications to generate a running system.

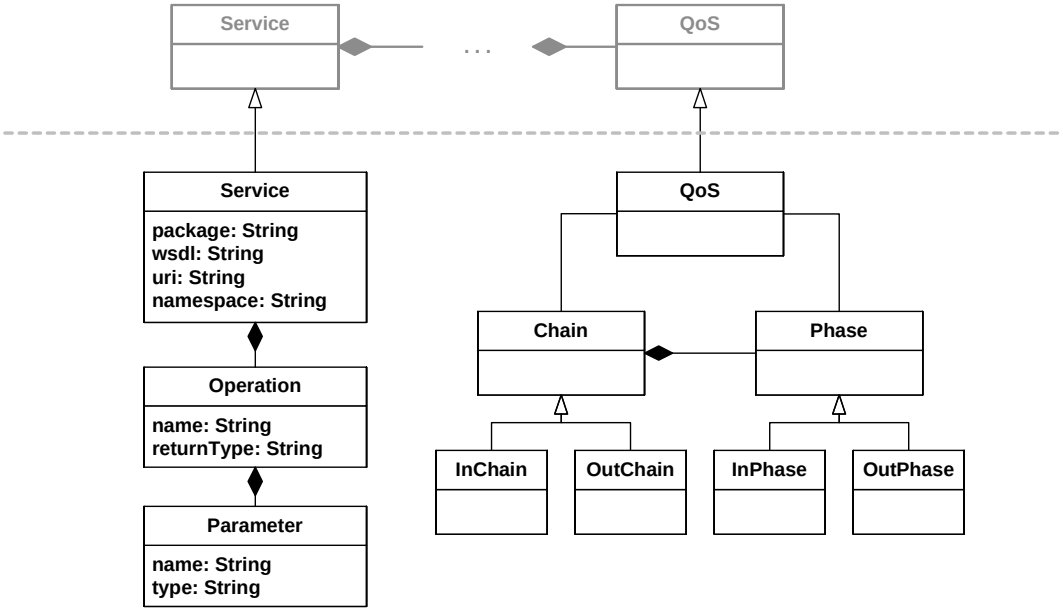


Figure 5.6: The low-level QUALA's language model

In Figure 5.6 we present the low-level QUALA's language model. The low-level classes `Service` and `QoS` extend the high-level classes `Service` and `QoS` respectively by using inheritance. In the low-level language model we provide classes for specifying a service's `Operations` and their `Parameters`. Furthermore, we provide classes for specifying in which `Chains` and in which `Phases` the performance-related QoS properties have to be measured, whereas `Chains` consist of multiple `Phases`. We divide chains and into `InChains` and `OutChains` that are responsible for handling the incoming and outgoing messages respectively. Also, we divide phases into `InPhases`

and `OutPhases`. `InPhases` are assigned to `InChains`, `OutPhases` are assigned to `OutChains`. We check the correct assignments of phases to chains by using the Frag Constraint Language (FCL) [135]. A `QoS` property is assigned to one or two chains (`1..2`) and in one or two phases (`1..2`), making it possible to specify the chains and phases in which the QoS properties have to be measured.

The low-level QuaLa's concrete syntax

The low-level QUALA is an embedded DSL, i.e., its concrete syntax is equivalent to the language workbench's syntax in which it was developed. We implemented QUALA usind the Frag language workbench[135, 136]. Hence, the low-level QUALA's concrete syntax is equivalent to Frag's syntax. We give an example of using the low-level QUALA within the industrial case study in Section 5.4.4.

5.4.3 QuaLa Code Generation Templates

```
public class <~GeneratorUtils removeNamespace [$condition qos]~>Interceptor
   extends AbstractSoapInterceptor {
...
     public void handleMessage(SoapMessage msg) throws Fault {
           <~ self applyIf {[list length [[$condition qos] phases]] == 2} {

          if(this.getPhase().equalsIgnoreCase(Phase.
                    <~QuaLaGenerator mapPhase [list index [[$condition qos] phases] 0]~>)) {

              InvocationContext qos =
                  (InvocationContext)msg.get(InvocationContext.class);
              if(qos==null) {
                 qos = new InvocationContext();
              }

              qos.set<~GeneratorUtils removeNamespace [$condition qos]~>(System.nanoTime());
              msg.setContent(InvocationContext.class, qos);
          } else if(this.getPhase().equalsIgnoreCase(Phase.
                    <~QuaLaGenerator mapPhase [list index [[$condition qos] phases] 1]~>)) {

              InvocationContext qos=
                  (InvocationContext)msg.getContent(InvocationContext.class);
               if(qos!=null) {
                   long nDiff = System.nanoTime()-qos.get<~GeneratorUtils removeNamespace [$condition qos]~>();
                    System.out.println("<~GeneratorUtils removeNamespace [$condition qos]~>Interceptor => "+nDiff);
                   qos.set<~GeneratorUtils removeNamespace [$condition qos]~>(nDiff);
               } else {
                   throw new Fault(
                         new Exception("<~GeneratorUtils removeNamespace [$condition qos]~>
                                      not found in invocation context!"));
               }
          }
      }
...
}
```

Figure 5.7: The QUALA code generation template for generating a QOS INTERCEPTOR

The QuaLa DSL consists of a code generator that produces executable code out of the high- and low-level QUALA specifications. In QUALA, we use a template-based code generation approach. In the Figure 5.7 we exemplify a code generation template to generate the interceptors that measure the

performance-related QoS properties.

As the QoS properties are measured between two phases of the message-flow, interceptors are placed in these two phases. In the first phase, the QoS interceptor takes the current time and puts it into the invocation context. In the second phase, the interceptor calculates the elapsed time, i.e., the time difference between the first execution of the interceptor and the current time. The calculated time difference is again stored in the invocation context and can be used for further processing.

Besides the interceptors for measuring the web services' performance-related QoS properties, the QUALA code generator generates the following components:

- A skeleton of the web service implementation that must be extended with the web services behaviour manually
- A host that hosts the web services
- Optionally, a client that for testing the web service invocations and behaviours

5.4.4 Using QuaLa within the Case Study

Because QUALA was developed within the scope of an industrial case study (see Chapter 3), we want to illustrate an example of using QUALA within the case study. First, we describe the usage of the high-level QUALA, followed by the usage of the low-level QUALA. In this example, we specify the QoS compliance concerns of the `Login`, `Search`, and `Stream` web services.

Using the High-level QuaLa

In Figure 5.8 we illustrate an example of using the high-level QUALA for specifying the MVNO's web services' QoS compliance concerns.

For the `Login` web service we define a rule for predictive QoS monitoring. The first condition specifies that the `UpTime` of the `Login` web service must be greater than 99% (`>99%`), otherwise we have to inform a system administrator (`mailto "sysadmin@mvno.com"`). The second condition specifies that the the `Login` service's `UpTime` must be greater than 95% (`>95%`), otherwise send an SMS to the given number (`smsTo "+1 234 5678"`).

For the `Search` web service we specify a rule of one composite condition. The composite condition consists of two atomic conditions saying that the `UpTime` must be greater than 99% (`>99%`) `AND` the `ProcessingTime` must be less then two minutes (`<2min`). In case one of the two atomic conditions gets violated, an e-mail should be send to the MVNO's system administrator (`mailto "sysadmin@mvno.com"`).

The `Stream` web service has to comply to two rules where each consists of one atomic condition. The first rule states that the `MinimalFrameRate` of the streamed multimedia content must be

```
WatchmeSLA {
        Login {
                UpTime>99% => mailto "sysadmin@mvno.org",
                UpTime>95% => smsto "+1 234 5678"
        }
        Search {
                UpTime>99% AND ProcessingTime<2min
                        => mailto "sysadmin@mvno.com",
        }
        Stream {
                MinimalFrameRate>30fps => mailto "sysadmin@mvno.org",
                DeliveryRate>80% => smsto "+1 234 5678"
        }
}
```

Figure 5.8: Using the high-level QUALA within the case study

greater then 30 frames per second (`>30fps`). If not, send an e-mail to the MVNO's system administrator (`mailto "sysadmin@mvno.com"`). The second rule specifies the the `DeliveryRate` of the streamed multimedia must be greater than 80% (`>80%`). If not, send an SMS to the specified number (`smsTo "+1 234 5678"`).

Using the Low-level QuaLa

We use the low-level QUALA within the industrial case study to specify the technological artifacts of measuring the performance-related QoS properties. First, we use the low-level QUALA for specifying the technological artifacts of the Apache CXF web service framework. Second, we use the low-level QUALA for extending the high-level specifications with the technological requirements.

Specifying the Apache CXF Architecture

In the example, we illustrate how the specified chains and phases, as well as between which phases the performance-related QoS properties have to be measured. As the low-level QUALA is an embedded DSL, its concrete syntax is equivalent to Frag's syntax [135, 136].

In Figure 5.9 we illustrate the usage of the low-level QUALA for specifying the Apache CXF web service framework's architecture. First, we define that the in- and out-chains of the server that hosts the web services (`cxf::InChain create ServerIn` and `cxf::OutChain create ServerOut`). We also specify the phases (`cxf::InPhase create InPreInvoke` and `cxf::InPhase create InInvoke`). The classes' prefix `cxf::` is the namespace of the low-level QUALA's language model. We've chosen this namespace because the low-level language model is designed for the Apache CXF web service framework. Then, we assign the phases to the chains (`ServerIn phases`

```
## the chains' specifications
cxf::InChain create ServerIn
cxf::OutChain create ServerOut
...

# the phases' specifications
cxf::InPhase create InPreInvoke
cxf::InPhase create InInvoke
...

# assign the phases to the chains
ServerIn phases {InPreInvoke InInvoke ...}

## specify where to measure the round-trip time
ProcessingTime classes cxf::QoS
ProcessingTime chains ServerIn
ProcessingTime phases {InPreInvoke InInvoke}
```

Figure 5.9: Example of using the low-level QUALA for specifying the technological artifacts

{`InPreInvoke InInvoke`}). Finally, we specify between which phases of which chain the web services' processing time have to be measured, i.e., between the `InPreInvoke` and `InInvoke` phases of the `ServerIn` chain. Equivalently we define the measuring points for each performance-related QoS property that is of interest within the case study.

Specifying the services' technical artifacts

Each service in the high-level QUALA specifications has to be extended with low-level technical concerns. In Figure 5.10 we illustrate how to use the low-level QUALA for specifying the services' technical artifacts.

In our case, we transform each service – `Login`, `Search`, and `Stream` – to an instance of the low-level class `Service` that is part of the `cxf` namespace (`Login classes cxf::Service`). Then, we specify the `package`, `WSDL`, `URI`, and `namespace` of each web service.

```
## LOGIN SERVICE
Login classes cxf::Service
Login package "eu.compas.watchme"
Login uri "http://localhost:5001/watchme/login"
Login wsdl "http://localhost:5001/watchme/login?wsdl"
Login namespace "http://www.compas-ict.eu/watchme/login"
Login operations [list build \
       [cxf::Operation create login -name "login" -returnType UUID -parameters [list build \
              [cxf::Parameter create pUsername -name "username" -type String]
              [cxf::Parameter create pPassword -name "password" -type String]]]]

## SEARCH SERVICE
Search classes cxf::Service
Search package "eu.compas.watchme"
Search uri "http://localhost:5001/watchme/search"
Search wsdl "http://localhost:5001/watchme/search?wsdl"
Search namespace "http://www.compas-ict.eu/watchme/search"
Search operations [list build \
       [cxf::Operation create search -name "search" -returnType String -parameters [list build \
              [cxf::Parameter create sMovie -name "movie" -type String]
              [cxf::Parameter create sLanguage -name "language" -type String]]]]

## STREAM SERVICE
Stream classes cxf::Service
Stream package "eu.compas.watchme"
Stream uri "http://localhost:5001/watchme/stream"
Stream wsdl "http://localhost:5001/watchme/stream?wsdl"
Stream namespace "http://www.compas-ict.eu/watchme/stream"
Stream operations [list build \
       [cxf::Operation create stream -name "stream" -parameters [list build \
              [cxf::Parameter create sStreamID -name "streamID" -type String]]]]
```

Figure 5.10: Extending the high-level QUALA specifications with technological artifacts

Generated Code

Now, we illustrate an excerpt of the case study's generated code by using QUALA. In Figure 5.11 we exemplify the generated QOS INTERCEPTOR for measuring the processing time.

As specified in the low-level QUALA (see Figure 5.9), we place the interceptor for measuring the web service's processing time into the two phases `PreInvoke` and `Invoke`. As specified in the code generation template (see Figure 5.7), in the `PreInvoke` phase the interceptors puts the current time into the invocation context, i.e., the current time before the web service invocation. In the `Invoke` phase the interceptors takes the current time again, i.e., the time after the web service invocation. The time difference between the time before and after the web service invocation results in the web service's processing time.

```
public class ProcessingTimeInterceptor extends AbstractSoapInterceptor {
...
	public void handleMessage(SoapMessage msg) throws Fault {
		if(this.getPhase().equalsIgnoreCase(Phase.PRE_INVOKE)) {
			InvocationContext qos =
				(InvocationContext)msg.getContent(
							InvocationContext.class);
			if(qos==null) {
				qos = new InvocationContext();
			}
			qos.setProcessingTime(System.nanoTime());
			msg.setContent(InvocationContext.class, qos);
		} else if(this.getPhase().equalsIgnoreCase(Phase.INVOKE)) {
			InvocationContext qos =
				(InvocationContext)msg.getContent(
							InvocationContext.class);
			if(qos!=null) {
				long nDiff = System.nanoTime()-qos.getProcessingTime();
				System.out.println("ProcessingTimeInterceptor => "+nDiff);
				qos.setProcessingTime(nDiff);
			} else {
				throw new Fault(new Exception(
					"ProcessingTime not found in invocation context!"));
			}
		}
	}
...
}
```

Figure 5.11: A generated QOS INTERCEPTOR for measuring the processing time

5.4.5 QuaLa – Concluding Remarks

During the development of QUALA within the scope of an industrial case study, by following our approach of tailoring model-driven DSLs for the various stakeholders, we discovered the following: The low-level QUALA can be divided into two languages. The first language is a language for describing the architecture of the used technology, i.e., on our case the Apache CXF web service framework. These technological artifacts must be described only once because the chains and the phases of the Apache CXF web service framework, as well as the way of measuring the performance-related QoS properties do not change. For example, the processing time will always be measured between the `InPreInvoke` and `InInvoke` of the `ServerIn` chain (see Figure 5.9). Only changes or updates of the underlying technology imply changes in the language model in the low-level architectural specifications, for example by switching from the Apache CXF web service framework to Apache Axis [113]. The second language is used for extending the high-level specifications with technological artifacts, such as the services' WSDL locations or namespaces (see Figure 5.10). These low-level specifications have to be done for each high-level specification. However, it is also possible to define in this case default-values for such attributes that can be derived from the high-level specifications.

5.5 Similar DSL Projects

In this section, we explain briefly how we applied our approach of tailoring model-driven DSLs in two other similar projects. We explain the DSLs' purpose, its' language model and exemplify the DSLs.

5.5.1 A DSL for Specifying a Role-Based Pageflow of Web Applications

Within this project, we developed a high-level DSL for describing an web-application's page flow based on the visitor's authorizations. A web application's pageflow describes to which web pages visitors can navigate, dependent on the current page. The visitor can only navigate to other web pages by interactions with hyperlinks or buttons. The subsequent web page depends on the hyperlink or button which the visitor clicks and . To avoid a late security integration into the web application's development process, we designed a DSL to combine the pageflow and the visitors' authorizations, using role-based access control models (RBAC) [94]. A well arranged readability of the pageflow can be achieved by defining the pageflow using Java-like `IF-ELSE` statements.

