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An architecture framework for enterprise IT service availability analysis

Ulrik Franke · Pontus Johnson · Johan König

Abstract This paper presents an integrated enterprise architecture framework for qualitative and quantitative modeling and assessment of enterprise IT service availability. While most previous work has either focused on formal availability methods such as fault trees or qualitative methods such as maturity models, this framework offers a combination.

First, a modeling and assessment framework is described. In addition to metamodel classes, relationships and attributes suitable for availability modeling, the framework also features a formal computational model written in a probabilistic version of the Object Constraint Language. The model is based on 14 systemic factors impacting service availability, and also accounts for the structural features of the service architecture.

Second, the framework is empirically tested in 9 enterprise information system case studies. Based on an initial availability baseline and the annual evolution of the 14 factors of the model, annual availability predictions are made and compared to the actual outcomes as reported in SLA reports and system logs.

The practical usefulness of the method is discussed based on the outcomes of a workshop conducted with the participating enterprises, and some directions for future research are offered.

Keywords Systems availability, Service availability, Downtime, Noisy-OR, System quality analysis, Enterprise Architecture, ArchiMate, Metamodel, OCL

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1 Introduction

Today, high availability is a sine qua non for IT service providers. For mission-critical applications, the demanded IT service availability levels continue to increase [50] – an indication that both businesses and customers increasingly expect availability all the time. However, this is easier said than done in the enterprise IT context. Enterprise systems – while critical to business operations – are typically part of complex integrated enterprise architectures tying together hundreds of systems and processes. This makes them difficult to maintain and the consequences of changes – e.g. in terms of availability – are hard to predict.

At the same time, many enterprises show little understanding of how much downtime is acceptable – or of the costs for such downtime [14]. An IBM study from the nineties concludes that unavailable systems cost American businesses $4.54 billion in 1996, due to lost productivity and revenues [23]. The report lists average costs per hour of downtime ranging from airline reservations at $89.5 thousand to brokerage operations at $6.5 million. It is probably safe to say that downtime costs have not decreased since.

A recent vivid reminder of the importance of high availability is the failing data centers of the leading European IT service provider Tieto in late November 2011. Sundkvist explains how a failed upgrade of storage equipment from EMC Corporation caused IT services of a great many seemingly unrelated Swedish enterprises to go down, including the national IT infrastructure enabling pharmacies to verify prescriptions, the SBAB bank, the Motor Vehicle Inspection Company and several municipalities [52]. Other recent examples of high impact IT service outages include the online banking operations of Bank of America in January 2011 as described by Charette [9] and the Nasdaq

OMX trading system for the Nordic and Baltic stock markets in June 2008 described by Askåker and Kulle [3].

The systems underpinning enterprise operations often live for many years [2], which has led to an increased interest in information system lifecycles [25]. One lesson to learn from incidents like the ones described above is that enterprise information systems need to be monitored and improved not only in the development phase, but throughout the entire software lifecycle. Recent research supports the importance of proper monitoring and good processes for change management [17]. A key aim of this paper is to offer a high level, portfolio-view modeling framework that could support decision makers not only in the design phase, but also in the operations phase of complex IT services.

1.1 Scope of the paper

High availability is important to IT managers in a particular sense. A manager faced with poor availability has two intertwined needs: (i) *prediction with adequate precision* of future availability and (ii) *action guidance*. She wants to be able to predict the future availability of her services, so that the enterprise can make proper decisions about business strategy, risk management, insurance etc. But she also wants the prediction to be action guiding, in the sense that it helps her to systematically improve the future availability, beginning with the actions that give the best return on investment.

These IT manager needs are the point of departure for the present paper. However, as we shall see in Section 3, they also highlight an existing blind spot in the literature. There are a number of studies addressing the reliability and availability of individual software and hardware components and a wealth of papers on architectures composed of such components. But this does not help a manager trying to prevent any future overnight "routine systems change" mishaps. The IT manager needs a method that considers the *enterprise* architecture, including change management and maintenance processes, not just the *systems* architecture. The fact that these processes are included is a key element in the ability of the framework to lend decision-support not only in the design phase, but also in the operations phase of complex IT services.

By adopting the enterprise perspective, the proposed framework aims for an "all-in-one" modeling approach to availability, spanning several levels of abstraction. The rationale is that there are many non-trivial dependencies between all the systems and processes in an enterprise architecture. While more detailed models are clearly desirable on each and every level of abstraction, such models need to be somehow interconnected with each other to keep track of the bigger picture. It is this interconnected level that is the proper domain of the framework proposed in this article. Indeed, it has been argued that enterprise IT differs from IT in general precisely by considering systems that are sometimes studied in their own right to be mere components of a larger architecture [26]. Some further pros and cons of the chosen abstraction level will be discussed in Section 8.

The genesis of the present paper is the Marcus and Stern "availability index" [37]. This index presents a qualitative cost-benefit analysis of various availability-increasing measures. A quantitative, expert-elicitation based elaboration of the index was presented by Franke et al. [17]. This paper extends the work in [17] by presenting a framework for modeling and assessment of IT service availability on the enterprise level that integrates the availability index with architectural aspects, that are also important for availability. The framework is action guiding, in the sense that the user can tell what needs to be done to improve availability (cf. the discussion in section 8.1). The paper also contains a description of nine case studies, where the modeling principles of the framework have been applied to various enterprise IT services.

1.2 Outline

The remainder of the paper is structured as follows: Section 2 defines the subject of the paper, viz. Enterprise IT service availability. Section 3 contrasts the present contribution with some related work. Section 4 introduces the framework used in the metamodeling part of the paper. Section 5 is the locus of the main contribution, presenting the framework for enterprise IT service availability analysis. Section 6 presents nine cases studies on the usage of the framework. Some further examples of the possibilities of the framework are given in Section 7. Section 8 offers a discussion of the strengths and weaknesses of the contribution, its practitioner relevance, and its software implementation in the EA^{2}T tool. Section 9 concludes this paper.

2 Enterprise IT service availability

We adopt the ITIL definition of *IT service* given by Taylor et al. [53]:

> "A Service provided to one or more Customers by an IT Service Provider. An IT Service is based

> on the use of Information Technology and supports the Customer's Business Processes. An IT Service is made up from a combination of people, Processes, and technology and should be defined in a Service Level Agreement."

Following ITIL, an IT service (Application) has a lifecycle that includes "Requirements, Design, Build, Deploy, Operate, Optimize" [53].

To understand the difference between IT in general and *enterprise IT*, it is useful to consider the definition made by Johnson [26]:

> "An enterprise software system is the interconnected set of systems that is owned and managed by organizations whose primary interest is to use rather than develop the systems. Typical *components* in enterprise software systems are thus considered as proper *systems* in most other cases. They bear names such as process control systems, billing systems, customer information systems, and geographical information systems." (Emphasis in original.)

As for *availability*, the literature offers several definitions. In this paper, we adopt the ITIL definition given by Taylor et al. [53]:

> "Ability of a Configuration Item or IT Service to perform its agreed Function when required."

Mathematically, availability is typically rendered in the following fashion (cf. e.g. [40]):

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \tag{1}$$

where MTTF denotes "Mean Time To Failure" and MTTR "Mean Time To Repair" or "Mean Time To Restore", respectively. The quotient is easy to interpret as the time that a system is available as a fraction of all time [47]. Sometimes, the term "Mean Time Between Failures" – MTBF – is used to emphasize that systems are repairable, and thus capable of failing several times. A more cautious availability estimate is found by instead using the "Maximum Time To Repair/Restore", corresponding to a worst-case scenario [37]. Since mean times are used, Eq. 1 is actually a measure of long-term performance of a system, i.e. a *steady state* system availability. Milanovic distinguishes the steady state availability from *instantaneous availability*, defined as "the probability that the system is operational (delivers the satisfactory service) at a given time instant" [40]. In this paper, the notion of availability always refers to steady state availability, unless explicitly stated otherwise.

It is instructive to contrast availability with the related, but different, notion of *reliability*, defined in ISO 8402 as follows (quoted by Rausand and Høyland [47]):

> "The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time."

As noted by Milanovic, the main difference between reliability and availability is that reliability refers to failure-free operation up until a failure occurs [40]. Availability, on the other hand, focuses on the failure-free operation over a longer period of time, allowing for system failures and repairs during the interval considered [40].

A related but wider concept is that of *dependability*. Avizienis et al. offer two definitions [4]:

> "The original definition of *dependability* is the ability to deliver service that can justifiably be trusted. This definition stresses the need for justification of trust. The alternate definition that provides the criterion for deciding if the service is dependable is the *dependability* of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable." (Emphasis in original.)

The framework described in this article addresses the steady state availability of enterprise IT services.

3 Related work

There are many frameworks, methods and tools for modeling IT (service) availability. In the following review, the most relevant to our work are described and contrasted with our approach.

A Bayesian reliability prediction algorithm integrated with UML, made to analyze reliability before system implementation, is proposed in a series of papers by Singh et al. [51, 11, 10]. The algorithm can be used throughout the system life-cycle in the sense that the reliability predictions generated in the design phase are re-used as prior probabilities in the test phase. A model-driven method for availability assessment of web services is offered by Bocciarelli and D'Ambrogio [6]. The availability assessment is part of a quality of service prediction method based on the business process execution language (BPEL) [30]. The paper by Bocciarelli and D'Ambrogio is similar to our contribution in the sense that it defines a metamodel that enables availability calculations in an automated fashion, and that it uses AND and OR gates to model architectural component relationships. However, both Singh et al. and Bocciarelli and D'Ambrogio differ from our approach in that they do not address any governance aspects of availability, such as IT service management process maturities.

Zambon et al. [63] address availability risk management by describing how the effects of incidents propagate throughout an IT infrastructure. The model is tested in a real-world case study. The paper is similar to ours in the sense that it models how incidents affecting availability spread throughout the architecture, but different in its focus on risk analysis.

Leangsuksun et al. [33] present a Unified Modeling Language (UML) tool for software reliability aiming to bridge the gap between the design process and reliability modeling. This is accomplished by a tool that fits UML system models with failure/repair rate-attributes and does reliability computations with the SHARPE tool [49]. The main contribution of Leangsuksun et al. is to integrate these tools with each other. However, only hardware failures are taken into account, whereas in our framework, both hardware and software failures can be modeled.

In her PhD thesis, Rodrigues [48] addresses software reliability prediction in the context of Model Driven Architecture (MDA). The thesis offers a UML reliability profile model which is used for scenario-based reliability prediction. The calculations are based on (i) the probabilities of component failures, and (ii) transition probabilities between scenario.

Bernardi and Merseguer [5] propose a UML profile for dependability analysis of real-time and embedded systems, as a part of the "Modeling and Analysis of Real-Time and Embedded Systems" (MARTE) project of the Object Management Group (OMG). Bernardi and Merseguer apply their profile in a case study.

Majzik et al. [35] delineate a dependability modeling approach based on UML. It aims to offer guidance in the early phases of system design. Majzik et al. show how structural UML diagrams can be processed to create a system-wide dependability model based on Timed Petri Nets (cf. e.g. [62] for more on this formalism).

Our work is different from that of Rodrigues, Bernardi and Merseguer and Majzik et al. in the sense that our framework also addresses IT service management process maturities.

Immonen [24] offers a method for availability and reliability prediction of software architectures. Its scope is similar to our approach, but it has only been validated using simulations, and unlike our approach it does not account for IT service management process maturities affecting availability.

Zhang and Pham [64] present an effort to identify factors affecting software reliability. Although the identified factors and their ranking are useful for guidance, Zhang and Pham offer no method to predict the outcomes of actions taken to improve system availability.

One important trend found in the literature is that failures are increasingly due to software failures and human error [18, 43, 45, 36], rather than hardware failures. This means that in order to meet the needs of IT managers, both systems architecture and governance (e.g. IT service management process maturities) must be studied more closely in concert. Methods that consider only a static environment where humans do not intervene and do not change the software will be unable to capture a lot of important causes of unavailability. Another important trend is the increasing service-orientation. With a shift of focus from technical platforms to business services, governance aspects and process maturities become more important.

To summarize, the main differences between our contribution and the related work is that (i) we consider not only the software architecture, but a wider enterprise architectural description that includes processes and their maturities, and (ii) we have tested the framework in nine case studies.

4 The P²AMF framework

This section introduces the architecture modeling formalisms needed for Section 5. The Predictive, Probabilistic Architecture Modeling Framework (P²AMF for short) is a framework for generic software system analysis [29]. P²AMF is based on the Object Constraint Language (OCL), a formal language used to describe expressions on models expressed in the Unified Modeling Language (UML) [1]. These expressions typically specify invariant conditions that must hold for the system being modeled, pre- and post-conditions on operations and methods, or queries over objects described in a model. One important difference between P²AMF and OCL is the probabilistic nature of P²AMF, allowing uncertainties in both attribute values and model structure. P²AMF is fully implemented in the Enterprise Architecture Analysis Tool (EA²T) [27, 7].[1]

A typical usage of P²AMF is to create a model for predicting, e.g., the availability of a certain type of application. Assume the simple case where the availability of the application is solely dependent on the availability of the redundant servers executing the application. The appropriate P²AMF expression then looks like this:

```
context Application:
  def: available : Boolean =
  self.server->exists(s:Server|s.available)
```

This example demonstrates the similarity between P²AMF and OCL, since the expression is not only a

[1] http://www.ics.kth.se/eaat

valid P^{2}AMF expression, but also a valid OCL expression. The first line defines the context of the expression, namely the application. In the second line, the attribute `available` is defined as a function of the availability of the servers that execute it. In the example, it is sufficient that there exists one available server for the application to be available.

However, not all valid P^{2}AMF statements are valid OCL statements. P^{2}AMF introduces two kinds of uncertainty that are not present in OCL:

Firstly, attributes may be stochastic. When attributes are instantiated, their values are thus expressed as probability distributions. For instance, the probability distribution of the instance `myServer.available` might be

```
P(myServer.available)=0.99
```

The probability that a `myServer` instance is available is thus 99%. For a normally distributed attribute `operatingCost` of the type `Real` with a mean value of $ 3 500 and a standard deviation of $ 200, the declaration would look like this,

```
P(myServer.operatingCost)=Normal(3500,200)
```

Secondly, the existence of objects and relationships may be uncertain. It may, for instance, be the case that we no longer know whether a specific server is still in service or whether it has been retired. This is a case of object existence uncertainty. Such uncertainty is specified using an existence attribute `E` that is mandatory for all classes,

```
context Server:
  def: E : Boolean
```

where the probability distribution of the instance `myServer.E` might be

```
P(myServer.E)=0.8
```

This attribute requires a subtle change in modeling practice: the modeler must sometimes allow objects such as the server above into the model, even though it is not certain that they exist. In some scenarios the server is still there, in others it has been retired – as reflected in the value of the attribute `E`. Clearly, if potentially non-existing objects were *not* allowed into the model, such scenario diversity could not be appropriately modeled. The metamodel, and ultimately the objective of the modeling as such, determines which potentially non-existing objects that ought to be modeled.

We may also be uncertain of whether `myServer` is actually still in the cluster that provides service to a specific application, i.e. whether there is a connection between the server and the application. Similarly, this relationship uncertainty is specified with an existence attribute `E` on the relationships. Thus, attributes on relationships are employed in P^{2}AMF:

```
context Uses:
  def: E : Boolean
```

The `Uses` relation is an *association class* (in the OCL sense), as are all the relations in P^{2}AMF. This is required for use of the `E` attribute.

A full exposition of the P^{2}AMF language is beyond the scope of this paper, but some more details can be found in the work of Ullberg et al. [59]. The probabilistic aspects are implemented in a Monte Carlo fashion [20]: In every iteration, the stochastic P^{2}AMF variables are instantiated with instance values according to their respective distribution. This includes the existence of classes and relationships, meaning that they are sometimes instantiated, sometimes not, depending on the distribution. Then, each P^{2}AMF statement is transformed into a proper OCL statement and evaluated using the EMF-OCL interpreter. The final value returned by the model when queried is a weighted mean of all the iterations.

5 An integrated framework for availability analysis

This section presents a framework for enterprise IT service availability analysis. The first subsections introduce two complementary approaches to availability modeling. Subsequently, it is shown how these approaches can be integrated into a single framework, and a metamodel with classes and attributes appropriate for availability analysis is presented.

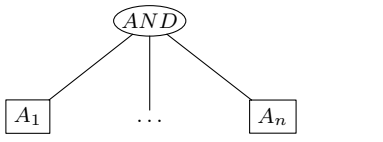
5.1 Modeling availability from components

One classical way of calculating the availability of a complex system is to follow a bottom-up approach from the availability of its components. Using the logic gates AND and OR, the average availability of the system as a whole can be inferred in a fault tree-like fashion (a more extensive treatment of Fault Tree Analysis (FTA) can be found in [16]). Such calculations assume independent average component availabilities. This formalism is illustrated in Fig. 1.

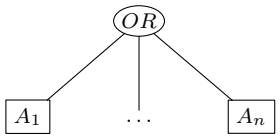
The AND case models non-redundant systems where the failure of a single component is enough to bring the system down.

The OR case models redundant systems where one or more component can fail without bringing the system down.

A simple example of how the building blocks and their mathematical equivalents are put together recursively is illustrated in Fig. 2.

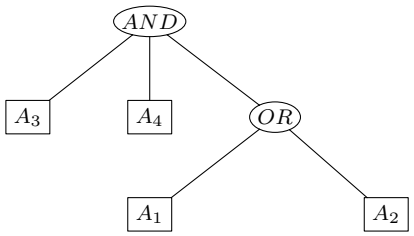


$$A_{tot} = \prod_{i=1}^{n} A_i$$



$$A_{tot} = \coprod_{i=1}^{n} A_i = 1 - \prod_{i=1}^{n}(1 - A_i)$$

Fig. 1 The basic cases for parallel and serial systems, respectively.



$$A_{tot} = A_3 A_4 (A_1 \sqcup A_2) = A_3 A_4 (1 - (1 - A_1)(1 - A_2))$$

Fig. 2 A simple example of system availability calculations.

In the realm of enterprise IT services, Närman et al. [41] have created a logic gate framework for availability analysis. The framework uses ArchiMate [58] as a graphical notation and has been tested for modeling precision in 5 case studies. A main result was that architectural models created using the proposed metamodel give availability figures that differ from availability measured log values only in the first or second decimal when expressed as percentages (e.g. an ATM system was estimated to have an availability of 99.92%, whereas logs for a 12 month period revealed an average of 99.86%).

ArchiMate was selected because it is a framework that keeps the number of entities down, yet captures a substantial amount of the concepts that need to be modeled. As described by Lankhorst et al. [32], the language was created following an extensive collection of requirements both from practitioners and from the literature. Furthermore, care has been taken to construct the language in such a way that relations between concepts are transitive [32, 60], which is very useful in the context of fault tree analysis.

5.2 Modeling availability at the system-level

While the component model is conceptually simple and mathematically precise, it also transfers the problem of availability estimation one level down; from system to components. Component availabilities are taken as given – if they are not, then there is nothing to aggregate.

An alternative line of reasoning, therefore, is to inquire about the *causes* of IT service unavailability. This is a difficult question. As described in Section 3, the existing literature mostly addresses availability (and reliability) in idealized cases, where IT systems and services are considered *in vitro*, i.e. in laboratory settings where software components are put together into architectures, the properties of which can be inferred by various models. However, *in vivo*, things are more complicated, as the building blocks of the idealized architectures are subject to a constant stream of functional upgrades, external service-provider downtime, inadequate monitoring, poor change management, etc. Furthermore, many of these failure factors are difficult to locate, architecturally.

Franke et al. [17] address this problem by using a holistic approach. Rather than detailing the architectural components of a service or system, 16 factors determining availability are evaluated at the level of the IT service as a whole. To quantify the factors, Franke et al. did a survey among 50 experts on IT systems availability, and thus created a Bayesian decision support model, designed to help enterprise IT system decision-makers evaluate the consequences of various courses of action *ex ante*. Cf. [17] for more details.

The mathematical model employed is a leaky Noisy-OR model, typically used to describe the interaction of n causes $X_1, \ldots, X_n$ to an effect Y (cf. [42] or [19] for more details). In this context, the effect Y is the *un*-availability of enterprise IT systems. Two assumptions are made, viz. (i) that each of the causes has a probability p_i of being sufficient for producing Y, and (ii) that the ability of each cause X_i, to bring about Y is independent. Mathematically, the following holds:

$$p_i = P(y|\bar{x}_1, \bar{x}_2, \ldots, x_i, \ldots, \bar{x}_n) \tag{2}$$

where x_i designates that causal factor X_i is present and $\bar{x}_i$ that it is absent. In other words, p_i is the probability that the effect Y will occur when causal factor p_i is present, and all other causal factors modeled are absent.

It follows that the probability of y given that a subset $\mathbf{X}_p \subseteq \{X_1, \ldots, X_n\}$ of antecedent causes are present can be expressed as:

$$P(y|\mathbf{X}_p) = 1 - (1 - p_0) \prod_{i:X_i \in \mathbf{X}_p} \frac{(1 - p_i)}{(1 - p_0)} \tag{3}$$

The probability p_0 is called the leak probability, and reflects the probability that Y will occur spontaneously, thus reflecting imperfections in the explicit model.

The probabilities p_i obtained from the expert elicitation [17] are listed in Table 1. The one difference between Table 1 and [17] is that two pairs of causal factors have been merged together $(1+9,\ 7+8)$, as indicated. The motivation is detailed in Appendix A, as are more precise definitions of each factor.

Table 1 Systemic causal factors with probabilities for refined Noisy-OR model.

	Causal factor X_i **Lack of best practice ...**	p_i
1+9	... physical environment & infrastructure redundancy	10.0%
2	... requirements and procurement	25.2%
3	... operations	23.0%
4	... change control	28.1%
5	... technical solution of backup	7.0%
6	... process solution of backup	3.6%
7+8	... data & storage architecture redundancy	9.6%
10	... avoidance of internal application failures	16.9%
11	... avoidance of external services that fail	8.7%
12	... network redundancy	7.6%
13	... avoidance of network failures	18.3%
14	... physical location	3.3%
15	... resilient client/server solutions	3.6%
16	... monitoring of the relevant components	26.1%

This model thus offers a way to explain the *un*-availability of enterprise IT systems in terms of *lack of best practice* in 14 (originally 16) different areas. However, a more practical typical concern is the availability of an entire park of systems, with a known prior availability baseline, e.g. 99.5%. The Bayesian model therefore needs to be rescaled to reflect this prior availability. Such a rescaled model can be used for reasoning about which best practice solutions to apply in order to further increase availability.

Franke et al. rescale the model with a rescaling factor α applied to all p_i, including p_0. It follows from Equation (3) that

$$A(\mathbf{X}_p) = 1 - P(y|\mathbf{X}_p) = (1-\alpha p_0) \prod_{i:X_i \in \mathbf{X}_p} \frac{(1-\alpha p_i)}{(1-\alpha p_0)} \quad (4)$$

where $A(\mathbf{X}_p)$ is the availability of a given system lacking the best practice factors listed in the vector $\mathbf{X}_p$.

5.3 An integrated approach

Comparing component and system-level availability modeling, we see that these approaches are complementary. The strength of the component-based approach lies in its focus on the interrelations between elements and services, thus capturing redundancy and other important notions of availability theory. This is an area where the system-level approach has a blind spot. Conversely, the system-level approach can incorporate important governance aspects such as architectural change control, requirements and procurement, and component monitoring – all factors impacting enterprise service availability, but non-localizable to any single component in an architecture and thus absent in a purely component-based framework.

Sections 5.4 and 5.5 introduce an integrated framework, where the two complementary approaches are reconciled and implemented together. This continues and extends previous work by Franke et al. [17] and Närman et al. [41], who have elaborated each approach separately in the enterprise IT context. The exposition revolves around the metamodel illustrated in Figure 3, giving an overview of the proposed framework. However, the framework is more than just the set of classes and attributes visible in the figure. As explained in Section 4, the derived attributes for the availability analysis are formally defined using OCL code. Following P^{2}AMF practice, these OCL expressions are not primarily used to impose model constraints, but rather as the combined query language and mathematics engine that implements the logic of the component-level and system-level availability models employed.