The DSL's Language Model

In Figure 5.12 we present the Pageflow DSL's language model by using a UML class diagram. Each `WebApplication` consists of a number of `Pages`, and one page is depicted as the `startPage`. `Pages` contain `NavigationRules` which define the page flow. The classes `If`, `ElseIf` and `Else` are defined to achieve a Java-like `IF-ELSE` page flow definition. These classes are derived from the `Decision` class which contains a reference to the subsequent web page through the `gotoPage` association. The referenced web page is displayed if the outcome of the performed actions is equivalent to a corresponding `outcome` attribute, specified in the `If` and `ElseIf` classes. If no corresponding `outcome` attribute is found, the web page specified by the `gotoPage` reference of the `Else` class is displayed to the visitor.

The assignment of RBAC to the definition of the pageflow is provided through the association between the `Decision` and `Role` classes. Hence, an `IF-ELSE` definition of a rolebased pageflow definition is achieved, such as

```
IF outcome="..." AND role="..." THEN gotoPage="..."
```

As introduced by Sandhu et al. [94], a `Role` consists of one or more `Users` and of one or more `Permissions`. A `Permission` is responsible for defining if a user has access to a certain web page or not. It is planned that more permissions will be introduced, e.g., write or publish web pages.

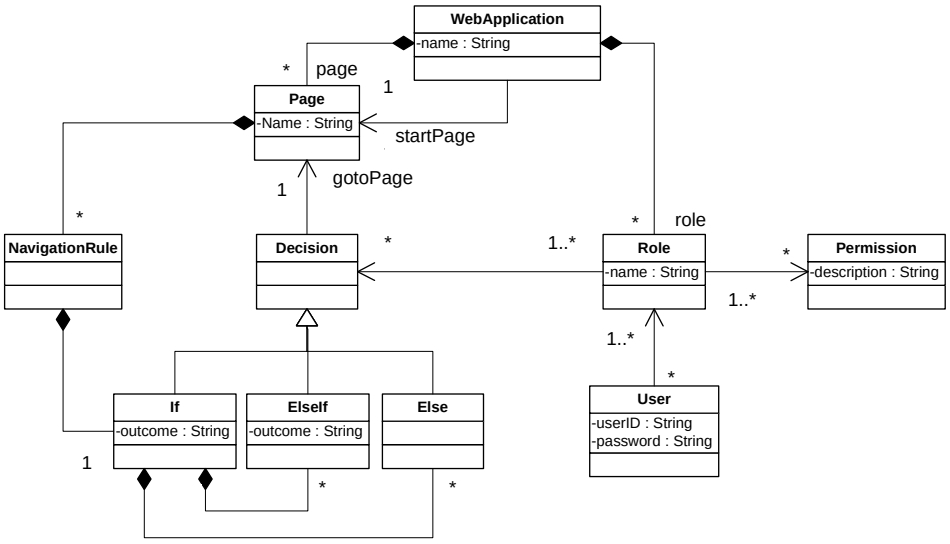


Figure 5.12: The Pageflow DSL's language model

An Example of the Pageflow DSL

In Figure 5.13 we illustrate an graphical representation of using the Pageflow DSL by using a UML object diagram. In this example, we use the Pageflow DSL for specifying the role-based pageflow of a user management web application. The page `ListUsers` contains one `NavigationRule` which consists of one `If` statement that links to the `UserDetails` page via the `gotoPage` link. The specified `outcome` attribute in the `if` object contains the string `gotoUserDetails`. Furthermore, a `roles` reference exists, which references to the `GroupMember` role. An example of an `IF-ELSE` definition of the rolebased pageflow is

```
IF outcome="gotoUserDetails" AND role="member1" THEN
                gotoPage="UserDetails"
```

All other navigation rules and their associations to roles are defined similar.

Pageflow DSL – Remarks

Within this project, we did not develop a low-level DSL that is used for describing the web application's technologies and platform. In particular, we used the Java Server Faces (JSF) technology for executing the web application. We developed the DSL's code generator to transform the high-level role-based pageflow definitions directly into an executable web application. We provide further information about role-based access control based on the pageflow of web applications in [78].

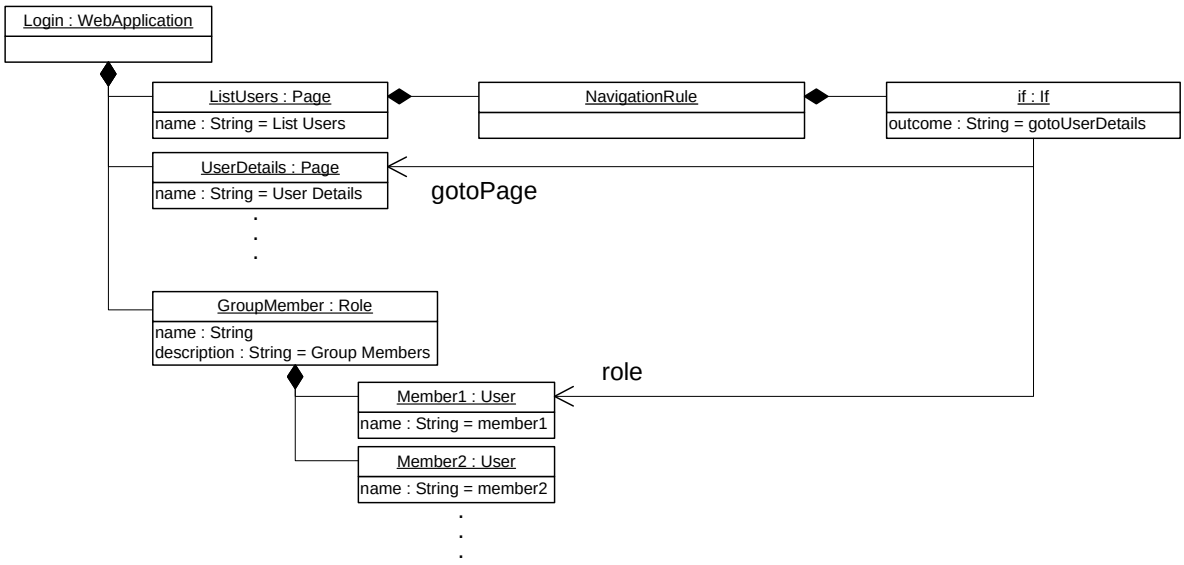


Figure 5.13: An example of using the Pageflow DSL

5.5.2 QoSTIL – QoS Test Instrumentation Language

To design SLAs, service providers need to know about their IT infrastructure's capabilities what their offered services can deliver [45]. The purpose of QoSTIL is to define complex test plans to perform and simulate performance test on web services. In QoSTIL we differentiate between simple and complex tests. Simple tests are performed to evaluate the services' performance-related QoS properties. Complex tests are described by composed simple tests using loops or parallel executions.

QoSTIL's Language Model

In Figure 5.14 we illustrate the QoSTIL's core language model. Each Test has a string attribute name which is used to identify it. Tests can have parameters (`Parameter`) and results (`Result`). Both parameters and results are subtypes of `FieldDefinition` and indirect subtypes of `Field` and therefore have a type, such as integer, and a name. All fields can be seen as variable slots that are used to store and access values by name. Parameters are used for input values that a test needs when it is executed and have to be filled by a test caller. Results have to be filled by the test implementation during the test execution. All parameters and results are contained in the test report that is returned after the execution of a test. The test results can easily be merged using aggregators, such as average, median, or minimum.

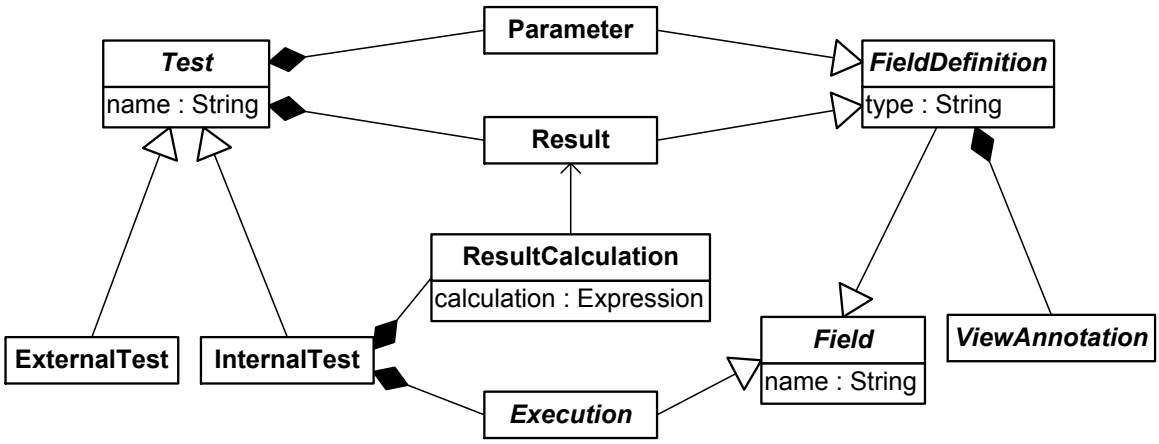


Figure 5.14: The QoSTIL's core language model

An Example of Using QoSTIL

In Figure 5.15 we illustrate an example of QoSTIL to get a better idea of QoSTIL's concrete syntax. The example defines a test named `example-test` which declares two typed parameters (`example-param1` and `example-param2`), an execution named `otherTestExecutions` of `OtherTest` that will be executed in a loop for `10` times with a value for the parameter `otherTestParam1` given by an expression, and three results (`example-result1`, `example-result2` and `example-result3`) including expressions that specify how their values are calculated. The value of `example-result2` is simply the result of the repeated execution, i.e., an array of test reports, and therefore needs to have the type `OtherTestReport[]`. The result of `example-result3` is the average value of the field named `otherTestResult1` from each of the test reports in the array. This assumes of course that the test definition of `OtherTest` does include this field.

```
test example-test {
        parameter double example-param1;
        parameter int example-param2;

        loop(10) execution otherTestExecutions:
                OtherTest(otherTestParam1 = example-param1 * 100);

        result int example-result1 = 5 * (example-param2 + 10);
        result OtherTestReport[] example-result2 =
                        otherTestExecutions;
        result double example-result3 =
                        otherTestExecutions.average(otherTestResult1);
}
```

Figure 5.15: A QoSTIL example

QoSTIL – Concluding Remarks

QoSTIL is an external DSL to provide its users a usable syntax for specifying web services performance tests. QoSTIL is a high-level language that does not include any technological details about how to perform the web service performance tests. Further information about QoSTIL and its usage is provided in [24].

5.6 Lessons Learned during the DSL Projects

The requirements within a domain change much more often than the technological requirements. One of the primary advantages of the separation into high-level and low-level languages is that the technical experts have to specify the technological aspects just once. For instance, the response time is measured within the defined phases every time, independent of the specified SLAs in the high-level language. Hence, the SLAs can be specified multiple times without changing any technological aspects. Furthermore, a common advantage of model-driven DSL approaches is that the language models are easily extensible. Hence, when following our approach, each language model can be separately extended in an easy way. In this context, a drawback is that technological requirements have to be redefined, or at worst remodeled, when the used technologies get changed.

A discovered disadvantage lies in the overlapping concerns between the different language layers when a horizontal separation into multiple sub-languages is provided. To find a remedy, model-driven DSL approaches provide facilities for extending high-level concerns with low-level concerns or vice versa, by using inheritance, associations, or compositions. For the time being, another disadvantage of our approach it that only a horizontal separation into multiple sub-languages is provided. Hence, our approach is not compatible with providing a vertical separation into different viewpoints or completely different domains. We envision solving this problem in our future work.

As shown, model-driven DSL approaches can suppress the arising drawbacks of providing multiple

languages which are tailored for the appropriate stakeholders. The following section mentions some related work and their differences to our approach.

5.7 Related Work

In this section we present some related work to our approach for supporting the stakeholders with model-driven DSLs. First, we list some languages for specifying QoS in distributed and service-oriented systems, followed by some approaches for developing DSLs.

5.7.1 Related Languages for Specifying QoS

In the literature, many languages for specifying a distributed system's QoS compliance concerns exists. To the best of our knowledge, there exists no language that provides a separation between technical and non-technical artifacts relevant for QoS monitoring. Furthermore, many developed DSLs of the QoS domain do not follow the MDD paradigm.

Although HQML (Hierarchical QoS Markup Language) provides three different levels of abstractions, it is an XML-based language, making it hard to use for non-technical stakeholders. HQML was designed for specifying the QoS concerns of web-based applications. The highest HQML abstraction level is the user level for specifying the application's attributes (e.g., description of service provider or service consumer), the QoS criteria (e.g, low, average, or high), and the service provider's price models (e.g., for transmitted byte charge). The application level QoS specifications includes the application's QoS compliance concerns. The resource level QoS specifications relate to the system's resource requirements, such as memory, bandwidth, or cpu.

The Distributed QoS Modeling Language (QML) [40], introduced by Frølund and Koistinen, is a language for specifying QoS in distributed object systems. The language consists of three elements: contract type, contract, and profile. Contracts are instances of contract types which consist of so-called dimensions, such as Time-to-Failure (TTF), availability, or number of failures. Dimensions are comparable to QoS concerns. Similar to our work, a contract is a list of QoS constraints, such as $latency < 3s$. A profile describes the QoS properties of a service and is linked service's interface.

To ease the integration with existing service descriptions, such as WSDL [126] or BPEL [76], the SLAng language [56] is defined by an XML-Schema. Using SLAng makes it possible to (1) give information about the service provider and service consumer, (2) define contractual statements, such as the SLA's duration and the payments in case of violation, and (3) technical QoS constraints. SLAng separates SLAs in horizontal and vertical types to regulate the different types of the involved parties. Vertical SLAs are application, hosting, persistence, and communication. Horizontal SLAs are service, container, and networking. SLAng also supports the specification of responsibilities of the service provider, the service consumer, or both.

The Contract Description Language (CDL) of the QuO framework [62] is designed to define SLAs between clients and remote objects within distributed systems. CDL allows to organize the possible QoS states, the needed monitoring and controlling information, actions if QoS states change, and when the information should be available.

The web service level agreements (WSLA) framework [48] offers an XML-based language for specifying the web services' performance-related QoS compliance concerns. The provided language by the WSLA framework is allows to specify SLA's parties, services, and obligations.

5.7.2 Related DSL Development Approaches

Pitkänen and Mikkonen [95] argue that well designed DSLs, modeling tools, and code generators increase the productivity. They concentrate on lightweight and modular DSLs instead of full-blown DSLs. Some situations of full-blown DSLs are described, e.g., several different implementation platforms. The lightweight approach can be an aid in defining the scope and concepts of DSLs before the implementation of a full-blown DSL starts. In comparison to our study, the systematic development approach can be applied to lightweight, as well as full-blown DSLs. The different design decisions and/or trade-offs, described in Section 5.3.3, are also valid for developing lightweight model-driven DSLs.

Bierhoff et al. [52] describe an incremental approach for developing DSLs. First, they choose an application and develop a DSL which is expressive enough to describe the application. Also, domain boundaries are defined. Then, the DSL grows until it is too expensive to extend it more. The approach is demonstrated on CRUD applications, i.e., create, retrieve, update, delete applications. The approach by Bierhoff et al. reflects the evolution of our three experiments described in Section 5.3.2. Also, we started by an initial experiment and extended it incrementally.

Maximilien et al. [64] developed a DSL for Web APIs and Services Mashups. A number of interesting design issues for DSLs are mentioned: (1) levels of abstraction, (2) terse code, (3) simple and natural syntax, and (4) code generation. These goals are very similar to our proposed claims. The developed DSL is used for SOAs, and the described approach and results are in line with our results.