The classes and attributes are detailed in the next few subsections. Reading these descriptions, it is recommended to continuously refer back to Figure 3. Such a parallel reading should aid in not losing sight of the bigger picture. The OCL code corresponding to derived metamodel attributes as well as some metamodel operations and invariants used in the implementation, are provided in Appendices B, C, and D, respectively.

5.4 Metamodel classes

On the class level, the metamodel is quite similar to the metamodel presented by Närman et al. [41]. It is based on the ArchiMate metamodel, and contains *active structure* elements, *behavioral* elements, *business processes*, and the *logic gates* necessary for the component-level availability modeling approach.

However, Närman et al. employ the component-based approach only, employing the fault tree formalism. As described in Sections 5.2 and 5.3, this ought to be complemented by the system-level approach capable of taking governance aspects into account as well. Therefore, the coherent combination of the two existing techniques for service availability modeling and analysis is the novel contribution of this new metamodel. The

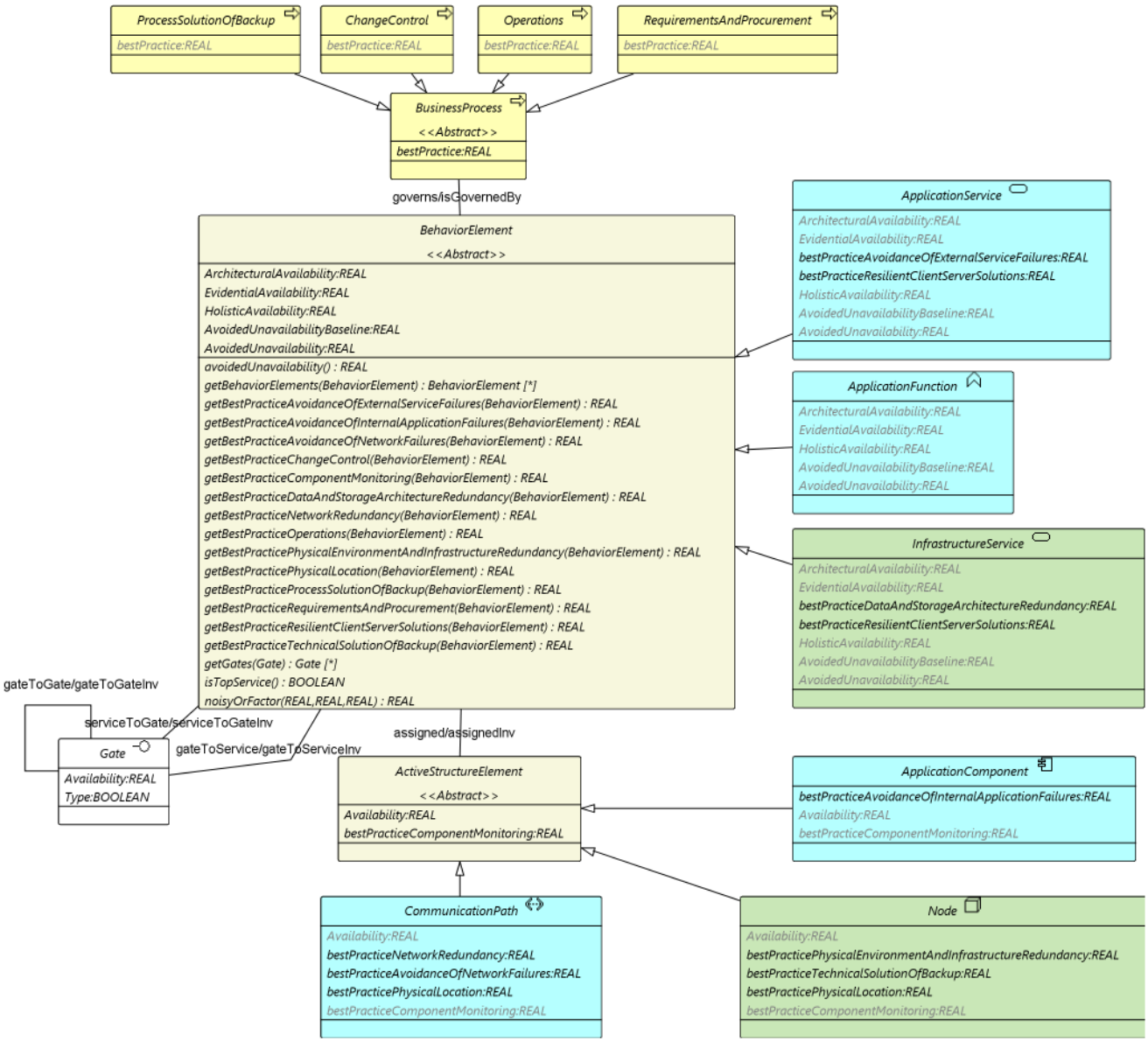


Fig. 3 The integrated metamodel for availability analysis.

details are found in the OCL code of Appendices B, C, and D, all of which was written for this metamodel.

More precisely, `BehaviorElement` is an abstract superclass (as signified by the `abstract` stereotype) with three subclasses: `ApplicationService`, `ApplicationFunction`, and `InfrastructureService`. Following UML, the $\twoheadrightarrow$ arrow signifies inheritance. Similarly, `ActiveStructureElement` is an abstract superclass with three subclasses: `Node`, `ApplicationComponent`, and `CommunicationPath`. These class concepts are shared with [41]. A `BehaviorElement` is realized by an `ActiveStructureElement` to which it is `assigned`. Whenever the metamodel is instantiated, every `ActiveStructureElement` generates at least one `BehaviorElement`. This is important, because it allows active structure elements of different types to realize a behavior of the same class but with different availabilities or other characteristics.

The `Gate` class has a Boolean attribute determining whether it acts as an AND (encoded as false) or OR (encoded as true) gate. In the EA^{2}T tool, the class icons (⩀ , ⩁) are changed accordingly, as seen in Fig. 4.

Furthermore, a `BusinessProcess` class has been introduced, not present in [41]. The `BusinessProcess` class has four subclasses, each corresponding to a process relevant for IT service availability:

`ProcessSolutionOfBackup` The process solution of backup regulates the use of the technical solution. This includes routines such as whether backups are themselves backed up, whether the technical equipment is used in accordance with its specifications, what security measures (logical and physical) are used to guard backups etc.

`ChangeControl` Change control is the process of controlling system changes. This applies to both hardware and software, and includes documentation of the actions taken.

`Operations` Operations is everyday system administration. This includes removing single points of failure, maintaining separate environments for development, testing and production, consolidating servers etc.

`RequirementsAndProcurement` Requirements and procurement reflect the early phases of system development and administration. This includes return on investment analyses, re-use of existing concepts, procuring software designed for the task at hand, negotiating service level agreements etc.

5.5 Metamodel attributes

All metamodel attributes will be given in the form `name:type`, referring to the standard OCL types defined in the OCL specification [1].

5.5.1 BehaviorElement

As `BehaviorElements` are the components connected by logic gates, their attributes form the backbone of the analysis. To reflect the system-level approach, some attributes are visible only at the top of the architecture, i.e. when they are attributes of instantiated class elements that do not contribute to the availability of other elements. This reflects the properties that are only considered at the system-level.

`ArchitecturalAvailability:Real` This attribute corresponds to standard notion of availability of the component-based model described in Section 5.1. Its value will be calculated differently depending on the architecture:

1. If the `BehaviorElement` is connected to a gate through the `gateToService` relation, the `ArchitecturalAvailability` will take the `Availability` value of the gate.
2. If the `BehaviorElement` is assigned to a single `ActiveStructureElement`, the `ArchitecturalAvailability` will take the `Availability` value of the structure element.
3. If the `BehaviorElement` is neither connected to a gate, nor to a structure element, its `ArchitecturalAvailability` is taken from its own `EvidentialAvailability` attribute.

`EvidentialAvailability:Real` This attribute is used to allow the user to set a "black box" architectural availability figure of a behavior element that is not modeled in detail.

`AvoidedUnavailability:Real` This attribute value is calculated based on the Noisy-OR model from [17]. It denotes the fraction $(0 - 100\%)$ of architectural *un*-availability that has been avoided by the best practice factors of Table 1. This is calculated by a call to the `avoidedUnavailability()` operation described in Appendix C.

In the EA^{2}T tool, this attribute is only visible when the `isTopService` operation (described in Appendix C) is `true`.

`AvoidedUnavailabilityBaseline:Real` This attribute is the baseline for avoided unavailability. This brings about path-dependence, in the sense that the model keeps track of a baseline starting point. The user supplies the baseline. The recommended way to do so is by modeling an architecture as faithfully as possible both when it comes to architectural availability and with respect to the best practice factors of Table 1. Calculating the model will then yield an initial `AvoidedUnavailability` that can be entered as baseline.

In the EA^{2}T tool, this attribute is only visible when the `isTopService` operation is `true`.

`HolisticAvailability:Real` This attribute corresponds to the richer – holistic – availability notion that results from the combination of the component-level and system-level approaches to availability. As this notion of availability is only applicable on the architecture as a whole, this attribute belongs only to the "top" `BehaviorElement`, typically corresponding to an aggregate of several other services. Formally, this "top" property is defined by the OCL operation `isTopService` described in Appendix C. It combines component-level availability with the system-level model by starting out with the `ArchitecturalAvailability`, and then adding or subtracting from it, depending on the level of `AvoidedUnavailability` relative to the `AvoidedUnavailabilityBaseline`. In the case of an improvement over the baseline, the `HolisticAvailability` is given by Eq. 5. In the case of a deterioration, the `HolisticAvailability` is given by Eq. 6.

$$\texttt{AvoidedUnavailability} \geq \texttt{AvoidedUnavailabilityBaseline}:$$

$$\begin{aligned}\texttt{HolisticAvailability} = {} & \texttt{ArchitecturalAvailability} + \\ & (1 - \texttt{ArchitecturalAvailability}) \cdot \\ & (\texttt{AvoidedUnavailability} - \\ & \texttt{AvoidedUnavailabilityBaseline}) / \\ & (\texttt{1-AvoidedUnavailabilityBaseline})\end{aligned} \tag{5}$$

$$\texttt{AvoidedUnavailability} < \texttt{AvoidedUnavailabilityBaseline}:$$

$$\begin{aligned}\texttt{HolisticAvailability} = {} & \texttt{ArchitecturalAvailability} + \\ & \texttt{ArchitecturalAvailability} \cdot \\ & (\texttt{AvoidedUnavailability} - \\ & \texttt{AvoidedUnavailabilityBaseline}) / \\ & \texttt{AvoidedUnavailabilityBaseline}\end{aligned} \tag{6}$$

In words, the holistic availability starts from the architectural availability found by aggregating the components of the architecture in a fault tree-like manner. In the case of an improvement it then adds a fraction of the complementary unavailability, this fraction being determined by the avoided unavailability, relative to its baseline and the baseline distance to full (100%) availability. Symmetrically, in the case of a deterioration it subtracts a fraction of the architectural availability, this fraction being determined by the avoided unavailability, relative to its baseline and the baseline distance to no (0%) availability.

In the EA^{2}T tool, this attribute is only visible when the `isTopService` operation is `true`.

5.5.2 Systemic causal factors

The systemic causal factors from [17] are all modeled as attributes of type Real, as detailed in Table 2. Here, they are listed in the same order as in Table 1. In Fig. 3, they can be found located in the appropriate class.

One particular difficulty arises with the application of the 14 attributes in an architectural context: In the Noisy-OR model, each factor is a singleton. However, in any sufficiently complex enterprise architecture there will be features such as *several* `ChangeControl` processes governing *several* services, *several* `CommunicationPaths` with *several* routines for failure management, *several* `Nodes` being monitored in *several* ways, etc. These several values need to be aggregated before they are fed to the Noisy-OR calculation of the `AvoidedUnavailability` attribute. In the current implementation, this is accomplished by returning the arithmetic mean of the best practice values found throughout the architecture.

The aggregation is non-trivial and could be computed in several ways. Varian [61] distinguishes three prototypical cases in the context of system reliability:

Table 2 Systemic causal factors in the metamodel.

Factor	Attribute name	Class(es)
1+9	bestPracticePhysical-Environment-AndInfrastructureRedundancy	Node
2	bestPractice	RequirementsAnd-Procurement
3	bestPractice	Operations
4	bestPractice	ChangeControl
5	bestPracticeTechnicalSolution-OfBackup	Node
6	bestPractice	ProcessSolutionOf-Backup
7+8	bestPracticeDataAndStorage-ArchitectureRedundancy	InfrastructureService
10	bestPracticeAvoidanceOf-InternalApplicationFailures	Application-Component
11	bestPracticeAvoidanceOf-ExternalServicesFailures	ApplicationService
12	bestPracticeNetwork-Redundancy	CommunicationPath
13	bestPracticeAvoidanceOf-NetworkFailures	CommunicationPath
14	bestPracticePhysicalLocation	Node, CommunicationPath
15	bestPracticeResilientClient-ServerSolutions	ApplicationService, InfrastructureService
16	bestPracticeComponent-Monitoring	ActiveStructure-Element

Total effort. Corresponds to a sum, or in our case an arithmetic mean (normalized sum) of maturities.

Weakest link. Corresponds to the minimum maturity.

Best shot. Corresponds to the maximum maturity.

There are reasonable cases of applicability for each of the alternatives. As Varian notes, many systems exhibit a mixture of the cases [61].

Having thus outlined the metamodel, we now turn to its application. Section 6 details case studies where real enterprise IT services from five companies have been modeled using the framework described.

6 Case studies

This section describes the case studies carried out to test the modeling capabilities of the framework proposed in the previous section.

6.1 Case study process

To test the predictions of the model, case studies were carried out at five enterprises from a number of different business areas. The case studies were executed according to the following process.

6.1.1 Start-up meeting

Each case study was initiated with a start-up meeting, where the researchers explained the scope of the case

Table 3 Overview of the participating companies.

Company	Service	Data set
Banking 1	ATM	Availability data, 60 months
Banking 2	Banking operations, branch IT services	Availability data, 57 months
	Internet bank	Availability data, 57 months
Banking 3	Internet bank, other service	Availability data, 36 months
	Internet bank, log in service 1	Availability data, 36 months
	Internet bank, log in service 2	Availability data, 36 months
Company 1	Service 1	Availability data, 36 months
	Service 2	Availability data, 36 months
Travel 1	Internet timetable service	Availability data, 37 months

study to the industry counterpart. The typical counterpart representative was a middle manager with a responsibility for a portfolio of IT systems supporting the business.

6.1.2 Service identification

After the start-up meeting, the next step was to find a suitable service – supported by the IT systems within the manager's portfolio – for the study. There where several requirements:

1. The service should have high availability requirements, and thus in this sense be important to the participant enterprise.
2. There should be historical availability data available for analysis.
3. There should be service experts available for interviews.
4. The service should have a history of less than perfect availability, so as to make for more relevant analysis.

The data required was aggregated SLA reports, or other similar documentation, on availability over time. No details on individual outages were required. The interviewees were required to be able to assess the evolution of the maturity level of each of the factors in Table 1.

6.1.3 Quantitative data collection

Following the identification of appropriate services, availability data on the selected services was collected. Depending on the routines of the enterprise, this data was sometimes readily available in aggregated form as SLA reports, sometimes had to be composed through architectural considerations and incident log analysis.

6.1.4 Interviews

Following service identification and collection of availability data, appropriate respondents where selected to be interviewed on the evolution of the 14 factors of Table 1 over time. Most interviews were conducted with several respondents who were all involved in the management of the service. In some cases interviewees had to find additional information which they supplied after the interview session. For each year of historical data, an assessment of each factor was documented. Thus a typical interview dataset consists of $14 \cdot n$ factor maturity assessments, for n years studied. The methodology for factor assessment is further elaborated in Appendix A.

6.2 Quantitative framework evaluation

The modeling framework described in the previous section was evaluated for quantitative precision. Using the first year of each time series as a base-line, an availability estimate was calculated for the following years using the model. This model was compared to the actual availability figures as reported in the data made available.

An overview of the participating companies is offered in Table 3. Five enterprises participated, contributing a total of nine services. Since availability is a competitive edge to these companies, the companies have been anonymized to the level required by them to consent to publication. Figure 4 illustrates one of the service architectures, modeled in the EA^{2}T tool.

As is evident from Table 3, most of the companies are from mature high availability businesses (banking), where the cost of downtime is often a top-management issue. Travel 1 is the exception. It can also be observed that a lot of the services analyzed are similar – Internet banks and Internet timetable services are relatively similar services, all offered through a web front-end, but typically being dependent upon middle-ware and mainframes behind the scene. The ATM service and banking branch IT service also share a lot of characteristics, being distributed systems, where terminals are geographically spread (to street corners and banking branches). However, they are still fully within the enterprises' domain of management, as opposed to the Internet-distributed services where the user typically uses a computer of her own.

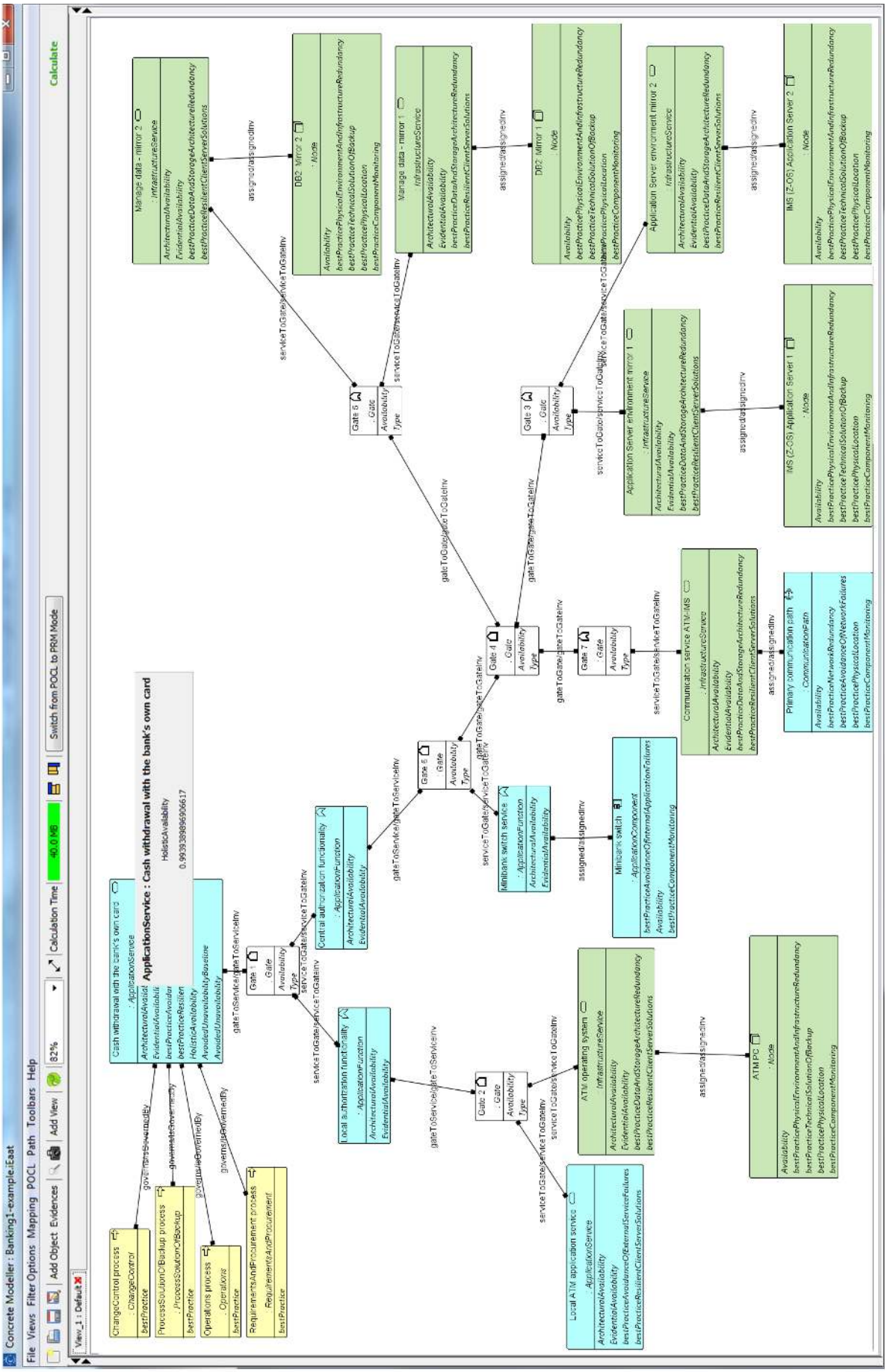


Fig. 4 ATM model from Banking 1, implemented in the EA^{2}T tool, using the metamodel described in section 5.

Even though most of the enterprises belong to high-availability businesses, their availability figures are markedly different. This should however not be interpreted as a sign of radically different service quality, but is mostly an effect of different ways of measuring and defining availability. In particular, Banking 2 had a very conservative approach to assigning availability figures, oftentimes considering services fully down even though only a fraction of their total functionality was really unavailable. This scheme is intended to keep (mostly company in-house) service-providers on their toes. However, it also has the unfortunate side-effect of giving an overly pessimistic appraisal of availability levels as compared to other companies.

6.3 Numerical results

Figures 5– 7 contrast the modeling figures with the actual availability data collected from the SLA reports and logs. The monthly availability data is shown along with annual (i.e. 12 month) availability averages and the corresponding annual predictions from the models. It is evident that there is a lot of variability in the availability levels on a monthly basis. The model predictions have only been created on an annual basis. The reasons for this are two-fold: (i) Only annual data on the 14 factors was collected through the interviews. One reason for this is the risk of interviewee fatigue, but it also reflects the fact that many of the factors are process-oriented and change gradually over time. It is more reasonable to expect annual trends than monthly abrupt changes in e.g. the change control. (ii) Many of the monthly availability time series exhibit seasonality, often with an availability peak during summer vacations. The seasonality, however, is not what the Bayesian decision support model aims to describe. Rather, the long term trend is the object of prediction, and this trend is better described by annual averaging.

It should be pointed out that the predictions of Figures 5–7 are cumulative, i.e. the models evolve over time after calibration at the start of the time series. For example, the prediction for the ATM system of Banking 1 is based only on the initial availability in 2006 and the evolution of the 14 factors from there on. No re-calibration has been carried out over the following years.

As seen in Figures 5–7, the predictions sometimes miss the mark by being too low, sometimes by being too high. At other times, as in the prediction for the ATM system of Banking 1, the prediction *mimics the changes of direction* of the actual availability data, but is consistently too low. This will be thoroughly discussed in Section 8.