Tolvanen [46] provides a guidance for defining and developing DSLs based on his long-year experiences in building DSLs. The development process is divided into four phases: (1) Identifying abstractions, (2) specifying the language models, (3) creating notations for the language based on the language models, and (4) defining model validators and code generators. The development phases are very similar to our observations. We started by defining abstractions of the domain, designed high- and low-level language models, developed a DSL with notations equivalent to the language models. Also, we provide model validators and code generators. The proposed approach by Tolvanen is similar to our systematic development approach for model-driven DSLs: (1) identifying the concepts of the domain and their relations, (2) designing the language models, (3) developing the DSLs based on the

language models, and (4) generating code of valid domain models through a code generator.

5.8 Summary

In this chapter, we presented an approach to support the differently skilled stakeholders that are involved in the design and development process of a QoS monitoring infrastrucutre. In our approach, we use model-driven DSLs that are tailored for the non-technical and technical stakeholders. Following our approach, low-level DSLs provide constructs that are tailored for technical experts, whereas high-level DSLs are tailored for domain experts. A suitable separation of concerns can be established by splitting the language model into high- and low-level models, where the high-level model extends the low-level model. Hence, a separation of technical and domain concerns can be established to present only the appropriate concerns to each of the different groups of stakeholders.

We have evaluated our approach with an explorative study on developing model-driven DSLs for SOAs. Within three experiments we have stated claims of investigations, illustrated the projects, and presented the evidences and counter-evidences of the stated claims. We have shown a developed model-driven DSL within the scope of the industrial case study, named QUALA. We separated QuaLa into two languages. The high-level QuaLa is tailored for experts of the QoS domain in order to specify the services' QoS compliance concerns. The low-level QuaLa is tailored for technical experts in order to specify where and how to measure the performance-related QoS properties within the Apache CXF web service framework.

Chapter 6

Incremental Development of Model-driven DSLs

To support the differently skilled stakeholders, we utilize model-driven Domain-specific Languages (DSLs), as described in the previous chapter (Chapter 5). However, developing model-driven DSLs conceals many problems. Because of a lacking domain understanding, the DSL's requirements are fuzzy and incomplete at early development stages. Fuzzy preliminary requirements are often quickly stretched out, and later on incrementally updated following subsequent communications between the stakeholders and the developers. After learning and knowing the domain concepts better, the stakeholders interpret the concepts differently. As a consequence, later changes are inevitable. To avoid complex and time-consuming updates, an incremental development approach is desired to keep the subsequent updates small and lightweight [49].

This chapter is organized as follows: In the following section, Section 6.1, we present an utilized incremental development approach to develop a model-driven DSLs. In Section 6.2 we exemplify how we have researched the incremental development approach during the development of the case study's Quality of Service Language (QUALA) DSL, dealing with permanent updates (see Section 5.4). Related DSL development approaches are listed in Section 6.3. The chapter concludes with a brief summary in Section 6.4.

6.1 An Incremental Development Approach

To put things right, we followed an incremental development approach that is based on existing development approaches. We applied the incremental development approach to develop the case study's QUALA DSL and state questions under research during the development lifecycle within the case study. The findings provide answers to the questions and should help developers of model-driven DSLs avoid complex and time-consuming updates in later development stages.

In Figure 6.1 we demonstrate an incremental development approach based on existing approaches, as described in [30, 49, 65, 111]. Our approach is two-fold. First, the modelling and the design of the domain model takes place. In our terminology, the domain model is equivalent to the DSL's language model. After developing a stable version of the domain model, the design and development of a DSL or the transformation rules are done.

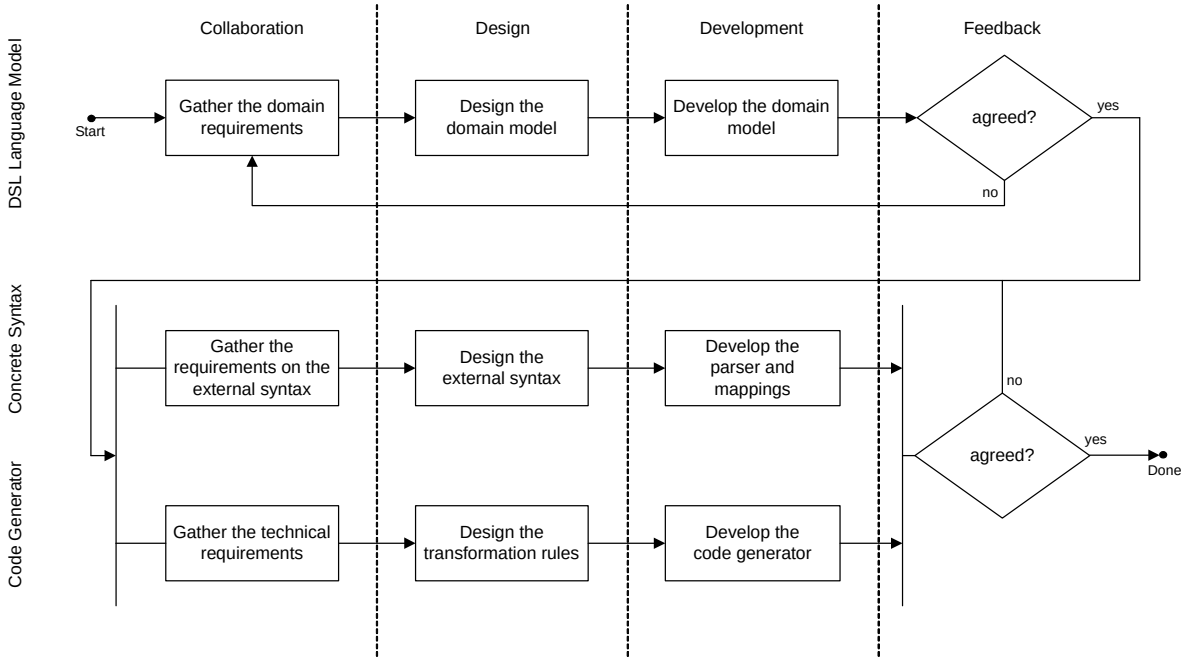


Figure 6.1: An incremental development approach

In general, the stakeholders can change their requirements at every stage in the process, making a strong collaboration between developers and stakeholders inevitable. Each development process – for the domain model and for the external DSL – is divided into the following four main activities or phases:

- **Collaboration**
  In the collaboration phase the stakeholders are in permanent interaction with each other. During this activity, the domain concepts and the requirements are defined. After this activity, every stakeholder should understand the domain concepts and the requirements correctly, following a commonly defined terminology.

- **Design**
  During the design phase the stakeholders create collaborative the domain model using, for example, a whiteboard. In our terminology, the domain model is equivalent to the DSL's language

model. The design of the domain model is based on the requirements and the gathered understandings about the domain. It is advisable that all stakeholders perform this activity together, for example by using domain analysis techniques [6]. This can also help in determining the scope of the domain [7].

- **Development**
  In the development stage the language developers develop the DSL's language model, using their favourite modeling tool or language workbench.

- **Feedback**
  After having developed the DSL's language model, the stakeholders give feedback on the model. The stakeholders test the developed language model and evaluate that the model contains the required domain concepts and that they can be expressed well. In case the domain model does not fulfil the requirements, the incremental process must be restarted. Otherwise, the development of the DSL transformation rules and concrete syntax can start.

At every stage of the development process, the stakeholders can change or extend the requirements. Hence, the DSL developers have to discuss the new requirements with the domain experts and perform changes in the domain model and its dependent components. In the presented approach, the DSL developers must collaborate with the domain experts until the design of the domain model is finished. Afterwards, the changes can be taken into the updating process of the DSL. The same incremental development approach can be used for each feature of the DSL.

6.2 Incremental Development of the QuaLa DSL

Within the case study, the requirements on the Quality of Service (QOS) domain and the QUALA DSL were changing and extending. Requirement changes and the QUALA's actual version were discussed in several meetings and telephone conferences during the case study's lifecycle. Within the case study, we research the incremental development approach. We present the evolution of the QUALA DSL in three different versions – initial, intermediate, and final. Then, we present the findings of the incremental development of the case study's QUALA DSL.

6.2.1 Researching the Incremental Development Approach

To research the incremental development approach, we state four questions under research during the development of the QUALA DSL (see Section 5.4) within the case study (see Chapter 3).

Question I

Is the incremental development approach applicable within the case study?

We apply the presented incremental development approach to develop QUALA within the industrial case study. This question focuses on the applicability of the incremental development approach.

Question II

How do changes in the DSL*'s language model impact its dependent components?*

Permanently changing domain requirements result in changes to the domain model, i.e., the DSL's language model. Based on the DSL's language model are the transformation rules and the DSL's concrete syntax. This question focuses on the impact of domain model changes to its dependent components' implementation.

Question III

What are the benefits of incremental development instead of following a non-incremental development approach?

To keep changes and updates in later stages of the development lifecycle as small as possible, we have followed an incremental development approach. This question focuses on the benefits of following an incremental rather than a non-incremental development approach.

Question IV

Are there general recommendations for similar projects?

We have developed the QUALA DSL within the case study to specify the QOS compliance concerns of a process-driven SOA. This question concentrates on the generalization of the findings during the incremental development of QUALA. General recommendations should help to develop model-driven DSLs incrementally in various projects.

6.2.2 The Evolution of QuaLa

In this section, we illustrate the evolution of the case study's QUALA DSL (see Section 5.4), stemming from evolving domain requirements. We present the evolution of QUALA's language model, its external concrete syntax, and their relationship on three versions – initial, intermediate, and final. The specification of the QOS compliance concerns, using the external syntax, is exemplified for the MVNO's `Search` service (see Table 3.1).

The Case Study's Context

The QUALA DSL was developed within the case study (see Section 3). The case study was conducted within an European research project[1] that started in February 2008 and lasted until January 2011 (36 months). The development team of the QUALA DSL for describing and ensuring the case study's QOS compliance concerns included the following stakeholders: six domain experts, two technical experts, and two language developers. All stakeholders were involved in the design of the QOS models and the QOS language. Two domain experts are also counted as foreseen language users, and one stakeholder was a domain expert, technical expert, and language developer at once. As the iterative approach assumes, the QOS domain's concepts and the case study's requirements were discussed permanently by the stakeholders. Several meetings and telephone conferences were held which brought more insights into the case sutdy's requirements on the QOS domain. Hence, the changing and enhancing requirements implied changes in the models and the language.

QuaLa's Initial Version

Requirements

The initial QOS requirement in the industrial case study was to annotate services with particular QOS compliance concerns. We list some requirements of QOS constraints in Table 6.1. For example, the case study's Search service must have an Up-Time of greater than 99% and a processing time of less than two minutes.

Service	**QoS Compliance Concerns**
Login	Up-Time $>$ 99%
Search	Up-time $>$ 99%, ProcessingTime $<$ 2min
Stream	DeliveryRate $>$ 90%, MinimalFrameRate $>$ 30fps

Table 6.1: Initial QOS compliance concerns

Implementation

In Figure 6.2 we illustrate the high-level QUALA's initial version, its language model, and the corresponding mapping. The upper portion of Figure 6.2 shows an example of specifying the services' QOS compliance concerns. The concrete syntax is textual and block-oriented. The QUALA users

[1] COMPAS – http://www.compas-ict.eu/

specify services by listing the service names and annotate them with the QOS compliance concerns within the curly braces ({...}).

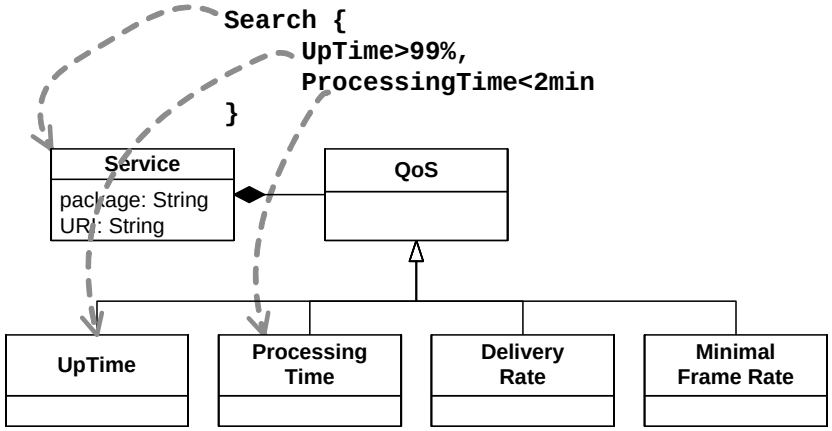


Figure 6.2: The initial version of QUALA

The lower portion of Figure 6.2 shows the QUALA's language model, i.e., the domain model. The class `Service` can be instantiated to define services, such as the `Search` service. Services can consist of QOS compliance concerns, using the composition between the `Service` and `QoS` classes. As listed in Table 6.1, all required QOS compliance concerns – `UpTime`, `Processing Time`, `DeliveryRate`, and `MinimalFrameRate` – are defined in QUALA's language model, and hence, can be used in the DSL. As required, the QUALA language model contains all the case study's required QOS domain concepts at this point in time.

QuaLa's Intermediate Version

During the project's lifetime, new requirements were discovered which lead to extensions and changes of the domain model, i.e., QUALA's language model. In this section we describe an intermediate version of the QUALA DSL that resulted from changing requirements.

Requirements

As an extension to the initial version, the intermediate version provides possibilities to specify Service Level Agreements (SLAs) [26, 120]. Furthermore, actions should be performed in case of SLA violations, such as sending an e-mail to the system administrator.

In Table 6.2 we list some examples of QOS compliance concerns corresponding to the offered services. For example, if the Up-Time of the case study's Search service is less than 99%, then send an e-mail to some responsible person, such as a system administrator.

Service	QoS Compliance Concerns	Action
Login	Up-Time $<$ 99%	Mail
Search	Up-Time $<$ 99%	Mail
	ProcessingTime $>$ 2min	SMS
Stream	DeliveryRate $<$ 90%	Mail
	MinimalFrameRate $<$ 30fps	Mail

Table 6.2: Intermediate QOS compliance concerns

Implementation

In Figure 6.3 we illustrate the high-level QUALA's intermediate version, its language model, and the corresponding mapping. As in the initial version, QUALA provides a textual and block-oriented concrete syntax, as shown in the upper portion of Figure 6.3. This time, the DSL users can specify an SLAs by writing its name, list the included services within the curly braces ({ . . . }), annotate them with QOS compliance concerns, and define an action that has to be performed if the corresponding QOS compliance concern is violated during the runtime of the system.

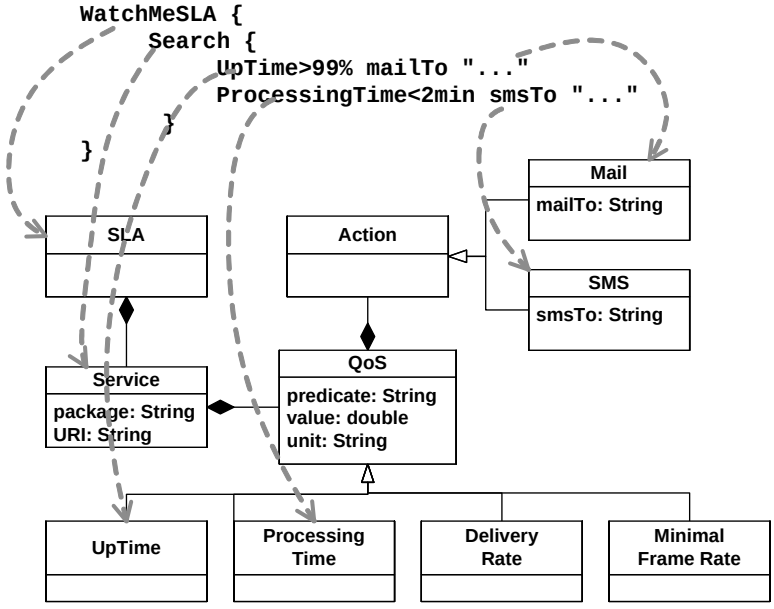


Figure 6.3: An intermediate version of QUALA

We illustrate the QUALA language model in the lower part of Figure 6.3. The main changes and extensions to the initial version (see Figure 6.2) lie in the introduction of the classes `SLA` and `Action`. To define SLAs, we introduced the composition between the `SLA` and `Service` classes. To define actions in case of SLA violations, we link the `Action` and `QoS` class. To define QOS constraints, we

extended the `QoS` class with the `predicate`, `value`, and `unit` attributes.

QuaLa's Final Version

In the case study's last year, the stakeholders agreed on new requirements and to update some old ones. In this section, we give information about QUALA's final version within the case study.

Requirements

Service	QoS Compliance Concerns, Rules, and Actions
Login	(Up-Time $<$ 99% $\Rightarrow$ Mail AND UpTime $<$ 95% $\Rightarrow$ SMS)
Search	(Up-Time $<$ 99% $\Rightarrow$ Mail AND Up-Time $<$ 95% $\Rightarrow$ SMS) OR Processing Time $<$ 2min $\Rightarrow$ Mail
Stream	(Up-Time $<$ 99% $\Rightarrow$ Mail AND Availability $<$ 95% $\Rightarrow$ SMS

Table 6.3: Final version of QOS compliance concerns

As extension to the intermediate version, in the final version it was required to define rules as combinations of QOS compliance concerns using logical operators, such as AND or OR. If a rule is violated, an appropriate action should be performed, similar to the previous version. The reason for introducing rules is to be able to define gradations of QOS compliance concerns, making predictive QOS monitoring possible.

An example of a QOS rule is: If the Availability is less then 99%, then send a e-mail to the system administrator, AND if the Availability is less then 95%, then send an SMS. In Table 6.3 we list some more examples of QOS compliance concerns corresponding the the case study's offered services.

Implementation

In Figure 6.4 we illustrate the case study's final high-level QUALA version, its language model model, and the corresponding mapping. In the upper portion we show the final QUALA's concrete syntax, having a textual and block-oriented concrete syntax. As required, the DSL provides the possibility of specifying QoS rules. Those are specified within braces ({ . . . }) and separated by commas (`,`).

The lower portion of Figure 6.4 illustrates QUALA's language model. As required, each `QoS` compliance concern can consist of multiple `Rules` which themselves can consist of `Conditions`. We differentiate between `AtomicCondition` and `CompositeCondition`. An `AtomicCondition` is

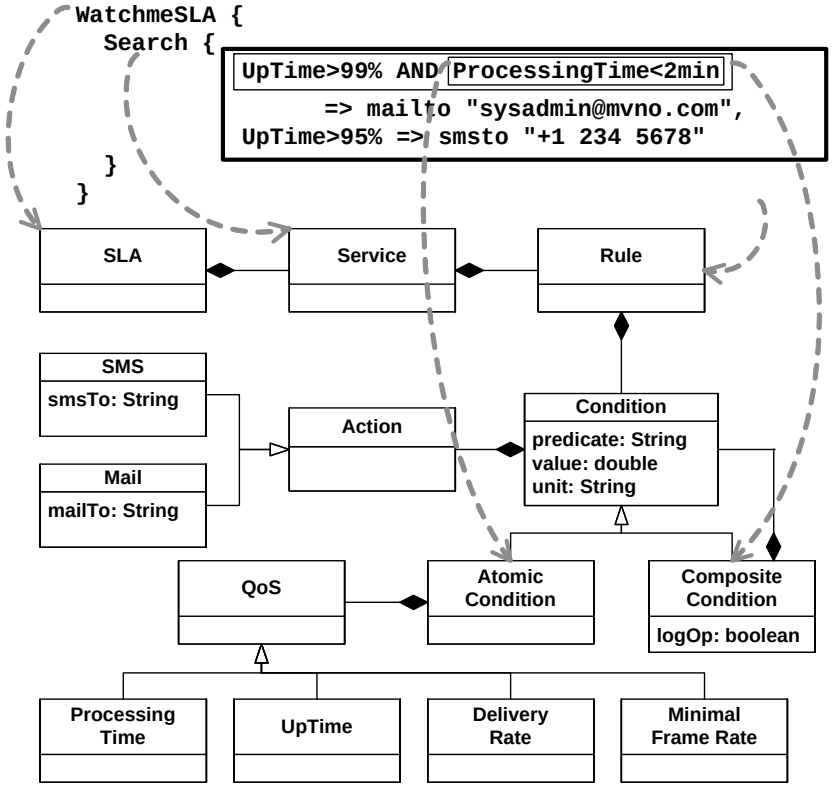


Figure 6.4: QUALA's final version

assigned to a `QoS` compliance concerns. A `CompositeCondition` consists of multiple `Conditions` – `AtomicCondition` and `CompositeCondition` – that are concatenated with logical operators. This modeling solution makes it possible to define fine granulated rules of QOS compliance concerns. The defined `Conditions` are checked during the system's runtime, and the associated `Actions` are performed if a `Condition` QOS compliance concern is violated.

6.2.3 Research Results of the Incremental Development Approach

In this section we give present the results to the stated research questions (see Section 6.2.1) during the QUALA development lifecycle. The results contribute to the thesis' fourth contribution: *Incremental development to support the stakeholders*.

Question I

Is the incremental development approach applicable within the case study?

In the context of the case study, the requirements were not well defined at the beginning, making later changes unavoidable. The changes required of the domain model had different origins: changing

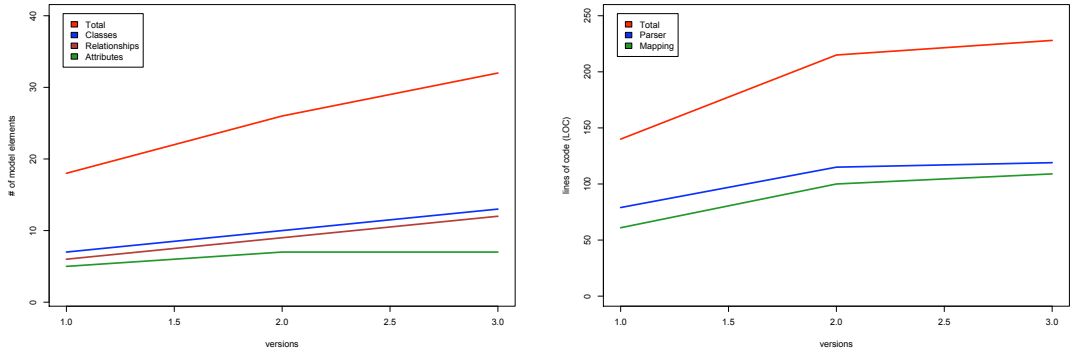
requirements of the stakeholders, more enhanced and broad understanding of the domain, or the different expertise of the stakeholders involved. The domain model matures from iteration to iteration until the requirements of the stakeholders were fulfilled. To answer the question, the choice of following an incremental development process was successful.

It was also important to twofold the incremental development process, starting with the domain model and following with the external DSL and transformations rules. The stakeholders requirements of the domain were captured in the domain model first. After a positive feedback of the stakeholders, the language developers began to implement the external DSLs and transformations rules on stable versions of the domain model.

Question II

How do changes in the DSL*'s language model impact its dependent components?*

To investigate the impact of the requirements' changes, we conduct a simple quantitative evaluation. First, we calculated and compared the absolute model size of each version of the QUALA language model [57] (see Figure 6.5(a)). The intermediate version of the domain model contains in total eight elements more than the initial version, meaning that the model size increased by about 50%. The third version increased by about 25% compared to the second version, because it contains six elements more than the second version. Comparing the initial and current versions, the model size increased by about 80%.



(a) Increased size of QUALA's language model (b) Increased LOC during QUALA's development

Figure 6.5: Quantitative evaluation of the QuaLa DSL's evolution

Quantitative measurements were taken from the parser and mapping implementations for each version of the external high-level QUALA (see Figure 6.5(b)). We used the Lines of Code (LOC) metrics [29], where we did not include comments and blank lines.

The intermediate version requires eight more parsing rules and five more mappings in comparison to the initial version. The reason lies in the comprehensive concrete syntax – compare the two syntaxes in Figure 6.2 and 6.3. The implementation of the intermediate QUALA's components has 75 LOCs more than the first one, meaning an increase of about 50%. Comparing the concrete syntaxes of the final and the intermediate version – see Figures 6.3 and 6.4 – the final version of the QUALA does not have many differences to the second version. The final QUALA increased about 25% compared to the intermediate one, but, increased about 85% in comparison to the initial one.

Question III

What can be the drawbacks of following a non-incremental development approach?

In an early stage of the development process the stakeholders' requirements are not well-defined and are subject to constant changes. Changes in the requirements change the domain model and affect its dependent components, such as code generators, parsers, or mappings. Comparing the enhancement of the QUALA implementations (see Figures 6.5(a) and 6.5(b)), a linear relation between the evolving domain model and the implementations can be observed. This means that the higher the number of changes in the language model, the higher the update efforts of the parsers and transformation rules. During the case study we discovered that it is not advisable to follow a non-incremental development approach and to develop the whole solution at once after a long design phase. To answer the question, a drawback of non-incremental development approaches is that the later and bigger the changes are the more complex is the development effort of new and changing requirements. As a result, a non-incremental development approach has to deal with time-consuming maintenance phases.

Question IV

Are there general recommendations for similar projects?

The current domain model contains four QOS compliance concerns that originate from the case study's requirements. Many other QOS measurements exists, such as described in [92], [98], [133], or [85]. Every version of the domain model and its dependent components can be extended easily. We recommend an incremental DSL development where in every iteration different features and sub-domains can be considered. It is important that changes on the domain model do not require costly and complex changes in the transformation rules or the external DSLs. One general recommendation is that the development of an external DSL or the transformation rules should only start when the domain experts are able to work with the concepts contained in the domain model and all requirements are fulfilled. The need for code generators or an external DSL can arise at any time during the development process.

In every iteration of an incremental development approach the requirements of new features and sub-domains can be considered, which can result only in extensions. For example, an extension of the

initial version (see Figure 6.2) was the specification of SLAs. In the second version (see 6.3) we had only to introduce the SLA class for SLA specifications. The transformation rules, parsers, or mappings can support the new features of the domain model easier at every iteration stage. Changes and updates can be kept small and lightweight because the domain model can evolve in a more independent way from the components that depend on the domain model.

A current shortcoming of embedded DSLs is their concrete syntax, making it difficult to use for domain experts who are unfamiliar with programming language concepts. Using tools, such as GraphViz [9] or Prefuse [14], enable the language developers to represent the current domain concepts to the domain experts in a graphical and understandable way. This can improve the domain experts' feedback should modification be needed.

6.3 Related Work on DSL Development

Kelly and Tolvanen [50] recommend that the DSL be maintained by a pilot DSL to see the influence of the required changes. The presented incremental DSL development is in contrast to our approach tailored for their MetaEdit+ CASE tool [51].

Pitkanen and Mikkonen [95] present a lightweight development approach, starting with high-level modelling of the domain specifications and transforming them into an architectural design model using a transformation tool. Comparable to our approach, their development approach does not include feedback loops. Their approach can be used in the initial development stage of our approach.

Sheard [104] gives a summary about a project that focuses on the evolution of DSLs. The evolution is divided in three stages: Infancy, Adolescence, and Maturity. An example of a embedded DSL's evolution is presented, where the developers ran into limitations of embedded DSLs, such as syntax, error messages, or performance. The project described does not follow the MDD paradigm, but, there is still a need for research to update the code generators and parsers if the concrete syntax or the domain model are changed.

Sprinkle et al. [106] formalize the evolution of the domain, the DSL, and the domain model. The authors consider various cases of evolution, such as domain semantics, domain types, or language syntax. Compared to our work, Sprinkle et al. do not consider changes in the usability of the DSL, i.e., the DSL's concrete syntax.

Bierhoff et al. [16] describe an incremental DSL development approach, where the DSL is based on an existing system. The DSL evolves until it is expressive enough to specify the applications functionality. Our approach is designed to develop model-driven systems from scratch which evolve on changing requirements.

Kosar et al. [55] compares various DSL implementation approaches of Mernik et al. [65] based on one DSL. The authors provide empirical results from implementing one language following ten different implementation approaches. In contrast to our approach, the implementation is considered as

a sub-process of the whole development process.

The W3C specifications WS-Agreement [131] and WS-Policy [132] provide facilities for specifying QOS constraints in web service-oriented systems. During the implementation of the industrial case study we did not want to be tied to existing standards. However, it is possible to define transformation rules for mapping the case study's QOS specifications onto WS-Agreement or WS-Policy specifications.

Nowadays, many tools exist to facilitate DSL development, such as xText [27], JetBrain's MPS [44], Ruby [32], or the MS DSL Tools [69]. Because most of the tools do not support model-driven DSLs, the DSL development approach starts with the definition of the DSL's concrete syntax that is mostly described in EBNF form. The tools do support the DSL evolution by regenerating the parsers and code generators if the concrete syntax gets changed. Our incremental development approach starts with the definition of the domain model, i.e., the DSL's language model, which evolves during the collaborations with the stakeholders.

6.4 Summary

In this chapter, Chapter 6, we have presented the an incremental development approach to develop model-driven DSLs. We have conducted and researched the approach within the industrial research case study (see Chapter 3) during the development of the QUALA DSL (see Section 5.4).

As first step, we started to collaborate with the stakeholder, discovering the concepts of the QOS domain and discussing the QUALA DSL's requirements. After designing and developing the domain model, i.e., the QUALA language model, the stakeholders gave feedback. In the case study, the QOS compliance concerns changed and were enhanced, making the maintenance of the QUALA DSL's implementation complex. We presented the evolution of the domain model and the DSL's external concrete syntax.

We have researched the incremental development approach during the QUALA DSL's development. Therefore, we stated research questions, focusing on the applicability of the incremental development approach, the impact of requirement changes in later development stages, general recommendations for similar model-driven DSL projects, and possible drawbacks of following a non-incremental approach. The findings discovered during the development within the case study answer the stated research questions.

Chapter 7

Extending an Existing Process-driven SOA to QoS-awareness

Nowadays, many organizations use a process-driven Service-oriented Architecture (SOA) to automate their business processes. The business processes' activities are aligned with IT web services to accomplish tasks mostly automatically [137]. However, an organization's business processes must adhere to many business compliance concerns, stemming from regulations, legislations, or internal policies [87]. In this chapter we explain how we have applied the architectural decision model (see Chapter 4) to extend an existing process-driven SOA to comply to internal Quality of Service (QOS) policies stemming from Service Level Agreement (SLA) upon the IT web services' performance. Furthermore, we will explain how we integrate the QuaLa DSL (see Section 5.4) into the existing process-driven SOA to support the stakeholders.

The chapter is structured as follows: In the following section, Section 7.1, we explain an existing process-driven SOA that is not QoS-aware. In Section 7.2 we explain the requirements for extending the existing architecture. The designed and developed QoS-aware process-driven SOA is explained in Section 7.3. In Section 7.4 we illustrate an architectural walkthrough based on the case study (see Chapter 3) for a better understanding of the QoS-aware architecture. We briefly summarize the chapter in Section 7.5.

7.1 An Existing Process-driven SOA

In Figure 7.1 we present an existing architecture that was build for modelling process-driven SOAs. The architecture is two-fold. First, at the design time, the modelling of the process-driven SOA's business processes, as well as the code generation of executable processes takes place. Second, during the runtime, an application server hosts a process engine and the web services. The process engine executes the generated business process code by orchestrating the web services.