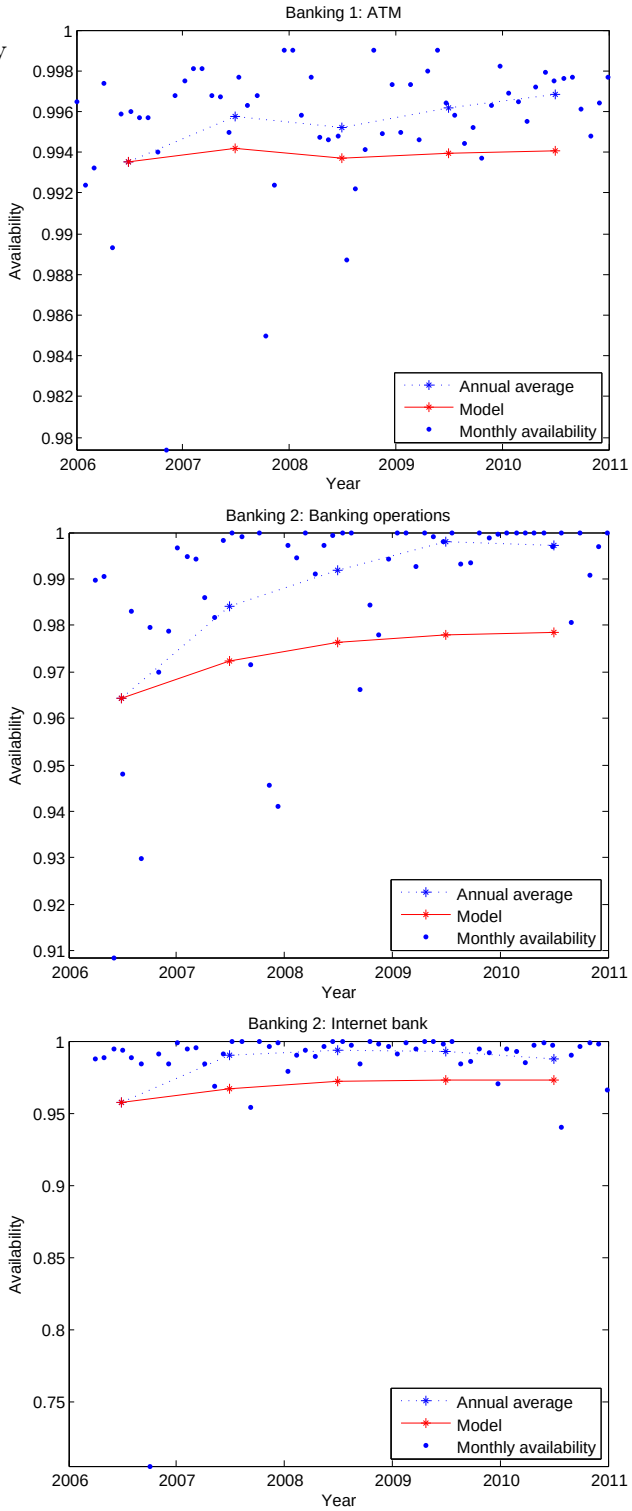
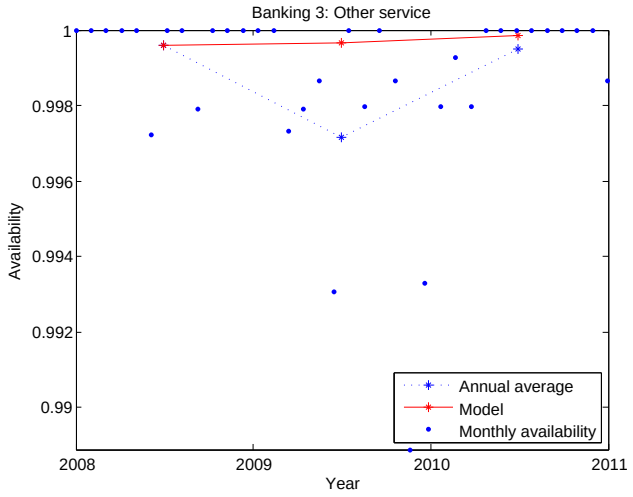
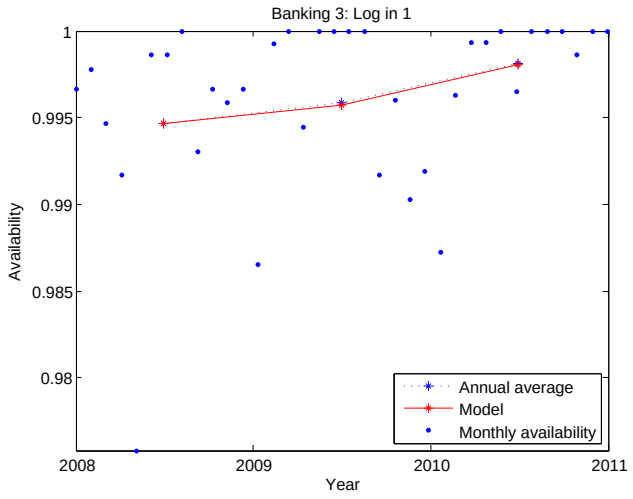


Fig. 5 Comparison of (i) annual average availability data, (ii) the corresponding model as offered by the framework, and (iii) the underlying monthly availability figures.





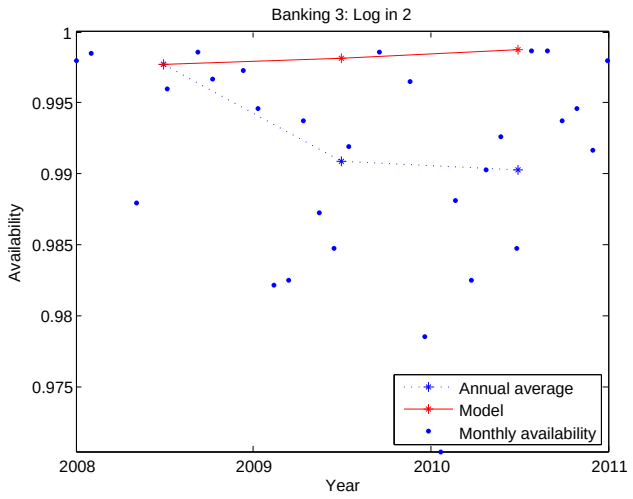
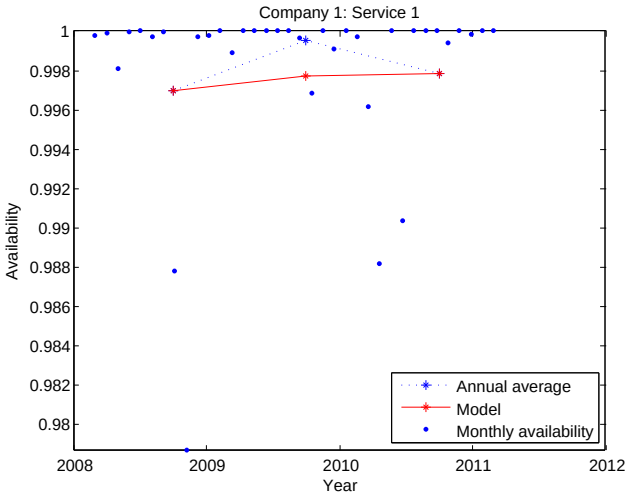
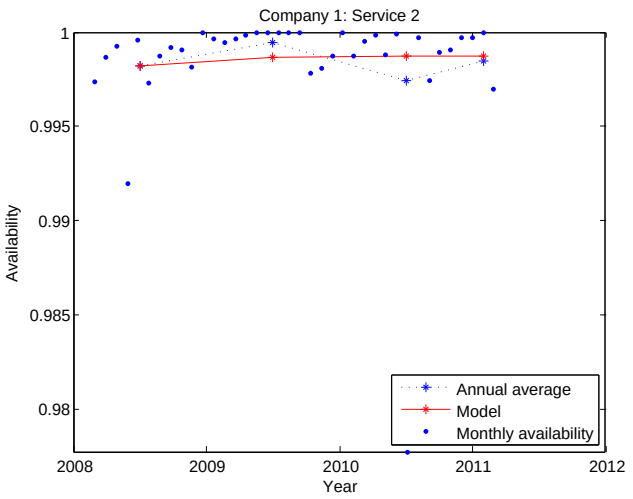


Fig. 6 Comparison of (i) annual average availability data, (ii) the corresponding model as offered by the framework, and (iii) the underlying monthly availability figures.





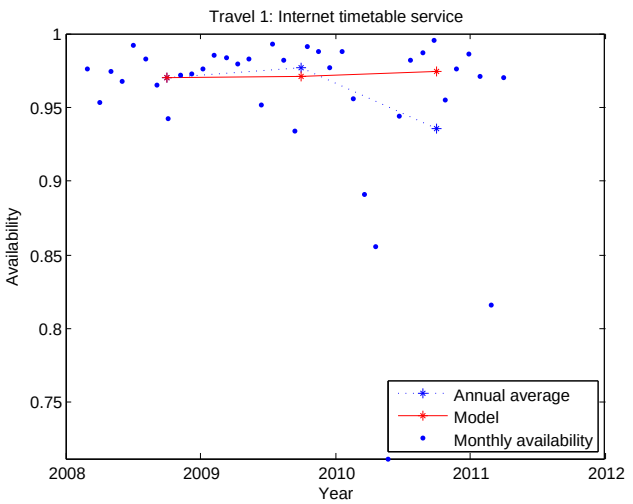


Fig. 7 Comparison of (i) annual average availability data, (ii) the corresponding model as offered by the framework, and (iii) the underlying monthly availability figures.

It should be noted that the 2011 annual average figures for Company 1, Service 2 are based on January and February only.

7 Further usage examples

The previous section does not make full use of the framework expressiveness, but rather focuses on the quantitative aspects of availability assessment in the spirit of the system-level approach. However, expressiveness and conceptual modeling capability is equally important. We now use the enterprise architecture illustrated in Figure 4 as a baseline for a few illustrations of the possibilities of the integrated framework.

These examples can be studied in greater detail in a screencast on the web page of the EA^{2}T tool.[2]

Combined effects The most straight-forward application of the holistic framework is to assess the effect of changes affecting *both* the component make-up of an architecture and its maturity in terms of the systemic causal factors. What would happen to the service availability of cash withdrawal if both (i) a redundant communication service could be installed, and (ii) the change management process could be improved? These assessments can easily be made using the framework implementation in the EA^{2}T tool.

Architectural modeling of processes Another advantage is the possibility to model how behavior elements can be governed by multiple processes, and how this impacts availability. What if there is not just a single overarching change management process for everything, but rather a multitude of such processes, each governing a different part of the architecture?

Uncertain architectures Sometimes, the enterprise modeler will be uncertain about the state of architecture with regard to availability. In some cases, this is due to ignorance on the part of the modeler: it can be difficult to know whether a particular process govern a particular service, or not. The people involved in managing that particular service know the answer. In other cases, the question is more fundamentally uncertain. If two servers are used for load-balancing, one of them might be capable of keeping the service running under low load conditions. If so, the pair ought to be modeled using an OR gate. However, under conditions of high load, a single server might not be able to cope, in which case the pair ought to be modeled using an AND gate. In this case there is no simple right or wrong answer, but a good architecture model ought to reflect this behavioral uncertainty. A more thorough description of the role of uncertainty in enterprise architecture can be found in the work of Johnson et al. [28]. Some empirical reasons for uncertainty in enterprise architectures can be found in the work of Aier et al. [2].

[2] `http://www.ics.kth.se/eaat`

8 Discussion

8.1 Quantitative evaluation

As seen in Section 3, the literature offers few comparable alternatives with the same scope as the framework proposed in Section 5. In this sense, it is difficult to appraise the numerical results presented in Figures 5–7. Nevertheless, the framework model can be compared with a reference prediction where the availability is assumed to remain constant, equal to the first year in the time series. For lack of a better predictor, this is a relevant baseline. Indeed, in the concluding workshop with the participating companies, the practitioners stated that re-using last year's figure, sometimes with a tiny inflation factor, is common practice in the industry.

A measure of the difference between the model and the baseline can be found by comparing the root-mean-square errors (RMSE), in percentage points, compared to the actual annual availability averages obtained from the companies, as illustrated in Table 4.

Table 4 reveals that the integrated framework model of Section 5 is superior to the constant baseline in five out of nine cases. In three of the remaining cases (Banking 3, Internet bank, other service, Banking 3, Internet bank, login service 2 and Company 1, Service 2) the differences are very small. In the last case (Travel 1, Internet timetable service) both predictions are much off the mark, though the framework model is a bit worse.

However, the monthly availability figures of Figure 7 tell a slightly different story. As can be seen in the plot, the main reason for the declining average availability in 2010 of the Internet timetable service is the exceptionally low values in April and May. Knowing that this is an Internet timetable service at a travel company, and knowing that the 2010 volcanic eruptions of Eyjafjallajökull on Iceland wreaked havoc with air travel across western and northern Europe, it is not hard to infer that the timetable service was put to severe stress in these months – and did not fully cope.