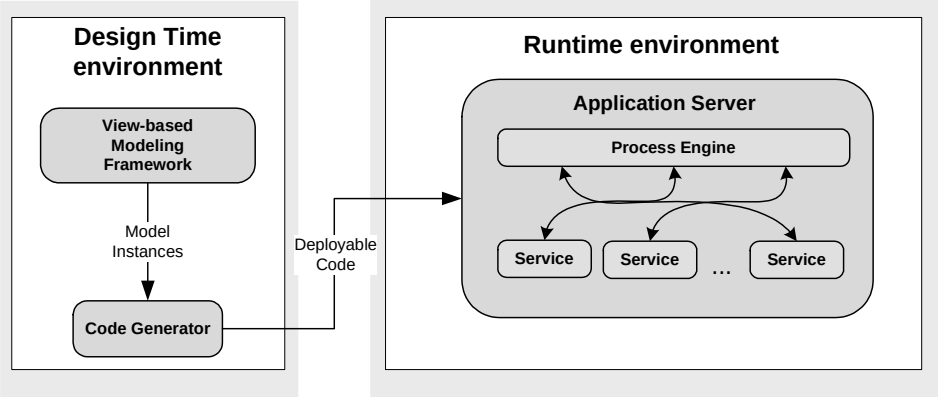


Figure 7.1: An existing architecture for modelling process-driven SOAs

To model the business processes, we use the View-based Modelling Framework (VBMF) [121]. The VbMF generates deployable Business Process Execution Language (BPEL) [76] code of the modeled business processes for the Apache ODE process engine [116]. The web services are deployed within the Apache CXF web service framework [115]. Now, the processes can be executed through orchestration of the web services by the process engine. The executing business processes do not, however, consider how to handle an enterprise's QoS compliance concerns. The challenging task is to extend the presented architecture for monitoring the services' performance-related QoS properties, so that an organization's business processes comply with negotiated QoS compliance concerns.

7.2 Requirements on the QoS-aware Process-driven SOAs

In this section we present the requirements for building a QoS-ware process-driven SOA. One major requirement is to use the MDD paradigm to design and build novel models which will ensure a business process' QoS compliance. An additional requirement is to build an event-driven architecture [66] to check the performance-related QoS measurements at the system's runtime.

Because of the involvement of technical and non-technical stakeholders at *design time*, we have to provide the stakeholders with a user-friendly solution for specifying the services' QoS compliance concerns. In addition, an integration between the stakeholder support and the VbMF is required. We have to extend the code generators to generate a QoS measuring mechanism that is reusable and separated from the services' implementation. During the *runtime*, an event-driven architecture [66] is required. The events should be used to check the business processes' QoS compliance concerns during its runtime. The *evaluation* of the performance-related QoS measurements should be possible during and after the SLAs' validity.

7.3 A QoS-aware Process-driven SOA

In this section we present how we applied the thesis' *Contribution I* and *Contribution II* to extend the presented process-driven SOA to ensure business compliance to QoS, fulfilling the requirements listed in the previous section We illustrate in Figure 7.2 the resultant QoS-aware process-driven SOA, where we sketch the extensions within the red boxes. We separate the integration of QoS-aware services or business process into: (1) Specifying the process-driven SOA's QoS compliance concerns at *design time*, (2) executing the process-driven SOA's services and business processes at *Runtime*, and (3) an *Evaluation* of the collected QoS data to detect SLA violations.

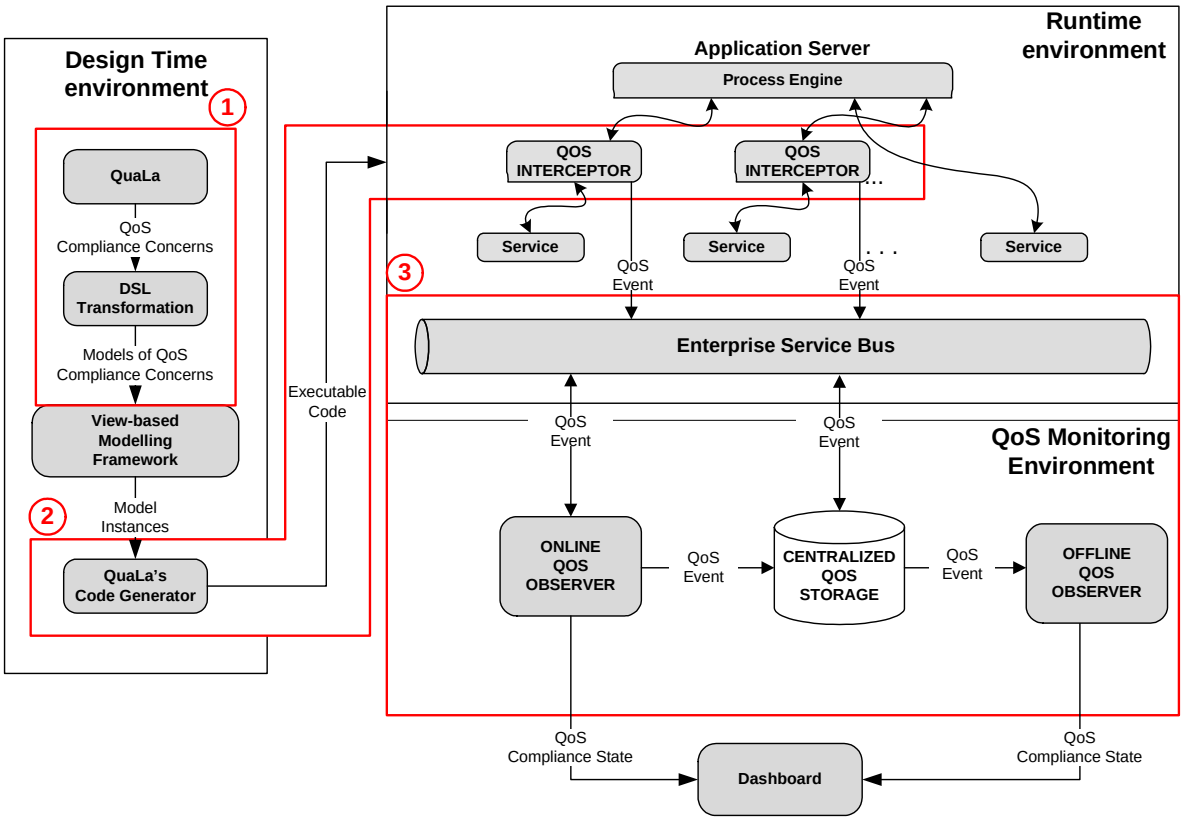


Figure 7.2: A QoS-aware Process-driven SOA

In the following, we present the designed and developed architectural extensions for a QoS-aware process-driven SOA:

Applying Contribution I:
An architectural decision model to design a QoS monitoring infrastructure

To measure the performance-related QoS properties, we implemented a *Code Generator* that generates QOS INTERCEPTORS for measuring the required performance-related QoS properties. We have decided in favour of the QOS INTERCEPTOR pattern, because it is, as required, a reusable solution and separates the measuring logic from the services' implementation. In addition, the Apache CXF web service framework [115] provides a convenient solution for hooking a QOS INTERCEPTOR into to service invocation path.

To fulfill the requirement of building an event-driven architecture, we use an Enterprise Service Bus (ESB) that manages the exchange of the events. The ESB uses a publish/subscribe mechanism for receiving and submitting the events for pre-defined topics. When invoking a web service, the service's QOS INTERCEPTOR emits events about the services' performance-related quality to the ESB. For example, the ESB defines a topic for events, such as QoS. Then, the QOS INTERCEPTORS emit the events to the ESB for the QoS topic, and each subscriber of the QoS topic receives the events.

To be aware of SLA violations regarding to the service consumers and to the third party providers, the resulting architecture provides an ONLINE QOS MONITOR and an OFFLINE QOS MONITOR (see Section 4.4.4).

To detect SLA violations during runtime, we decided in favor of a ONLINE QOS MONITORING (see Section 4.4.4) that uses a CENTRALIZED QOS OBSERVER (see Section 4.4.5) and extends the QOS OBSERVER pattern [124]. The CENTRALIZED QOS OBSERVER subscribes to the ESB using the pre-defined topic for QoS events. All published events have a common format that contains an event type, a timestamp of occurrence, and some type-dependent properties. The online QoS monitoring and management concepts will be provided to validate the compliance concerns that can only be validated at runtime and to provide governance of compliance concerns. We detect SLA violations by implementing the CENTRALIZED QOS OBSERVER with a Complex Event Processing (CEP) logic. SLA violations are forwarded to a web-based dashboard, such as described in [105]. The dashboard serves as a visualization medium for displaying the business processes' and services' performance-related QoS measurements and eventual SLA violations.

To detect SLA violations after the SLA duration, we needed a OFFLINE QOS MONITORING solution. We decided to develop an *Event Log* component that is subscribed to the *ESB*'s QoS topic, receives the events, and stores them in a centralized storage. To evaluate the received events after the business processes' execution, we developed an *Evaluation Component* that is responsible for evaluating the received events regarding SLA violations. Equivalent as the ONLINE QOS MONITORING component, the evaluation component forwards the evaluation results to the dashboard.

However, there is no component in the architecture to predict SLA violations automatically, such as described in [20], [139], or [58]. The QuaLa DSL can be used to define appropriate rules to fire

actions in order to take well-timed corrective actions manually. In addition, the architecture does not provide mechanisms that perform appropriate actions automatically to prevent SLA violations.

Applying Contribution II:
Supporting the stakeholders with tailored domain-specific languages

To support the differently skilled stakeholders we use model-driven DSLs (see Chapter 5). In Section 5.4 we present the Quality of Service Language (QUALA), a tailored model-driven Domain-specific Language (DSL) to specify the services' QoS compliance concerns as well as to specify the technical details to measure the performance-related QoS properties. We use QuaLa within this architecture to support the stakeholders.

In addition, we have built an *DSL Editor* that can be used by the stakeholders for describing the services' QoS compliance concerns. For an integration with VbMF, we had to build a *DSL Transformation* that integrates the QuaLa specifications, i.e., the services' QoS compliance concerns, with the VbMF modelled business process and services.

7.4 A Case Study's Architectural Walkthrough

For a better understanding of the model-driven process-driven SOA for ensuring QoS-aware business processes, we describe the architecture for the case study (see Chapter 3). The case study's MVNO (i.e., the service provider) requires an ONLINE QOS MONITORING solution to get a permanent overview of the services' QoS compliance state, making it possible for the MVNO to prevent SLA violations when services quality decrease.

At the *design time*, the MVNO's domain experts use the high-level QuaLa DSL (see Section 5.4.1) to specify the QoS compliance concerns of the business processes' services, i.e., `Login`, `Search`, and `Stream`. Technical experts use the low-level QuaLa DSL (see Section 5.4.2) to extend the high-level specifications with required technical artefacts to generate an executable QoS-aware business processes. Examples of using the high-level and low-level QuaLa DSL are given in Section 5.4.4.

During the business processes' *runtime*, at every invocation of a QoS-aware web service, the services' QOS INTERCEPTOR emits events to the ESB. The QOS OBSERVER of the ONLINE QOS MONITORING component receives the events, evaluates them, and forwards the evaluation results to the dashboard. The MVNO's auditors see the evaluation results on the dashboard and can take appropriate actions manually to prevent possible SLA violations. For example, if auditors observe a permanent decreasing quality of the `Search` service, they can inform the technical experts to check for reasons and to take counteractive actions.

7.5 Summary

In this chapter we illustrated how we have extended an existing model-driven process-driven SOA to ensure business compliance. We concentrated on performance-related QoS compliance concerns that are defined in SLAs between the service provider and a service consumer. We have shown where the extended architecture reflects the main contributions of this thesis and gave an architectural walk-through based on the case study (see Section 3).

The QoS-aware process-driven SOA is an event-driven architecture, meaning that events are used to validate the business' QoS compliance. We have illustrated the support of the various stakeholders to specify the process-driven SOA's QoS compliance concerns, as well as the placement of the generated QOS INTERCEPTORS for measuring the performance-related QoS properties. The presented architecture provides online and offline QoS monitoring, making it possible to detect SLA violations during and after the business processes execution.

Chapter 8

Conclusion

Monitoring Quality of Service (QOS) in service-oriented systems is inevitable in case Service Level Agreements (SLAs) upon the services' performance-related QoS compliance concerns are negotiated between service providers and service consumers. To design a QoS monitoring infrastructure, architectural design decisions about measuring, evaluating, and storing the performance-related agreements must be taken. To specify the performance-related agreements, differently skilled stakeholders must be supported, ranging from business to technical experts. Because of fuzzy requirements on the QoS domain in the early development stages, the requirements enhance and change frequently.

In this chapter we conclude the thesis. In Section 8.1 we summarize the thesis' questions under research (see Section 1.3). Then, we iterate over the thesis' contributions (see Section 1.4) in Section 8.2. In Section 8.3 we explain potential future research challenges in the area of monitoring QoS in service-oriented systems.

8.1 Summary of the Research Questions

Research Question I:

How to design a QoS monitoring infrastructure in order to detect or prevent SLA violations?

During the design of an appropriate QoS monitoring infrastructure, many architectural design decisions arise. This research question concentrated on the various design decisions that must be taken during the decision making process. In this thesis, we focus on architectural design decisions about measuring, storing, and evaluating the performance-related QoS properties that are negotiated within SLAs.

Research Question II:
How to support the differently skilled stakeholders to specify the performance-related QoS agreements?

After having designed a QoS monitoring infrastructure, most of its component can be generated automatically using Model-driven Development (MDD). Various stakeholders are involved in the management and maintenance phases of the running QoS monitoring infrastructure. The stakeholders are differently skilled, ranging from business to technical background knowledge. Business experts know how and which performance-related QoS properties are specified within the SLAs. Technical experts have experience in the used technologies to develop a QoS monitoring infrastructure. This research question focuses on the problem of including all stakeholders within the process of a specifying the performance-related QoS clauses within the SLAs.

Research Question III:
How to develop an appropriate stakeholder support, dealing with permanent changing requirements?

In early stages, the requirements of a QoS monitoring infrastructure are fuzzy and incomplete, stemming from different stakeholder interpretations of the QoS domain. After becoming more familiar with the domain concepts, the requirements of the QoS monitoring infrastructure evolve and change. The later the changes, the more complex and time-consuming the updates. The research questions focuses on approaching solutions to deal with permanent changing requirements.

Research Question IV:
How to integrate a QoS monitoring solution into an existing service-oriented system?

Nowadays, organizations utilize service-oriented system to automate their inner- and cross-organizational business processes. A service-oriented system must be extended to ensure internal policies, stemming from performance-related QoS negotiations within SLAs. In thesis we wanted to research how the thesis' contributions can be used to extend an existing process-driven Service-oriented Architecture (SOA) to comply to performance-related agreements.

8.2 Summary of the Scientific Contributions

Contribution I:
An architectural decision model to design a QoS monitoring infrastructure

In this thesis we have present an architectural design decision model to help the designers through the decision making process. We concentrated on design decisions regarding measuring, storing,

and evaluating performance-related QoS agreements. The architectural decision model contains design decisions and requirements that we have discovered in a thorough literature review as well as within the case study (see 3). In the model, we differentiate between criteria, system-specific, and implementation-specific requirements. The presented model proposes design solutions that are based upon well-established design patterns. Criteria and requirements influence design decisions in the selection of the model's design solutions. We have evaluated the architectural decision model within the case study (see Section 3).

Contribution II:
Supporting the stakeholders with tailored domain-specific languages

To support the differently skilled stakeholders we introduce an approach to specify performance-related QoS properties embedded in the SLAs. The approach focuses on utilizing Domain-specific Languages (DSLs), developed following the MDD paradigm. In our approach, we divide a model-driven DSL into multiple sub-languages at different abstraction levels. Each sub-language is tailored to the appropriate stakeholders. We have evaluated the approach within an explorative study of providing tailored languages within SOAs. We illustrate the Quality of Service Language (QUALA) DSL, a developed model-driven DSL within the scope of an industrial case study for specifying a service's performance-related QoS compliance concerns and actions in case of violations. The DSL is separated into two different languages, tailored for business and technical experts.

Contribution III:
Incremental development of domain-specific languages

In this thesis we have presented an incremental development approach to develop model-driven DSLs. We have made a study and researched the approach within the case study (see Chapter 3). The study's research questions focus on (1) the applicability of an incremental approach, (2) the impact of changing requirements, (3) drawbacks of non-incremental development approaches, and (4) general recommendations for developing model-driven DSLs incrementally. We provide answers to the study's research questions based on the findings during the incremental development of the case study's QuaLa DSL.

Contribution IV:
Extending an existing process-driven SOA to QOS-awareness

We have used the aforementioned contributions to extend an existing process-driven SOA to monitor performance-related QoS agreements. The existing system consists of a modelling framework to generate executable business processes that orchestrate the SOA's services. First, we had to utilize

the architectural design decision model to design an appropriated QoS monitoring infrastructure. The resultant QoS monitoring infrastructure uses QOS INTERCEPTORS to measure, a CENTRALIZED ONLINE QOS OBSERVER and a CENTRALIZED OFFLINE QOS OBSERVERS to evaluate, and a CENTRALIZED QOS STORAGE to store the performance-related QoS properties. We had afterwards to develop a DSL to support the stakeholders in specifying the services' performance-related QoS properties. We extended the QuaLa DSL (see Section 5.4) to integrate with the existing modelling framework. Then, we extend the QuaLa code generator to generate QOS INTERCEPTORS that measure the services' performance-related QoS properties and submit the measurements to the CENTRALIZED QOS OBSERVER for evaluation.

8.3 Potential Future Research

As illustrated, monitoring agreements on the services' performance in a service-oriented systems is a challenging task. In the thesis we present approaches to reduce the design and development efforts of a QoS monitoring infrastructure, involving differently skilled stakeholders. However, there are still a lot of research challenges in this area. In this section we explain some, from our point of view, potential research challenges.

In this thesis, we have presented a QoS monitoring infrastructure that informs some system administrators or responsible persons via an e-mail or an SMS in case of potential future SLA violations. The system administrators or responsible persons must take appropriate actions to avoid the SLA violations manually. Can such corrective provisions be automated?

In the thesis' contributions we have used MDD to generate the QoS monitoring infrastructure's components automatically. We have used DSLs to support the differently skilled stakeholders to specify the services' performance-related QoS agreemements. But, the generated code must be extended with manual implementations. Is it possible to enable full code generation?

A QoS monitoring infrastructure is a complex software system that has many requirements. Fulfilling one requirement can bring trade-offs for other requirements. We have presented an architectural design decision model to enhance the decision making process and to fulfill the requirements as good as possible. In the future, we want to research general architectural decision models to design complex distributed systems. How can the requirements of such a system be gathered from the stakeholders? And how can MDD help to develop complex distributed systems?

Bibliography

[1] A. Agrawal, M. Amend, M. Das, C. Keller, M. Kloppmann, D. König, F. Leymann, R. Müller, G. Pfau, K. Ploesser, R. Rangaswamy, A. Rickayzen, M. Rowley, P. Schmidt, I. Trickovic, A. Yiu, and M. Zeller. Web Services Human Task (WS-HumanTask), version 1.0, 2007. → pages 77

[2] Y. Afek, M. Merritt, and G. Stupp. Remote Object Oriented Programming with Quality of Service or Java's RMI over ATM, 1996. → pages 40, 136

[3] C. Alexander, S. Ishikawa, and M. Silverstein. *A Pattern Language: Towns, Buildings, Construction*. Oxford University Press, New York, 1977. ISBN 0195019199. → pages 22

[4] G. Alonso, F. Casati, H. Kuno, and V. Machiraju. *Web Services – Concepts, Architectures and Applications*. Springer, October 2003. ISBN 3642078885. → pages 9, 10

[5] Anton Jansen and Jan Bosch. Software Architecture as a Set of Architectural Design Decisions. In *WICSA '05: Proceedings of the 5th Working IEEE/IFIP Conference on Software Architecture*, pages 109–120, Washington, DC, USA, 2005. IEEE Computer Society. ISBN 0-7695-2548-2. doi:http://dx.doi.org/10.1109/WICSA.2005.61. → pages 74

[6] G. Arango. Domain analysis – from art form to engineering discipline. *SIGSOFT Softw. Eng. Notes*, 14(3):152–159, 1989. ISSN 0163-5948. doi:http://doi.acm.org/10.1145/75200.75224. → pages 101

[7] Arie Deursen and Paul Klint. Little Languages: Little Maintenance? Technical report, CWI (Centre for Mathematics and Computer Science), Amsterdam, The Netherlands, 1997. → pages 101

[8] Arno Schmidmeier. Aspect oriented DSLs for business process implementation. In *DSAL '07: Proceedings of the 2nd workshop on Domain specific aspect languages*, page 5, New York, NY, USA, 2007. ACM. ISBN 978-1-59593-659-8. doi:http://doi.acm.org/10.1145/1255400.1255405. → pages 74, 76

[9] AT&T Research. Graphviz - Graph Visualization Software. http://www.graphviz.org/. → pages 110

[10] C. Aurrecoechea, A. T. Campbell, and L. Hauw. A survey of QoS architectures. *Multimedia Systems*, 6:138–151, May 1998. ISSN 0942-4962. doi:10.1007/s005300050083. URL http://portal.acm.org/citation.cfm?id=277956.277958. → pages 21

[11] P. Avgeriou and U. Zdun. Architectural Patterns Revisited – A Pattern Language. In *Proceedings of 10th European Conference on Pattern Languages of Programs (EuroPlop 2005)*, pages 1 – 39, Irsee, Germany, July 2005. → pages 31

[12] T. Baar. Correctly defined concrete syntax. *Software and System Modeling*, 7(4):383–398, 2008. → pages 70

[13] E. Badidi, L. Esmahi, M. A. Serhani, and M. Elkoutbi. WS-QoSM: A Broker-based Architecture for Web Services QoS Management. In *Innovations in Information Technology, 2006*, pages 1–5, 2006. doi:10.1109/INNOVATIONS.2006.301883. → pages 46, 53, 137, 140

[14] Berkely Institute of Design. The Prefuse Visualization Toolkit. http://prefuse.org/. → pages 110

[15] P. Bianco, G. A. Lewis, and P. Merson. Service Level Agreements in Service-Oriented Architecture Environments. Technical report, Software Engineering Institute, Carnegie Mellon University, Pittsburgh, PA, 2001. → pages 21

[16] K. Bierhoff, E. Liongosari, and K. Swaminathan. Incremental Development of a Domain-Specific Language That Supports Multiple Application Styles. In *OOPSLA – 6th Workshop on Domain Specific Modeling*, pages 67–78, October 2006. → pages 110

[17] Borland. VisiBroker – A Robust CORBA Environment for Distributed Processing, 2009. → pages 45, 137

[18] F. Buschmann, R. Meunier, H. Rohnert, P. Sommerlad, and M. Stal. *Pattern-Oriented Software Architecture, Volume 1: A System of Patterns*. Wiley, 1996. ISBN 978-0-471-95869-7. → pages 5, 21

[19] F. Buschmann, K. Henney, and D. C. Schmidt. *Pattern-Oriented Software Architecture, Volume 4: A Pattern Language for Distributed Computing*. Wiley, 2007. ISBN 978-0-470-05902-9. → pages 5, 21, 24, 40, 45

[20] M. Castellanos, F. Casati, U. Dayal, and M.-C. Shan. Intelligent Management of SLAs for Composite Web Services. In N. Bianchi-Berthouze, editor, *Databases in Networked Information Systems*, volume 2822 of *Lecture Notes in Computer Science*, pages 158–171. Springer Berlin / Heidelberg, 2003. → pages 116

[21] Cisco. Cisco IOS IP Service Level Agreements (SLAs), 2011. http://www.cisco.com/go/ipsla *(last accessed: February 2011)*. → pages 46, 53, 137, 140

[22] J. O. Coplien. Design Pattern Definition – Software Patterns. http://hillside.net/patterns/222-design-pattern-definition *(last accessed: February 2011)*. → pages 22

[23] K. Czarnecki and U. W. Eisenecker. *Generative Programming — Methods, Tools, and Applications*. Addison-Wesley Longman Publishing Co., Inc., 6th edition, 2000. → pages 25

[24] H. Czedik-Eysenberg. Generating Performance-Related Quality of Service Tests for Web Services using a Domain-Specific Language. *Master Thesis*, Vienna University of Technology, 2011. → pages 94

[25] F. Daniel, F. Casati, V. D'Andrea, E. Mulo, U. Zdun, S. Dustdar, S. Strauch, D. Schumm, F. Leymann, S. Sebahi, F. d. Marchi, and M.-S. Hacid. Business Compliance Governance in Service-Oriented Architectures. In *Proceedings of the 2009 International Conference on Advanced Information Networking and Applications*, pages 113–120, Washington, DC, USA, 2009. IEEE Computer Society. ISBN 978-0-7695-3638-5. doi:10.1109/AINA.2009.112. URL http://portal.acm.org/citation.cfm?id=1578016.1578257. → pages 1

[26] G. Di Modica, O. Tomarchio, and L. Vita. Dynamic SLAs management in service oriented environments. *Journal of Systems and Software*, 82(5):759–771, 2009. ISSN 0164-1212. doi:http://dx.doi.org/10.1016/j.jss.2008.11.010. → pages 104

[27] Eclipse. Xtext, 2009. http://www.eclipse.org/Xtext/. → pages 111

[28] Eclipse.org. Xtext – Language Development Framework. http://www.eclipse.org/Xtext/. → pages 70

[29] N. Fenton and S. L. Pfleeger. *Software metrics (2nd ed.): a rigorous and practical approach*. PWS Publishing Co., Boston, MA, USA, 1997. ISBN 0-534-95600-9. → pages 108

[30] M. Fowler. *Domain-Specific Languages*. Addison-Wesley Professional, October 2010. ISBN 0321712943. → pages 69, 82, 100

[31] M. Fowler. Language Workbenches: The Killer-App for Domain Specific Languages? http://www.martinfowler.com/articles/languageWorkbench.html, June 2005. → pages 73

[32] J. Freeze. Creating DSLs with Ruby, 2006. http://www.artima.com/rubycs/articles/ruby_as_dsl.html. → pages 111

[33] J. Freeze. Creating DSLs with Ruby. Ruby Code & Style, March 2006. → pages 69

[34] S. Frølund and J. Koistinen. Quality of Service Specification in Distributed Object Systems Design. In *COOTS*, pages 1–18. USENIX, 1998. → pages 11

[35] E. Gamma, R. Helm, R. Johnson, and J. Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley Professional, 1995. → pages 5, 21, 22, 34, 36, 59, 66

[36] M. Goedicke, K. Koellmann, and U. Zdun. Designing runtime variation points in product line architectures: three cases. *Science of Computer Programming*, 53(3):353–380, 2004. → pages 73

[37] J. Greenfield and K. Short. *Software Factories: Assembling Applications with Patterns, Frameworks, Models & Tools*. J. Wiley and Sons Ltd., 2004. → pages 73, 74

[38] R. Hauck and H. Reiser. Monitoring Quality of Service across Organizational Boundaries. In *Proceedings of the Third International IFIP/GI Working Conference on Trends in Distributed Systems: Towards a Universal Service Market*, pages 124–137, London, UK, 2000. Springer-Verlag. ISBN 3-540-41024-4. → pages 21

[39] C. Hentrich and U. Zdun. Patterns for Process-Oriented Integration in Service-Oriented Architectures. In *Proceedings of 11th European Conference on Pattern Languages of Programs (EuroPlop 2006)*, pages 141–189, Irsee, Germany, July 2006. → pages 10

[40] J. Hoffert, D. Schmidt, and A. Gokhale. DQML: A Modeling Language for Configuring Distributed Publish/Subscribe Quality of Service Policies. In *Proceedings of the OTM 2008 Confederated International Conferences, CoopIS, DOA, GADA, IS, and ODBASE 2008. Part I on On the Move to Meaningful Internet Systems:*, OTM '08, pages 515–534, Berlin, Heidelberg, 2008. Springer-Verlag. ISBN 978-3-540-88870-3. doi:http://dx.doi.org/10.1007/978-3-540-88871-0_38. → pages 67, 95

[41] T. Holmes, H. Tran, U. Zdun, and S. Dustdar. Modeling Human Aspects of Business Processes - A View-Based, Model-Driven Approach. In *ECMDA-FA*, pages 246–261, 2008. doi:10.1007/978-3-540-69100-6_17. → pages 77

[42] P. Hudak. Building Domain-Specific Embedded Languages. *ACM Comput. Surv.*, 28, December 1996. ISSN 0360-0300. → pages 69

[43] IBM and SAP. WS-BPEL Extension for People. http://www.ibm.com/developerworks/webservices/library/specification/ws-bpel4people/. → pages 77

[44] JetBrains. Meta Programming System, 2009. http://www.jetbrains.com/mps/index.html. → pages 111

[45] L. jie Jin, V. Machiraju, and A. Sahai. Analysis on Service Level Agreement of Web Services. Technical report, HP Laboratories, 2002. → pages 1, 9, 11, 92

[46] Juha-Pekka Tolvanen. Domain-Specific Modeling: How to Start Defining Your Own Language. http://www.devx.com/enterprise/Article/30550 (last accessed: July 2008). → pages 96

[47] A. Keller and H. Ludwig. The WSLA Framework: Specifying and Monitoring Service Level Agreements for Web Services. *Journal of Network and Systems Management*, 11(1):57–81, 2003. ISSN 1064-7570. doi:http://dx.doi.org/10.1023/A:1022445108617. → pages 1

[48] A. Keller and H. Ludwig. The WSLA Framework: Specifying and Monitoring Service Level Agreements for Web Services. *Journal of Network and Systems Management*, 11:57–81, 2003. ISSN 1064-7570. URL http://dx.doi.org/10.1023/A:1022445108617. 10.1023/A:1022445108617. → pages 21, 67, 96

[49] S. Kelly and J.-P. Tolvanen. *Domain-Specific Modeling: Enabling Full Code Generation*. John Wiley & Sons, March 2008. ISBN 0470036664. → pages 69, 99, 100

[50] S. Kelly and J.-P. Tolvanen. *Domain-Specific Modeling: Enabling Full Code Generation*. John Wiley & Sons, March 2008. ISBN 0470036664. → pages 68, 69, 70, 110

[51] S. Kelly, K. Lyytinen, and M. Rossi. MetaEdit+: A Fully Configurable Multi-User and Multi-Tool CASE and CAME Environment. In *CAiSE 96: Proceedings of the 8th International Conference on Advances Information System Engineering*, pages 1–21, London, UK, 1996. Springer-Verlag. ISBN 3-540-61292-0. → pages 110

[52] Kevin Bierhoff and Edy S. Liongosari and Kishore S. Swaminathan. Incremental Development of a Domain-Specific Language That Supports Multiple Application Styles. In *OOPSLA 6th Workshop on Domain Specific Modeling*, pages 67–78, October 2006. → pages 96

[53] G. Kiczales, J. Lamping, A. Mendhekar, C. Maeda, C. V. Lopes, J.-M. Loingtier, and J. Irwin. Aspect–Oriented Programming. In *ECOOP*, pages 220–242, 1997. → pages 65

[54] G. Kiczales, E. Hilsdale, J. Hugunin, M. Kersten, J. Palm, and W. G. Griswold. An Overview of AspectJ. In *ECOOP '01: Proceedings of the 15th European Conference on Object-Oriented Programming*, pages 327–353, London, UK, 2001. Springer-Verlag. ISBN 3-540-42206-4. → pages 65