It is instructive to consider the implications of this carefully. An architecture-based model – using whatever mathematical formalism or guiding principle – can only be expected to predict changes to availability that

Table 4 Mean RMSE (percentage points) for the models compared to a no-changes baseline.

Enterprise IT service	**Model RMSE (percentage points)**	**Baseline RMSE (percentage points)**
Banking 1, ATM	0.208%	0.254%
Banking 2, Banking operations, branch IT services	1.674%	2.903%
Banking 2, Internet bank	1.997%	3.339%
Banking 3, Internet bank, other service	0.180%	0.173%
Banking 3, Internet bank, log in service 1	0.012%	0.258%
Banking 3, Internet bank, log in service 2	0.786%	0.714%
Company 1, Service 1	0.125%	0.192%
Company 1, Service 2	0.090%	0.086%
Travel 1, Internet timetable service	2.744%	2.467%
Average	0.868%	1.154%
Error size compared to baseline (percent)	75%	100%
Improvement over baseline (percent)	25%	

are in some sense *internal*. It is not reasonable to expect a prediction of *external* factors such as the ash cloud disruptions based on a description of ones own enterprise architecture. What the architecture based framework can be expected to predict is the impact of long term internal changes, whether they are for the better (such as process improvements) or for the worse (such as an increasingly complex web of software that can be maintained and modified only at an ever larger cost). Looking at the plots of Figures 5–7, other similar cases can be observed. Large, unpredictable disruptions often make annual averages go awry – but equally often the model offered by the framework points in the general direction of what to expect for any given month, including the back-to-normal month after the large outage.

A more profound problem has to do with whether valid predictions for different kinds of systems can be made based on a single general model. However, while every software system is unique, every software system cannot have a unique model of its own. Constructing such models is far too costly. Indeed, the very idea of statistics is to look at sets exhibiting variation, inferring general information from the particular samples. For some applications, the precision of a given model will not be sufficient. For others, it will. As discussed below, practitioners in the industry do find the results of our framework useful in several contexts.

Sudden outages can sometimes be better predicted by more elaborate techniques such as the time series analysis approach proposed by Liang [34]. However, there is an important caveat: Such models typically offer no guidance at all on cause and effect. A time-series model can accurately model for instance seasonality. However, an IT manager is not helped much by knowing e.g. that service availability is at its best in July (as many practitioners maintain), because this knowledge in no way contributes to improving availability in, say, November. It is far better to know e.g. that the process of requirements and procurement needs to be improved. This is the kind of action guidance that is offered by the integrated architecture framework of Section 5.

To summarize, it is reasonable to expect a model to reflect long term availability changes, but unreasonable to expect it to predict sudden outages.

8.2 Practitioner relevance

The considerations in the previous section naturally lead to the issue of practitioner relevance. If quantitative evaluation is difficult, it is even more important to secure qualitative evaluation by involving practitioner stakeholders in the development of new theories and methods. Only through careful stakeholder interaction can enterprise IT service modeling properly support software systems throughout the entire life cycle.

In May 2011, a workshop was conducted with representatives from the the participating companies. Five representatives attended. The typical representative was a middle manager, responsible for a portfolio of IT systems that support the business. All of the representatives had participated as respondents and data providers throughout the study. The workshop lasted for two hours, and was hosted by the researchers. The workshop started with a presentation of the participants, followed by an introduction by the researchers and a presentation of the results from the studies (i.e. the results found in Section 6 and Table. 4). Following a short break, the second half of the workshop was dedicated to a group discussion, where the practitioners made a number of important remarks:

First of all, there is a gap between the desire to model and predict availability and the actual state of the practice. Most of the companies do not use any sophisticated means to predict future availability levels. Rather, it is common practice to re-use last year's fig-

ure, sometimes with a tiny inflation factor. However, this is not to say that there is no interest in or demand for more advanced modeling techniques. On the contrary, the participants identified a number of important areas where the ability to model and predict availability would be highly useful:

- When large changes are made in an architecture, it is most often known – or assumed – that availability will suffer. The ability to quantify this gut feeling would improve risk management in projects.
- A prognosis, based on a credible method, of future service availability carries weight in communications with senior management. One of the workshop participants gave an example of when such a prognosis convinced the business that the availability predicted was too poor, leading to allocation of a budget for improving availability levels.
- Whenever check lists with bullet points for improving availability are proposed, it would be useful to be able the predict the estimated result of each action, so as to prioritize among them.
- The use of external services is on the rise, making service provision much less transparent. In particular, this is the case when services are delivered by sub-contractors to sub-contractors, i.e. when a kind of *layering* of services occurs. Many companies are immature when it comes to writing service level agreements (SLAs), and this is made even worse by opaque service layering. This is an area where architectural modeling and availability prediction can shed light on complicated phenomena.
- Compared to mechanical systems, the use of safety margins is very immature in IT service architecture. One workshop participant, with degrees in both construction and computer engineering, pointed out that whereas bridges are often built with four- or eight-fold safety factors, IT systems are often just built to cope precisely with the foreseen load. Better techniques for modeling and prediction of availability can help to make the IT service provision area more mature in this respect. However, it should be noted that the behavior of mechanical systems is often more linear (or in some other sense regular) than that of IT systems, making the latter more difficult to analyze.

Furthermore, the importance of qualitative modeling should not be underestimated. Qualitative models are useful to create a shared understanding of a problem, as well as for reasoning about system behavior and component interactions and dependencies. As a result, qualitative modeling often leads to insights about system behavior that leads to better decision making [12].

To summarize, the practitioner community can use the proposed integrated framework for rule-of-thumb decision making when planning, budgeting and prioritizing future investments to improve availability. This is illustrated by the *Combined effects* case in section 7. Such decision-making does not only enable prognoses, but also trade-offs based on the cost/benefit ratio of different actions to improve IT service availability. The workshop participants were not aware of any existing method with similar characteristics.

8.3 Tool support

One important aspect of framework usability is tool support. A tool can implement complicated theories and models in a faithful way, yet not require the user to fully grasp their minute detail. This enables the end user to focus on his or her core competencies, while still making use of for example the advanced availability modeling and prediction offered by the framework described in this paper.

The implementation of the metamodel in the EA^{2}T tool shown in the previous section has great potential in terms of adoption and usability. The tool is being used in a number of research projects on software quality attributes, including interoperability [59], maintainability [15] and security [7]. It has also been used to model large enterprise systems in a number of master theses, e.g. [44].

Furthermore, to alleviate the workload when creating enterprise architecture models, data to populate models with entities and relations can be collected automatically [8]. This is a promising road ahead, in particular as one of the practitioner concerns listed above is the increasing complexity and decreasing understandability of enterprise architectures. Automatic data collection is one way to keep up the pace.

8.4 Pros and cons of the integrated approach

The metamodel presented offers a high-level description language that includes many aspects relevant to the availability of the services in an enterprise architecture. The idea is to capture dependencies between different domains, even though these are often modeled by themselves in greater detail. Lankhorst describes the division of labor between enterprise architecture modeling and other kinds of related modeling [31]:

> "A main objective of enterprise architecture is to reveal the relations between the different domains, and to provide a high-level overview.

> As such, you should always check the validity of any existing models, and incorporate their information on an appropriate level of abstraction; domain-specific models provide more details about parts of the enterprise than an enterprise architecture model. As such, an enterprise architecture model should, for example, not be considered a replacement for the existing information models or business process models."

In the context of availability modeling, Lankhorst's division of labor means that our metamodel is not intended to *replace* but rather *complement* the existing modeling practices or tools. There are a lot of competent vendors offering advanced tools for tasks relevant to availability: picking the top three factors from Table 1 we find *change control* addressed by products from e.g. ERP vendor, HP, Aldon, Quest Software, IntelliCorp, Revelation Software, Phire, *component monitoring* addressed by products from e.g. BMC Software, HP, Quest Software, and IBM, and *requirements and procurement* addressed by products from e.g. IBM-Telelogic, iRise, all according to the Gartner consultancy [46]. Milanovic offers a good academic review of tools for availability assessment [40].

To understand the intended division of labor, it is useful to consider an analogy to Computer Aided Design (CAD) and Engineering (CAE). It is certainly true that buckling of columns and lighting of a room are quite different, but it is also true that there is a need for software tools that visualize their interdependencies to architects, since columns both carry loads and block windows. At some point, these concerns need to be deconflicted and resolved. However, such a resolution does not necessarily need to be based on the most profound theories available – if simplifications need to be introduced to get diverse phenomena into the same model, so be it.

Our metamodel is not intended to be the basis of complete and very detailed architectural models of enterprises. Instead, it is meant to offer a way to capture and make explicit relations between processes and services that are often lost when more detailed models are built. Such a bird's-eye view is necessary to avoid metaphorical stove-pipes and visualize the effects of changes throughout the entire architecture. In this respect, the fault-tree modeling formalism is very suitable. It allows some complex systems-of-systems to be represented as a single component, exhibiting only an average availability, while others can be modeled in greater detail. This offers the flexibility necessary to tailor models to practical needs, without being hampered by arduous data collection costs. Similarly, the Noisy-OR model is flexible in the sense that factors can be left unspecified in architectural descriptions, in which case the model simply assumes a default value.

If the metamodel is used in this way, to build relatively light-weight models of enterprise architectures, its use is relatively simple and not very time-consuming. When models similar in scope and granularity were built using the metamodel prescribed by Närman et al., no model required more than 20 man-hours of work, including both modeling and data collection [41].

9 Summary and conclusions

This paper has demonstrated an integrated enterprise architecture framework for quantitative availability modeling and assessment of enterprise services. Specifically, one component-based and one system-level method have been integrated into a single metamodel. In addition to entities, relationships and attributes, the framework features a formal computational model, implemented in P^{2}AMF, that enables quantitative availability assessment and prediction. The framework has been fully implemented in the EA^{2}T tool, and demonstrated using nine case studies.

To summarize, there are three strong arguments that speak in favor of the assessment and prediction framework presented in this paper:

Precision The method delivers fair predictions, validated by nine case studies. Compared to the no-changes baseline, the root mean squared error (in percentage points) is on average 25% smaller.

Uniqueness No comparable method capable of predicting availability on the level of enterprise services and with proper empirical validation has been found in the literature. Most other methods deal only with the technical architecture, abstracting away important issues such as change management processes and governance. These are precisely the kind of instruments that are available to most IT managers.

Action guidance As opposed to most other methods, our integrated framework offers concrete advise to a decision-maker aiming to improve – not merely predict – availability of IT services. The combination of the component-based and system-level approaches offers a powerful tool to reason about improvements and their effects.

9.1 Implications and future work

For the research community, this contribution offers an empirical benchmark that can be used to assess the strengths and weaknesses of other methods for availability assessment and prediction.

For the practitioner community, this contribution can be used for rule-of-thumb decision making when planning, budgeting and prioritizing future investments in availability.

Another natural direction for future work is further improvement of the prediction method. Such improvement could take several forms such as (i) further case studies for calibration, (ii) further refinements of the factor operationalizations, or (iii) experiments to complement the case study method used here.

Another, related direction for future work is to assess the modeling effort using the framework. One dimension is the cost (time required) of data collection, others include ease-of-use and usefulness [13].

Finally, automated data collection, in the spirit of [8], is an interesting future direction. The difficulty of obtaining and maintaining data is often highlighted as a key difficulty with the enterprise architecture discipline. Automatic tool-based data collection and subsequent analysis could make the framework described in this article considerably more prone to be adopted by practitioners.

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A Appendix: ITIL operationalization of the Bayesian expert model

A major challenge in the use of the system-level model [17] is the operationalization of the 16 factors. In the expert survey, the factor descriptions were – deliberately – kept short and general. As the survey respondents were all selected based on academic publications, detailed specifications in terms of enterprise operating procedures, processes and activities were not deemed appropriate. However, as we now turn to practical use, there is a need to offer unambiguous operationalizations of the factors. This is a prerequisite for being able to assess whether a company meets the "best practice" level or not.

Making "best practice" an unambiguous notion might seem futile. However, in the area of IT Service Management (ITSM), the IT Infrastructure Library (ITIL) [55, 57, 56, 53, 54] has become *the* de facto ITSM framework [39, 38, 21]. ITIL adoption is also a prescription offered to enterprises by influential consultancies such as Gartner [22].