[55] T. Kosar, P. E. Martínez López, P. A. Barrientos, and M. Mernik. A preliminary study on various implementation approaches of domain-specific language. *Inf. Softw. Technol.*, 50(5): 390–405, 2008. ISSN 0950-5849. doi:http://dx.doi.org/10.1016/j.infsof.2007.04.002. → pages 110

[56] D. D. Lamanna, J. Skene, and W. Emmerich. SLAng: A Language for Defining Service Level Agreements. In *Proceedings of the The Ninth IEEE Workshop on Future Trends of Distributed Computing Systems*, FTDCS '03, pages 100–, Washington, DC, USA, 2003. IEEE Computer Society. ISBN 0-7695-1910-5. → pages 11, 67, 95

[57] C. F. J. Lange. Model Size Matters. In *Workshop on Model Size Metrics at MoDELS06*, 2006. → pages 108

[58] P. Leitner, A. Michlmayr, F. Rosenberg, and S. Dustdar. Monitoring, Prediction and Prevention of SLA Violations in Composite Services. In *ICWS*, pages 369–376. IEEE Computer Society, 2010. ISBN 978-0-7695-4128-0. → pages 21, 116

[59] L. Lewis and P. Ray. Service level management definition, architecture, and research challenges. In *Global Telecommunications Conference, 1999. GLOBECOM '99*, volume 3, pages 1974–1978 vol.3, 1999. doi:10.1109/GLOCOM.1999.832515. → pages 1

[60] Z. Li, Y. Jin, and J. Han. A Runtime Monitoring and Validation Framework for Web Service Interactions. In *Proceedings of the Australian Software Engineering Conference*, pages 70–79, Washington, DC, USA, 2006. IEEE Computer Society. ISBN 0-7695-2551-2. doi:10.1109/ASWEC.2006.6. → pages 43, 53, 56, 136, 139, 140, 141

[61] D. Lorenzoli and G. Spanoudakis. EVEREST+: Run-time SLA violations prediction. In *Proceedings of the 5th International Workshop on Middleware for Service Oriented*

Computing, MW4SOC '10, pages 13–18, New York, NY, USA, 2010. ACM. ISBN 978-1-4503-0452-8. doi:http://doi.acm.org/10.1145/1890912.1890915. URL http://doi.acm.org/10.1145/1890912.1890915. → pages 53, 139, 140

[62] J. Loyall, R. Schantz, J. Zinky, and D. Bakken. Specifying and Measuring Quality of Service in Distributed Object Systems. *Object-Oriented Real-Time Distributed Computing, IEEE International Symposium on*, 0, 1998. doi:http://doi.ieeecomputersociety.org/10.1109/ISORC.1998.666767. → pages 41, 96, 136

[63] A. Mani and A. Nagarajan. Understanding quality of service for Web services – Improving the performance of your Web services, 2002. http://www.ibm.com/developerworks/library/ws-quality.html, *last accessed: February 2011*. → pages 12, 13, 26, 35, 39, 135, 136

[64] E. M. Maximilien, H. Wilkinson, N. Desai, , and S. Tai. A domain specific-language for web apis and services mashups. In *Proceedings of 5th International Conference on Service Oriented Computing (ICSOC), LNCS 4749, Springer-Verlag*, pages 13–26, Vienna, Austria, 2007. → pages 73, 96

[65] M. Mernik, J. Heering, and A. M. Sloane. When and how to develop domain-specific languages. *ACM Comput. Surv.*, 37(4):316–344, 2005. ISSN 0360-0300. doi:http://doi.acm.org/10.1145/1118890.1118892. → pages 69, 100, 110

[66] B. M. Michelson. Event-Driven Architecture Overview. *Patricia Seybold Group*, 2006. → pages 114

[67] A. Michlmayr, F. Rosenberg, P. Leitner, and S. Dustdar. Comprehensive QoS monitoring of Web services and event-based SLA violation detection. In *MWSOC '09: Proceedings of the 4th International Workshop on Middleware for Service Oriented Computing*, pages 1–6, New York, NY, USA, 2009. ACM. ISBN 978-1-60558-848-3. doi:http://doi.acm.org/10.1145/1657755.1657756. → pages 36, 53, 135, 139, 140

[68] A. Michlmayr, F. Rosenberg, P. Leitner, and S. Dustdar. End-to-End Support for QoS-Aware Service Selection, Binding, and Mediation in VRESCo. *IEEE Transactions on Services Computing*, 3:193–205, 2010. ISSN 1939-1374. doi:http://doi.ieeecomputersociety.org/10.1109/TSC.2010.20. → pages 21, 43, 136

[69] Microsoft. Domain-Specific Language Tools, 2009. http://msdn.microsoft.com/en-us/library/bb126235.aspx. → pages 111

[70] Microsoft. .NET, . http://www.microsoft.com/net/. → pages 35

[71] Microsoft. .NET Remoting, . http://msdn.microsoft.com/en-us/library/kwdt6w2k(v=vs.71).aspx. → pages 43, 136

[72] Microsoft. Windows Communication Framework, . http://msdn.microsoft.com/en-us/netframework/aa663324.aspx. → pages 35

[73] Microsoft. Windows Performance Counters, . http://msdn.microsoft.com/en-us/library/ms735098.aspx. → pages 35, 135

[74] E. Mulo, U. Zdun, and S. Dustdar. An event view model and DSL for engineering an event-based SOA monitoring infrastructure. In J. Bacon, P. R. Pietzuch, J. Sventek, and U. Çetintemel, editors, *DEBS*, pages 62–72. ACM, 2010. ISBN 978-1-60558-927-5. → pages 69

[75] OASIS. Universal Description, Discovery and Integration (UDDI). http://www.oasis-open.org/committees/uddi-spec/doc/tcspecs.htm. → pages 9, 10

[76] OASIS. Web Services Business Process Execution Language Version 2.0, 2007. http://docs.oasis-open.org/wsbpel/2.0/OS/wsbpel-v2.0-OS.html. → pages 95, 114

[77] E. Oberortner, U. Zdun, and S. Dustdar. Patterns for Measuring Performance-Related QoS Properties in Distributed Systems. In *Pattern Languages of Programming Conference (PLoP)*. → pages 2, 21

[78] E. Oberortner, M. Vasko, and S. Dustdar. Towards Modeling Role-Based Pageflow Definitions within Web Applications. In *Proc. of the 4th International Workshop on Model-Driven Web Engineering (MDWE 2008)*, volume 389 of *CEUR Workshop Proceedings*, pages 1–15, Toulouse, France, Sept. 2008. CEUR-WS.org. URL http://CEUR-WS.org/Vol-389/paper01.pdf. → pages 91

[79] E. Oberortner, U. Zdun, and S. Dustdar. Domain-Specific Languages for Service-Oriented Architectures: An Explorative Study. In *ServiceWave '08: Proceedings of the 1st European Conference on Towards a Service-Based Internet*, pages 159–170, Berlin, Heidelberg, 2008. Springer-Verlag. ISBN 978-3-540-89896-2. doi:http://dx.doi.org/10.1007/978-3-540-89897-9_14. → pages 69

[80] E. Oberortner, U. Zdun, and S. Dustdar. Tailoring a model-driven Quality-of-Service DSL for various stakeholders. In *MISE '09: Proceedings of the 2009 ICSE Workshop on Modeling in Software Engineering*, pages 20–25, Washington, DC, USA, 2009. IEEE Computer Society. ISBN 978-1-4244-3722-1. doi:http://dx.doi.org/10.1109/MISE.2009.5069892. → pages 2

[81] E. Oberortner, U. Zdun, and S. Dustdar. Tailoring a model-driven Quality-of-Service DSL for Various Stakeholders. In *MISE '09: Proceedings of the 2009 ICSE Workshop on Modeling in Software Engineering*, pages 20–25, Washington, DC, USA, 2009. IEEE Computer Society. ISBN 978-1-4244-3722-1. doi:http://dx.doi.org/10.1109/MISE.2009.5069892. → pages 11

[82] E. Oberortner, U. Zdun, S. Dustdar, A. Betkowska Cavalcante, and M. Tluczek. Supporting the Evolution of Model-driven Service-oriented Systems: A Case Study on QoS-aware Process-driven SOAs. In *IEEE International Conference on Service-Oriented Computing and Applications (SOCA)*, pages 1–4, 2010. doi:10.1109/SOCA.2010.5707172. → pages 2

[83] Object Management Group (OMG). Common Object Request Broker Architecture/Internet Inter-ORB Protocol (CORBA/IIOP), 2008. → pages 45, 137

[84] Object Management Group (OMG. Quality Of Service For CCM (QOSCCM), 2008. → pages 43, 136

[85] L. O'Brien, P. Merson, and L. Bass. Quality Attributes for Service-Oriented Architectures. In *SDSOA '07: Proceedings of the International Workshop on Systems Development in SOA Environments*, Washington, DC, USA, 2007. IEEE Computer Society. ISBN 0-7695-2960-7. doi:http://dx.doi.org/10.1109/SDSOA.2007.10. → pages 12, 13, 109

[86] L. O'Brien, P. Merson, and L. Bass. Quality Attributes for Service-Oriented Architectures. In *SDSOA '07: Proceedings of the International Workshop on Systems Development in SOA Environments*, page 3, Washington, DC, USA, 2007. IEEE Computer Society. ISBN 0-7695-2960-7. doi:http://dx.doi.org/10.1109/SDSOA.2007.10. → pages 11, 12, 21

[87] M. Papazoglou. Compliance Requirements for Business-process driven SOAs. In A. Mazzeo, R. Bellini, and G. Motta, editors, *E-Government Ict Professionalism and Competences Service Science*, volume 280 of *IFIP International Federation for Information Processing*, pages 183–194. Springer Boston, 2008. → pages 113

[88] M. Papazoglou. Compliance Requirements for Business-process driven SOAs. In A. Mazzeo, R. Bellini, and G. Motta, editors, *E-Government Ict Professionalism and Competences Service Science*, volume 280 of *IFIP International Federation for Information Processing*, pages 183–194. Springer Boston, 2008. → pages 1

[89] M. P. Papazoglou. Service-Oriented Computing: Concepts, Characteristics and Directions. In *WISE*, pages 3–12. IEEE Computer Society, 2003. ISBN 0-7695-1999-7. → pages 9

[90] R. E. Pattis. EBNF: A Notation to Describe Syntax. online available at http://www.cs.cmu.edu/~pattis/misc/ebnf.pdf. → pages 82

[91] V. Perrone, D. Bolchini, and P. Paolini. A Stakeholders Centered Approach for Conceptual Modeling of Communication-Intensive Applications. In *SIGDOC '05: Proceedings of the 23rd annual international conference on Design of communication*, pages 25–33, New York, NY, USA, 2005. ACM. ISBN 1-59593-175-9. doi:http://doi.acm.org/10.1145/1085313.1085323. → pages 71

[92] S. Ran. A model for web services discovery with QoS. *SIGecom Exch.*, 4(1):1–10, 2003. doi:http://doi.acm.org/10.1145/844357.844360. → pages 109

[93] S. Ran. A Model for Web Services Discovery with QoS. *SIGecom Exch.*, 4(1):1–10, 2003. doi:http://doi.acm.org/10.1145/844357.844360. → pages 12, 21

[94] Ravi S. Sandhu and Edward J. Coyne and Hal L. Feinstein and Charles E. Youman. Role-Based Access Control Models. *Computer*, 29(2):38–47, 1996. ISSN 0018-9162. doi:http://dx.doi.org/10.1109/2.485845. → pages 90

[95] Risto Pitkänen and Tommi Mikkonen. Lightweight Domain-Specific Modeling and Model-Driven Development. In *OOPSLA, 6th Workshop on Domain Specific Modeling*, pages 159–168, October 2006. → pages 96, 110

[96] F. Rosenberg. *QoS-Aware Composition of Adaptive Service-Oriented Systems*. PhD thesis, Vienna University of Technology, 2010. → pages 21, 35, 135

[97] F. Rosenberg, C. Platzer, and S. Dustdar. Bootstrapping Performance and Dependability Attributes of Web Services. In *ICWS '06: Proceedings of the IEEE International Conference on Web Services*, pages 205–212, Washington, DC, USA, 2006. IEEE Computer Society. ISBN 0-7695-2669-1. doi:http://dx.doi.org/10.1109/ICWS.2006.39. → pages 13

[98] F. Rosenberg, C. Platzer, and S. Dustdar. Bootstrapping Performance and Dependability Attributes of Web Services. In *ICWS '06: Proceedings of the IEEE International Conference on Web Services*, pages 205–212, Washington, DC, USA, 2006. IEEE Computer Society. ISBN 0-7695-2669-1. doi:http://dx.doi.org/10.1109/ICWS.2006.39. → pages 12, 14, 21, 41, 56, 109, 136, 140

[99] A. Sahai, A. Sahai, A. Durante, A. Durante, V. Machiraju, and V. Machiraju. Towards Automated SLA Management for Web Services. Technical report, Software Technology Laboratory, HP Laboratories, 2001. → pages 11

[100] A. Sahai, V. Machiraju, M. Sayal, L. J. Jin, and F. Casati. Automated SLA Monitoring for Web Services. In *IEEE/IFIP DSOM*, pages 28–41. Springer-Verlag, 2002. → pages 21, 36, 45, 53, 56, 135, 137, 139, 140, 141

[101] SAS. ARM – Application Response Measurement. *(last accessed: February 2011)*. → pages 41, 136

[102] D. C. Schmidt. Model-Driven Engineering. *IEEE Computer*, 39(2), February 2006. → pages 68

[103] D. C. Schmidt, H. Rohnert, M. Stal, and D. Schultz. *Pattern-Oriented Software Architecture: Patterns for Concurrent and Networked Objects*. John Wiley & Sons, Inc., New York, NY, USA, 2000. ISBN 0471606952. → pages 5, 21, 24, 36

[104] T. Sheard. Evolving Domain Specific Languages – Project Summary. → pages 110

[105] P. Silveira, C. Rodríguez, F. Casati, F. Daniel, V. D'Andrea, C. Worledge, and Z. Taheri. On the Design of Compliance Governance Dashboards for Effective Compliance and Audit Management. In *Proceedings of the 3rd Workshop on Non-Functional Properties and SLA Management in Service-Oriented Computing (NFPSLAM-SOC'09)*, 2009. → pages 28, 116

[106] J. Sprinkle, J. Gray, and M. Mernik. Fundamental Limitations in Domain-Specific Language Evolution. *IEEE Transactions on Software Engineering*, 35(3), 2009. → pages 110

[107] T. Stahl and M. Voelter. *Model-Driven Software Development*. J. Wiley and Sons Ltd., 2006. → pages 74

[108] T. Stahl, M. Voelter, and K. Czarnecki. *Model-Driven Software Development: Technology, Engineering, Management*. John Wiley & Sons, 2006. ISBN 0470025700. → pages 68, 70

[109] Steve Cook. Domain-Specific Modeling and Model Driven Architectures. http://www.bptrends.com, 2004. → pages 74

[110] A. Strauss and J. Corbin. *Grounded theory in practice*. Sage, London, 1997. → pages 73, 75

[111] M. Strembeck and U. Zdun. An Approach for the Systematic Development of Domain-Specific Languages. *Softw. Pract. Exper.*, 39(15):1253–1292, 2009. ISSN 0038-0644. doi:http://dx.doi.org/10.1002/spe.v39:15. → pages 69, 82, 100

[112] Sun Developer Network. JavaServer Faces Technology. Available online at http://java.sun.com/javaee/javaserverfaces/. → pages 78

[113] The Apache Software Foundation. Apache Axis, . http://axis.apache.org/. → pages 43, 89, 136

[114] The Apache Software Foundation. Apache Axis2, . http://ws.apache.org/axis2/. → pages 12, 43, 136