To make the factors understandable and applicable to practitioners, they were translated into the ITIL language. This appendix explains the meaning of the causal factors, using ITIL as a frame of reference. During the case studies, the texts offered in this appendix were used to explain to practitioners how to think about the factors, in order to be able to assess their level of best practice.

To cast the factors into the ITIL language, the five ITIL volumes were studied, and the ITIL recommendations, processes, activities and examples were mapped to the factors in Table 1. In so doing, care was taken to retain the original meaning of the factors, as first articulated in the expert survey. In order to make sure that the interpretation of ITIL was correct, two certified ITIL experts were – independently – asked to offer input and feedback. As a result, a number of changes were made so as to better express the factors in ITIL terminology. The biggest change made during this feedback phase was the merging of factors *physical environment* with *infrastructure redundancy* into one single factor, and *data redundancy* with *storage architecture redundancy* into another single factor. Each pair of factors was deemed close to indistinguishable in ITIL wording. Thus, following the expert validation of the ITIL operationalization, the 16 survey factors were converted into 14, as illustrated in Table 1.

If two causal factors i and j in the leaky Noisy-OR model described by Eq. (3) are to be merged into a single factor k, it is reasonable to require that the original model and the new, merged model are unanimous in their availability predictions when they are semantically equivalent, i.e.:

$$P(y|\bar{x}_1, \bar{x}_2, \ldots, x_i, \ldots, x_j, \ldots \bar{x}_n) = P(y|\bar{x}_1, \bar{x}_2, \ldots, x_k, \ldots \bar{x}_n) \quad (7)$$
$$P(y|\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_i, \ldots, \bar{x}_j, \ldots \bar{x}_n) = P(y|\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_k, \ldots \bar{x}_n) \quad (8)$$

It follows from Eq. (3) that such a model preserving merger requires the following equality to hold:

$$p_k = \frac{p_i + p_j - p_i p_j - p_0}{1 - p_0} \quad (9)$$

This relation has been used when performing the mergers recommended by the ITIL experts. In all reasonable models, of course, $p_0 \neq 1$, so the divisor is non-zero.

A.1 Descriptions of the 14 ITIL factors

In the following section, each of the 14 factors are described in more detail. The introductory italic text of each factor presents the description used in the expert survey, when the probability of the factor to cause system unavailability was estimated. Then follows a description where each factor is presented in further detail with reference to the appropriate ITIL documentation [55, 57, 56, 53, 54]. Wordings are re-used from the ITIL volumes and the certified ITIL experts to the largest extent possible.

Physical environment and Infrastructure redundancy
The physical environment, including such things as electricity supply, cooling and cables handling, can affect the availability of a system. Infrastructure redundancy goes further than data and storage redundancy. Separate racks and cabinets may not help if all electricity cables follow the same path liable to be severed or if separate cables end at the same power source.

Factors to be considered include the following:

- Building/site
- Major equipment room
- Major data centres
- Regional data centres and major equipment centres
- Server or network equipment rooms
- Office environments

For a more detailed description of each factor, cf. ITIL Service Design [57] Appendix E, Table E.1-6.

Remark: Physical security/access control is part of this category as well.

Requirements and procurement

Requirements and procurement reflect the early phases of system development and administration. This includes return on investment analyses, re-use of existing concepts, procuring software designed for the task at hand, negotiating service level agreements etc.

This factor is about development of new systems and services, not about those already taken into operation. Business requirements for IT availability should at least contain (ITIL Service Design [57], p. 112):

- "A definition of the VBFs [Vital Business Functions] supported by the IT service
- A definition of IT service downtime, i.e. the conditions under which the business considers the IT service to be unavailable
- The business impact caused by loss of service, together with the associated risk
- Quantitative availability requirements, i.e. the extent to which the business tolerates IT service downtime or degraded service
- The required service hours, i.e. when the service is to be provided
- An assessment of the relative importance of different working periods
- Specific security requirements
- The service backup and recovery capability."

There should also be Service Level Requirements (SLR).

Note that poor requirements management is often a root cause behind other faults, covered by the other factors.

Operations

Operations is everyday system administration. This includes removing single points of failure, maintaining separate environments for development, testing and production, consolidating servers etc.

"All IT components should be subject to a planned maintenance strategy." (ITIL Service Design [57], p. 120.)

"Once the requirements for managing scheduled maintenance have been defined and agreed, these should be documented as a minimum in:

- SLAs [Service Level Agreements]
- OLAs [Operational Level Agreements]
- Underpinning Contracts
- Change Management schedules
- Release and Deployment Management schedules" (ITIL Service Design [57], p. 120.)

"Availability Management should produce and maintain the Projected Service Outage (PSO) document. This document consists of any variations from the service availability agreed within SLAs." (ITIL Service Design [57], p. 121.)

Incident management aims to "restore normal service as quickly as possible and minimize the adverse impact on business operations" (ITIL Service Operation [53], p. 46.). Incidents are managed using an incident model which should include:

- "The steps that should be taken to handle the incident
- The chronological order these steps should be taken in, with any dependences or co-processing defined
- Responsibilities - who should do what
- Timescales and thresholds for completion of the actions
- Escalation procedures; who should be contacted and when
- Any necessary evidence-preservation activities" (ITIL Service Operation [53], p. 47)

"Service Operation functions must be involved in the following areas:

- Risk assessment, using its knowledge of the infrastructure and techniques such as Component Failure Impact Analysis (CFIA) and access to information in the Configuration Management System (CMS) to identify single points of failure or other high-risk situations
- Execution of any Risk Management measures that are agreed, e.g. implementation of countermeasures, or increased resilience to components of the infrastructures, etc.
- Assistance in writing the actual recovery plans for systems and services under its control
- Participation in testing of the plans (such as involvement in off-site testing, simulations etc) on an ongoing basis under the direction of the IT Service Continuity Manager (ITSCM)
- Ongoing maintenance of the plans under the control of IT Service Continuity Manager ITSCM and Change Management
- Participation in training and awareness campaigns to ensure that they are able to execute the plans and understand their roles in a disaster
- The Service Desk will play a key role in communicating with the staff, customers and users during an actual disaster" (ITIL Service Operation [53], p. 77)

The problem management process should contain the following steps (ITIL Service Operation [53], p. 60):

- Problem detection
- Problem logging
- Categorization
- Prioritization
- Investigation and Diagnosis
- Create Known Error Record
- Resolution
- Closure

Change control
Change control is the process of controlling system changes. This applies to both hardware and software, and includes documentation of the actions taken.

This factor is about systems and services already taken into operation, not about those under development. This is just a subset of the full ITIL Change Management process.

The seven Rs of Change Management: "The following questions must be answered for all changes:

- Who RAISED the change?
- What is the REASON for the change?
- What is the RETURN required from the change?
- What are the RISKS involved in the change?
- What RESOURCES are required to deliver the change?
- Who is RESPONSIBLE for the build, test and implementation of the change?
- What is the RELATIONSHIP between this change and other changes?" (ITIL Service Transition [56], p. 53)

The following is a list of activities from an example process for a normal change (ITIL Service Transition [56], p. 49):

- Record the Request for Change (RFC)
- Review Request for Change (RFC)
- Assess and evaluate change
- Authorize change
- Plan updates
- Co-ordinate change implementation
- Review and close change record

Questions to be addressed include: Is there unavailability caused by standard changes that are pre-approved and do not go through the cycle above? Is there unavailability caused by unauthorized changes? Is there access control, or can unauthorized people make changes? Is there a Service Asset and Configuration Management (SACM, described in ITIL Service Transition [56], p. 65 ff.) process?

Technical solution of backup
The technical solution of backup includes the choice of back-up media, whether commercial or a proprietary software is used, whether old media can still be read, whether full, cumulative or differential backup is chosen etc.

The technical aspects of a backup strategy should cover:

- "How many generations of data have to be retained - thus may vary by the type of data being backed up, or what type of file (e.g. data file or application executable)
- The type of backup (full partial, incremental) and checkpoints to be used
- The locations to be used for storage (likely to include disaster recovery sites) and rotation schedules
- Transportation methods (e.g. file transfer via the network, physical transportation in magnetic media)
- Testing/checks to be performed, such as test-reads, test restores, check-sums etc." (ITIL Service Operation [53], p. 93)

Process solution of backup
The process solution of backup regulates the use of the technical solution. This includes routines such as whether backups are themselves backed up, whether the technical equipment is used in accordance with its specifications, what security measures (logical and physical) are used to guard backups etc.

The business requirements for IT service continuity must be properly determined to define the strategy. The requirements elicitation has two steps: 1. Business Impact Analysis and 2. Risk Analysis (ITIL Service Design [57], p. 128 ff).

The process aspects of a backup strategy should cover:

- "What data has to be backed up and the frequency and intervals to be used

[...]

- *Recovery Point Objective.* This describes the point to which data will be restored after recovery of an IT Service. This may involve loss of data. For example, a Recovery Point Objective of one day may be supported by daily backups, and up to 24 hours of data may be lost. Recovery Point Objectives for each IT service should be negotiated, agreed, and documented in OLAs [Operational Level Agreements], SLAs [Service Level Agreements] and UCs [Underpinning Contracts].

– *Recovery Time Objective.* This describes the maximum time allowed for recovery of an IT service following an interruption. The Service Level to be provided may be less than normal Service Level Targets. Recovery Time Objectives for each IT service should be negotiated, agreed, and documented in OLAs, SLAs and UCs" (ITIL Service Operation [53], p. 93-94, emphasis in original.)

The restore process must include these steps:

– "Location of the appropriate data/media
– Transportation or transfer back to the physical recovery location
– Agreement on the checkpoint recovery point and the specific location for the recovered data (disk, directory, folder etc)
– Actual restoration of the file/data (copy-back and any roll-back/roll-forward needed to arrive at the agreed checkpoint)
– Checking to ensure successful completion of the restore – with further recovery action if needed until success has been achieved
– User/customer sign-off" (ITIL Service Operation [53], p. 94)

Data and storage architecture redundancy
Data redundancy means that data stored on a disk remains available even if a particular disk crashes. Such data redundancy is often achieved through RAID. Storage architecture redundancy refers to redundancy at the level above disks: RAID may not help if all raided disks are placed in a single cabinet or rack, or if disks are connected through the same data paths and controller.

Is there a separate team or department to manage the organization's data storage technology such as (ITIL Service Operation [53], p. 97):

– Storage devices(disks, controllers, tapes etc.)
– Network Attached Storage (NAS), Storage Attached Network (SAN), Direct Attached Storage (DAS) and Content Addressable Storage (CAS)

Is there someone responsible for:

– "Definition of data storage policies and procedures
– File storage naming conventions, hierarchy and placement decisions
– Design, sizing, selection, procurement, configuration and operation of all data storage infrastructure
– Maintenance and support for all utility and middleware data-storage software
– Liaison with Information Lifecycle Management team(s) or Governance teams to ensure compliance with freedom of information, data protection and IT governance regulations
– Involvement with definition and agreement of archiving policy
– Housekeeping of all data storage facilities
– Archiving data according to rules and schedules defined during Service Design. The Storage teams or departments will also provide input into the definition of these rules and will provide reports on their effectiveness as input into future design
– Retrieval of archived data as needed (e.g. for audit purposes, for forensic evidence, or to meet any other business requirements)
– Third-line support for storage- and archive-related incidents" (ITIL Service Operation [53], p. 97)

All redundancy decisions should have been through an appropriate requirements engineering process (the requirements engineering process is defined on ITIL Service Design, pp. 167 ff.).

Avoidance of internal application failures
Systems can become unavailable because of internal application failures, e.g. because of improper memory access or hanging processes.