[115] The Apache Software Foundation. Apache CXF, . http://cxf.apache.org/. → pages 12, 42, 43, 59, 82, 114, 116, 136

[116] The Apache Software Foundation. Apache ODE, . http://ode.apache.org/. → pages 114

[117] The Apache Software Foundation. Apache TCPMon, . http://ws.apache.org/commons/tcpmon/. → pages 45, 137

[118] The Community OpenORB Project. OpenORB. http://openorb.sourceforge.net/. → pages 43, 136

[119] The Open Group. SLA Management Handbook – Volume 4: Enterprise Perspective, 2004. → pages 13, 28

[120] The Service Level Agreement Zone. SLA Information Zone, 2002. http://www.sla-zone.co.uk (last accessed: January 2010). → pages 104

[121] H. Tran, U. Zdun, and S. Dustdar. View-based and Model-driven Approach for Reducing the Development Complexity in Process-Driven SOA. In W. Abramowicz and L. A. Maciaszek, editors, *BPSC*, volume 116 of *LNI*, pages 105–124. GI, 2007. ISBN 978-3-88579-210-9. → pages 76, 77, 114

[122] H. Tran, U. Zdun, and S. Dustdar. View-based integration of process-driven soa models at various abstraction levels. In *R.-D. Kutsche and N. Milanovic, Editors, Proceedings of First International Workshop on Model-Based Software and Data Integration MBSDI 2008*, pages 55–66. Springer, April 2008. → pages 76, 77

[123] Vito Perrone and Davide Bolchini and Paolo Paolini. A Stakeholders Centered Approach for Conceptual Modeling of Communication-Intensive Applications. In *SIGDOC '05: Proceedings of the 23rd annual international conference on Design of communication*, pages 25–33, New York, NY, USA, 2005. ACM. ISBN 1-59593-175-9. doi:http://doi.acm.org/10.1145/1085313.1085323. → pages 74

[124] M. Voelter, M. Kircher, and U. Zdun. *Remoting Patterns – Foundations of Enterprise, Internet, and Realtime Distributed Object Middleware.* Wiley & Sons, October 2004. → pages 5, 21, 24, 26, 27, 33, 36, 40, 42, 48, 51, 66, 116

[125] W3C. Simple Object Access Protocol (SOAP), 2000. http://www.w3.org/TR/soap. → pages 9, 10

[126] W3C. Web Services Description Language (WSDL), 2001. http://www.w3.org/TR/wsdl. → pages 9, 10, 95

[127] Q. Wang, Q. Ye, and L. Cheng. An Inter-Application and Inter-Client Priority-Based QoS Proxy Architecture for Heterogeneous Networks. In *ISCC '05: Proceedings of the 10th IEEE Symposium on Computers and Communications*, pages 819–824, Washington, DC, USA, 2005. IEEE Computer Society. ISBN 0-7695-2373-0. doi:http://dx.doi.org/10.1109/ISCC.2005.30. → pages 45, 137

[128] S. Wildermuth. Textual Domain Specific Languages for Developers, 2009. http://msdn.microsoft.com/en-us/library/dd441702.aspx. → pages 70

[129] E. Wohlstadter, S. Tai, T. Mikalsen, I. Rouvellou, and P. Devanbu. GlueQoS: Middleware to Sweeten Quality-of-Service Policy Interactions. In *Proceedings of the 26th International Conference on Software Engineering*, ICSE '04, pages 189–199, Washington, DC, USA, 2004. IEEE Computer Society. ISBN 0-7695-2163-0. → pages 41, 136

[130] World Wide Web Consortium (W3C). Web Services Architecture Requirements, 2004. http://www.w3.org/TR/wsa-reqs/. → pages 9

[131] World-Wide-Web Consortium (W3C). Web Services Agreement Specification (WS-Agreement), 2004. → pages 111

[132] World-Wide-Web Consortium (W3C). Web Services Policy 1.5 - Framework, 2007. http://www.w3.org/TR/ws-policy/. → pages 111

[133] W. D. Yu, R. B. Radhakrishna, S. Pingali, and V. Kolluri. Modeling the Measurements of QoS Requirements in Web Service Systems. *Simulation*, 83(1):75–91, 2007. ISSN 0037-5497. doi:http://dx.doi.org/10.1177/0037549707079228. → pages 12, 21, 109

[134] U. Zdun. Tailorable language for behavioral composition and configuration of software components. *Computer Languages, Systems and Structures: An International Journal*, 32(1): 56–82, 2006. → pages 73

[135] U. Zdun. The Frag Language. http://frag.sourceforge.net/. → pages 70, 84, 86

[136] U. Zdun. A DSL toolkit for deferring architectural decisions in DSL-based software design. *Information and Software Technology*, 52(7):733 – 748, 2010. ISSN 0950-5849. doi:DOI:10.1016/j.infsof.2010.03.004. → pages 70, 84, 86

[137] U. Zdun and S. Dustdar. Model-Driven and Pattern-Based Integration of Process-Driven SOA Models. In F. Leymann, W. Reisig, S. R. Thatte, and W. M. P. van der Aalst, editors, *The Role of Business Processes in Service Oriented Architectures*, volume 06291 of *Dagstuhl Seminar Proceedings*. Internationales Begegnungs- und Forschungszentrum fuer Informatik (IBFI), Schloss Dagstuhl, Germany, 2006. → pages 1, 4, 113

[138] U. Zdun and M. Strembeck. Reusable Architectural Decisions for DSL Design: Foundational Decisions in DSL Development. In *Proc. of the 14th European Conference on Pattern Languages of Programs (EuroPLoP)*, Irsee Monastery, Germany, July 2009. → pages 70

[139] L. Zeng, C. Lingenfelder, H. Lei, and H. Chang. Event-Driven Quality of Service Prediction. In *Proceedings of the 6th International Conference on Service-Oriented Computing*, ICSOC '08, pages 147–161, Berlin, Heidelberg, 2008. Springer-Verlag. ISBN 978-3-540-89647-0. doi:http://dx.doi.org/10.1007/978-3-540-89652-4_14. → pages 21, 116

Appendix A

Summary of Architectural Design Decisions, Requirements, and Solutions

A.1 Design Decision: WHICH SLA PARTY NEEDS QOS MONITORING?

Design Decision	WHICH SLA PARTY NEEDS QOS MONITORING?
Requirements	- Are services provided or consumed?
Solution	SERVICE PROVIDER QOS MONITORING
Description	The service provider wants to introduce a QoS monitoring infrastructure
Forces:	- Measuring of server-side performance-related QoS properties is possible
Consequences:	- Client-side performance-related QoS properties cannot be measured
Known Uses:	- Windows Performance Counters (WPC) [73] - Mani and Nagarajan [63]
Solution	SERVICE CONSUMER QOS MONITORING
Description	The service consumer wants to introduce a QoS monitoring infrastructure
Forces:	- Measuring of client-side performance-related QoS properties is possible
Consequences:	- Server-side performance-related QoS properties cannot be measured
Known Uses:	- The QUATSCH QoS monitoring framework [96]
Solution	COMBINED QOS MONITORING
Description:	The service provider and the service consumer agree on a common QoS monitoring infrastructure
Forces:	- Client- and server-side performance-related QoS properties can be measured
Consequences:	- Service provider and service consumer have to agree on a common QoS monitoring infrastructure
Known Uses:	- Michlmayr et al. [67] - Sahai et al. [100]

Table A.1: WHICH SLA PARTY NEEDS QOS MONITORING?

A.2 Design Decision: WHERE SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

Design Decision	WHERE SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?
Requirements	- Minimal performance overhead - Preciseness - Performance-related QoS properties - Reusability - Access to the clients'/services' implementation - Access to the middleware implementation is required - Separation of concerns is required
Solution	Pattern: QOS INLINE
Description:	Instrument the client's and the remote object's implementation with local measuring points by placing them directly into their implementation.
Forces:	- minimal performance overhead - precise QoS measurements - no access to the middleware required - does not influence other measurements
Consequences:	- acess to the implementation is required - no separation of concerns - not reusable
Known Uses:	- Mani and Nagarajan [63]
Solution	Pattern: QOS WRAPPER
Description:	Instrument the client's and remote object's implementations with local QOS WRAPPERS that are responsible for measuring the performance-related QoS properties. Let the clients invoke the remote objects using a client-side QOS WRAPPER. Extend the remote objects with a server-side QOS WRAPPER that receives the client's requests.
Forces:	- no access to implementation required - minimal performance overhead - separation of concern - reusable - precise QoS measurements - no access to the middleware required
Consequences:	- can not measure transmission-specific QoS properties
Known Uses:	- Afek et al. [2] - Quality Objects (QuO) [62] - Wohlstadter et al. [129] - The Application Resource Measurement (ARM) API [101] - Rosenberg et al. [98]
Solution	Pattern: QOS INTERCEPTOR
Description:	Hook QOS INTERCEPTORS into the invocation path that are responsible for measuring the performance-related QoS properties.
Forces:	- no access to the implementation required - minimal performance overhead - separation of concerns - reusable
Consequences:	- access to middleware necessary - can influences other measurements, hence - can lead to not precise QoS measurements
Known Uses:	- The OpenORB project [118] - .NET Remoting [71] - Axis [113], Axis2 [114], and Apache CXF [115] - QoS CORBA Component Model (QOSCCM) [84] - The VRESCo runtime environment [68] - Li et al. [60]

Solution	Pattern: QOS REMOTE PROXY
Description:	Implement and setup a QOS REMOTE PROXY in the client's and remote object's LAN that takes over the responsibility of measuring the performance-related QoS properties. In the client's LAN, configure each client to invoke the remote objects via the LAN's QOS REMOTE PROXY. In the server's LAN, make each remote object only be accessible via a QOS REMOTE PROXY.
Forces:	- no access to the implementation required - separation of concerns - reusable - no access to middleware necessary
Consequences:	- can have performance overhead - can influence other measurements, hence - can lead to not precise QoS measurements
Known Uses:	- The QoS-Adaptation proxy [127] - The VisiBroker [17] environment of the Corba IIOP specifications [83]. - The Apache TCPMon [117] tool - Sahai et al. [100] - WS-QoSM [13] - The Cisco IOS IP SLA [21]

Table A.2: HOW TO MEASURE PERFORMANCE-RELATED QOS PROPERTIES?

A.3 Design Decision: WHEN SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

Design Decision	WHEN SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?
Requirements	- Minimal performance overhead - Scalability - Preciseness
Solution	**PERIODIC QOS MEASURING**
Description:	Send periodically, in pre-defined time intervals, probe requests to the service to measure the performance-related QoS properties permanently.
Forces:	- performance overhead increases in case of a short time interval - high scalability in case of a long time interval - precise measuring results if setting a short time interval
Consequences:	- minimal performance overhead if setting a long time interval - low scalability in case of a short time interval - imprecise measuring results if setting a long time interval
Solution	**Pattern: EVENT-TRIGGERED QOS MEASURING**
Description:	Send probe requests to service to measure the performance-related QoS properties in case certain events occur in the system.
Forces:	- minimal performance overhead if events occur rarely - scalability increases in case of rare event occurrence - precise measuring results if events occur frequently
Consequences:	- performance overhead in case of high event frequency - low scalability if events occur frequently - imprecise measuring results in occur rarely
Solution	**INVOCATION-BASED QOS MEASURING**
Description:	Measure the performance-related QoS properties only in real service invocations.
Forces:	- minimal performance overhead - high scalability - precise measurements if services are invoked often
Consequences:	- imprecise measuring results if services are invoked rarely

Table A.3: WHEN SHOULD THE PERFORMANCE-RELATED QOS PROPERTIES BE MEASURED?

A.4 Design Decision: WHEN SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

Concern	WHEN SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?
Requirements	- Detect or prevent SLA violations - Dependency on the third parties' quality - Scalability - Minimal performance overhead
Solution	ONLINE QOS OBSERVER
Description:	The evaluation of the performance-related QoS measurements takes place during the SLA's validity.
Forces:	- It is possible to detect and prevent SLA violations. - Decreases of the third party services' quality can be recognized on time.
Consequences:	- A performance overhead is possible. - The scalability decreases.
Known Uses:	- Sahai et al. [100] updates the QoS measurements at regular time intervals. - Li et al. [60] monitor the performance-related QoS measurements using the ONLINE QOS OBSERVER solution. - Michlmayer et al. [67] developed a ONLINE QOS OBSERVER for detecting SLA violations. - The EVEREST+ framework [61] predicts SLA violations during the system's runtime.
Solution	OFFLINE QOS OBSERVER
Description:	The evaluation of the performance-related QoS measurements takes place after the SLA's validity.
Forces:	- SLA violations can be detected. - A minimal performance overhead is provided. - The scalability increases.
Consequences:	- SLA violations can not be prevented. - It is difficult to recognize decreases of the third party services' quality.

Table A.4: WHEN SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

A.5 Design Decision: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

Concern	WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?
Requirements	- Scalability - Minimal performance overhead - Reusability
Solution	**LOCALIZED QOS OBSERVER**
Description:	The evaluation of the performance-related QoS measurements takes place within a localized component
Forces:	- A minimal performance overhead is possible - Reusable in case the evaluation is not implemented with the clients' or services' implementation. - The scalability increases because all the measurements are evaluated locally
Consequences:	- *think about it...*
Known Uses:	- Rosenberg et al. [98] evaluate the services' performance-related QoS compliance concerns, utilizing a LOCALIZED QOS OBSERVER.
Solution	**CENTRALIZED QOS OBSERVER**
Description:	The evaluation of the performance-related QoS measurements takes place within a centralized component
Forces:	- Reusable for all clients and services
Consequences:	- A performance overhead is possible because all clients and services must transmit the measurements to the CENTRALIZED QOS OBSERVER - The scalability can decrease
Known Uses:	- The *SLA violation engine* [100] - WS-QoSM [13] - The CISCO IOS IP SLAs [21] - Li et al. [60] - Michlmayer et al. [67] - The EVEREST+ framework [61]

Table A.5: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE EVALUATED?

A.6 Design Decision: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE STORED?

Concern	WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE STORED?
Requirements	- Performance overhead - Scalability - Reusabiliy - Preciseness
Solution	LOCALIZED QOS STORAGE
Description:	The performance-related QoS measurements are stored at each client or service locally
Forces:	- minimal performance overhead - high scalability - using a WRAPPER pattern to store the performance-related QoS measurements enhances the reusability
Consequences:	- can influence the performance-related QoS measurements, resulting in imprecise measurements - dependent on the implementation strategy of the LOCALIZED QOS STORAGE - implementing the storing mechanism that stores the performance-related QoS properties in the LOCALIZED QOS STORAGE is not reusable
Influences:	- easier evaluation in case of using a LOCALIZED QOS OBSERVER - more time-consuming evaluation in case of deciding in favour of a CENTRALIZED QOS OBSERVER - the performance-related QoS measurements can be stored locally, resulting in a minimal performance overhead and higher scalability
Solution	CENTRALIZED QOS STORAGE
Description:	The performance-related QoS measurements are stored in a centralized storage
Forces:	- Easier CENTRALIZED QOS EVALUATION because the measurements do not have to be collected together
Consequences:	- A performance overhead can arise - Scalability decreases dependent on the number of services and clients - A LOCALIZED QOS EVALUATION is not advisable
Known Uses:	- Sahai et al. [100] - Li et al. [60]
Influences:	- easier evaluation in case of using a CENTRALIZED QOS OBSERVER - in case of a LOCALIZED QOS OBSERVER the evaluation becomes more time-consuming - the measuring solution has to submit the performance-related QoS measurements to the CENTRALIZED QOS OBSERVER resulting in a performance overhead

Table A.6: WHERE SHOULD THE PERFORMANCE-RELATED QOS MEASUREMENTS BE STORED?