When new software is released and deployed, the plans should define:

– "Scope and content of the release
– Risk assessment and risk profile for the release
– Organizations and stakeholders affected by the release
– Stakeholders that approved the change request for the release and/or deployment
– Team responsible for the release
– Approach to working with stakeholders and deployment groups to determine the:
  – Delivery and deployment strategy
  – Resources for the release and deployment
  – Amount of change that can be absorbed" (ITIL Service Transition [56], p. 91)

For software in operation, the following must be in place or considered (ITIL Service Operations [53], p. 133-134):

– Modeling, workload forecasting and workload testing
– Testing by an independent tester
– Up to date design, management and user manuals
– Process of application bug tracking and patch management
– Error code design and error messaging
– Process for application sizing and performance
– Process for enhancement to existing software (functionality and manageability)
– Documentation of type of brand of technology used

Avoidance of external services that fail
Systems can become unavailable because they depend on external services that fail.

Service Level Management includes (ITIL Continual Service Improvement [54]):

- "Identifying existing contractual relationships with external vendors. Verifying that these Underpinning Contracts (UCs) meet the revised business requirements. Renegotiating them, if necessary." (pp. 28-29)
- "Create a Service Improvement Plan (SIP) to continually monitor and improve the levels of services" (p. 29)
- An implemented monitor and data collection procedure (Service monitoring should also address both internal and external suppliers since their performance must be evaluated and managed as well (p. 46).)

- Service Level Management (SLM)
  - "Analyze the Service Level Achievements compared to SLAs and service level targets that may be associated with the Service Catalogue
  - Document and review trends over a period of time to identify any consistent patterns
  - Identify the need for service improvement plans
  - Identify the need to modify existing OLAs [Operational Level Agreements] or UCs [Underpinning Contracts]" (ITIL Continual Service Improvement [54] p. 59)

Key elements of successful supplier management:

- "Clearly written, well-defined and well-managed contract

[...]

- Clearly defined (and communicated) roles and responsibilities on both sides
- Good interfaces and communications between the parties
- Well-defined Service Management processes on both sides
- Selecting suppliers who have achieved certification against internationally recognized certifications, such as ISO 9001, ISO/IEC 20000, etc." (ITIL Service Design [57], p. 164)

Network redundancy
Network redundancy, e.g. by multiple connections, multiple live networks or multiple networks in an asymmetric configuration, is often used to increase availability.

Important configurations for redundancy include:

- Diversity of channels: "provide multiple types of access channels so that demand goes though different channels and is safe form a single cause of failure." (ITIL Service Strategy [55], p. 177)
- Density of network: "add additional service access points, nodes, or terminals of the same type to increase the capacity of the network with density of coverage." (ITIL Service Strategy [55], p. 177)
- Loose coupling: "design interfaces based on public infrastructure, open source technologies and ubiquitous access points such as mobile phones and browsers so that the marginal cost of adding a user is low." (ITIL Service Strategy [55], p. 177)

Avoidance of network failures
Network failures include the simplest networking failure modes, e.g. physical device failures, IP level failures and congestion failures.

Important factors include:

- "Third-level support for all network related activities, including investigation of network issues (e.g. pinging or trace route and/or use of network management software tools – although it should be noted that pinging a server does not necessarily mean that the service is available!) and liaison with third-parties as necessary. This also includes the installation and use of 'sniffer' tools, which analyze network traffic, to assist in incident and problem resolution.
- Maintenance and support of network operating system and middleware software including patch management, upgrades, etc.
- Monitoring of network traffic to identify failures or to spot potential performance or bottleneck issues.
- Reconfiguring or rerouting of traffic to achieve improved throughput or batter balance – Definition of rules for dynamic balancing/routing" (ITIL Service Operation [53], p. 96)

Physical location
The physical location of hardware components can affect the recovery time of a malfunctioning system. This is the case for instance when a system crashes and requires technicians to travel to a remote data center to get it up again.

Has physical location been taken into account when fixing the Recovery Time Objective (RTO)? The overall backup strategy must include:

- *Recovery Time Objective.* This describes the maximum time allowed for recovery of an IT service following an interruption. The Service Level to be provided may be less than normal Service Level Targets. Recovery Time Objectives for each IT service should be negotiated, agreed, and documented

in OLAs, SLAs and UCs" (ITIL Service Operation [53], p. 93-94, emphasis in original.)

Physical location is partly addressed in the detailed description of Facility Management (ITIL Service Operation [53], Appendix E: E2, E3, E4 and E6).

Resilient client/server solutions
In some client/server solutions, a server failover results in the clients crashing. In more resilient client/server solutions, clients do not necessarily fail when the server fails.

Typically, the following activities should be undertaken:

- "Third-level support for any mainframe-related incidents/problems"

[...]

- Interfacing to hardware (H/W) support; arranging maintenance, agreeing slots, identifying H/W failure, liaison with H/W engineering.
- Provision of information and assistance to Capacity Management to help achieve optimum throughput, utilization and performance from the mainframe." (ITIL Service Operation [53], p. 95)

Other activities include:

- "Providing transfer mechanisms for data from various applications or data sources
- Sending work to another application or procedure for processing
- Transmitting data or information to other systems, such as sourcing data from publication on websites
- Releasing updated software modules across distributed environments
- Collation and distribution of system messages and instructions, for example Events or operational scripts that need to be run on remote devices
- Multicast setup with networks. Multicast is the delivery of information to a group of destination simultaneously using the most efficient delivery route
- Managing queue sizes.
- Working as part of Service Design and Transition to ensure that the appropriate middleware solutions are chosen and that they can perform optimally when they are deployed
- Ensuring the correct operation of middleware through monitoring and control
- Detecting and resolving incidents related to middleware
- Maintaining and updating middleware, including licensing, and installing new versions
- Defining and maintaining information about how applications are linked through Middleware. This should be part of the CMS [Configuration Management System]" (ITIL Service Operation [53], p. 99)

There should exist a transition strategy for how to release client/server systems from testing into production (ITIL Service Transition [56], p. 38 ff.). Do not forget that requirements engineering and change control might be the root cause of failures in this domain!

Monitoring of the relevant components
Failover is the capability to switch from a primary system to a secondary in case of failure, thus limiting the interruption of service to only the takeover time. A prerequisite for quick failover is monitoring of the relevant components.

Instrumentation is about "defining and designing exactly how to monitor and control the IT Infrastructure and IT services" (ITIL Service Operation [53], p. 45). The following needs to be answered:

- "What needs to be monitored?
- What type of monitoring is required (e.g. active or passive; performance or output)?
- When do we need to generate an event?
- What type of information needs to be communicated in the event?
- Who are the messages intended for?" (ITIL Service Operation [53], p. 45)

Examples of important monitoring needs include:

- "CPU utilization (overall and broken down by system/service usage)
- Memory utilization
- IO rates (physical and buffer) and device utilization
- Queue length (maximum and average)
- File storage utilization (disks, partition, segments)
- Applications (throughput rates, failure rates)
- Databases (utilization, record locks, indexing, contention)
- Network transaction rates, error and retry rates
- Transaction response time
- Batch duration profiles
- Internet response times (external and internal to firewalls)
- Number of system/application log-ons and concurrent users
- Number of network nodes in use, and utilization levels." (ITIL Service Operation [53], p. 74)

For each incident: Was it/could it reasonably have been foreseen, or does lack of foresight indicate poor monitoring? Is there end-to-end monitoring?

B Appendix: OCL code for derived metamodel attributes

B.1 BehaviorElement

B.1.1 ArchitecturalAvailability:Real

```
if gateToServiceInv->notEmpty()
then
  gateToServiceInv.Availability
else
  if assigned->notEmpty()
  then
    assigned.Availability->sum()
  else
    EvidentialAvailability
  endif
endif
```

B.1.2 AvoidedUnavailability:Real

```
if isTopService()=false
then
  null
else
  avoidedUnavailability()
endif
```

B.1.3 HolisticAvailability:Real

```
if isTopService()=false
then
  null
else
  if (AvoidedUnavailability-AvoidedUnavailabilityBaseline) >= 0
  then
    ArchitecturalAvailability+
    (1-ArchitecturalAvailability)*
    (AvoidedUnavailability-AvoidedUnavailabilityBaseline)/
    (1-AvoidedUnavailabilityBaseline)
  else
    ArchitecturalAvailability+
    ArchitecturalAvailability*
    (AvoidedUnavailability-AvoidedUnavailabilityBaseline)/
    AvoidedUnavailabilityBaseline
  endif
endif
```

It should be noted that the final divisor is zero (i.e. the expression is undefined) if `AvoidedUnavailabilityBaseline` = 1. However, as the leakage of the Noisy-OR model prevents `AvoidedUnavailability` from ever reaching 1, a *baseline* value of 1 is also impermissible. This is enforced using the `baselineCheck` invariant.

C Appendix: OCL code for metamodel operations

C.1 BehaviorElement

C.1.1 isTopService():Boolean

This operation checks whether the current `BehaviorElement` is the top service, i.e. whether it has no causal successors. The reason for doing this is that the holistic availability ought only be evaluated at a single point in the architecture, viz. at its "top". This follows from the fact that holistic availability accounts for non-localizable properties.

```
if
  serviceToGate->isEmpty()
then
  true
else
  false
endif
```

C.1.2 getBehaviorElements(BehaviorElement):BehaviorElement[*]

This operation returns the set of all `BehaviorElements` causally prior to the one given as argument, including itself. This is implemented in a recursive fashion.

```
getGates(curr.gateToServiceInv)->asSet()->
excluding(null).serviceToGateInv->asSet()->
collect(be:BehaviorElement | getBehaviorElements(be)->
asSet()->excluding(null))->asSet()->
union(getGates(curr.gateToServiceInv)->asSet()->
excluding(null).serviceToGateInv->asSet())->
asSet()->union(curr->asSet())
```

`curr` is the `BehaviorElement` given as argument.

C.1.3 getGates(Gate):Gate[*]

This operation returns the set of all gates connected to the one given as argument through other gates (not through `BehaviorElements`).

```
curr->excluding(null).gateToGateInv->
collect(g:Gate | getGates(g))->asSet()->
union(curr->excluding(null).gateToGateInv->asSet())
->union(curr->asSet())
```

`curr` is the `Gate` given as argument.

*C.1.4 getBestPractice*CausalFactor*(BehaviorElement):Real*

This set includes 14 operations, one for each of the best practice attribute factors of Table 2. While similar, the 14 P^{2}AMF implementations differ a bit from each other. Each operation traverses the architectural model, using the `getBehaviorElements` and `getGates` operations, to find all attributes of the relevant kind. The arithmetic mean of the attribute values is returned. If no attributes of the relevant kind are found, the default value 0.5 is returned. `getBestPracticeAvoidanceOfExternalService-Failures` represents the basic case:

```
let current : Set(ApplicationService) =
getBehaviorElements(top)->
  select(oclIsTypeOf(ApplicationService))->asSet()->
  excluding(null).oclAsType(ApplicationService)->asSet() in
if current->size()=0 then
--If no elements exist, we assume 50% best practice
  0.5
else
  current.bestPracticeAvoidanceOfExternalServiceFailures->
  sum()/current->size()
endif
```

`top` is the `BehaviorElement` given as argument.

If the attributes sought belong to more than one class, these several class types must be found, as in `getBestPracticeResilientClientServerSolutions`:

```
let current1 : Set(InfrastructureService) =
  getBehaviorElements(top)->
  select(oclIsTypeOf(InfrastructureService))->asSet()->
  excluding(null).oclAsType(InfrastructureService)->asSet() in
let current2 : Set(ApplicationService) =
  getBehaviorElements(top)->
  select(oclIsTypeOf(ApplicationService))->asSet()->
  excluding(null).oclAsType(ApplicationService)->asSet() in
if current1->size()+current2->size()=0 then
--If no elements exist, we assume 50% best practice
  0.5
else
  (current1.bestPracticeResilientClientServerSolutions->sum()+
  current2.bestPracticeResilientClientServerSolutions->sum())
  /(current1->size()+current2->size())
endif
```

Sometimes the attributes belong to a class that has to be accessed through a relationship, e.g. `isGovernedBy` in `getBestPracticeChangeControl`:

```
let current : Set(ChangeControl) =
  getBehaviorElements(top).isGovernedBy->
  select(oclIsTypeOf(ChangeControl))->asSet()->
  excluding(null).oclAsType(ChangeControl)->asSet() in
if current->size()=0 then
--If no elements exist, we assume 50% best practice
  0.5
else
  current.bestPractice->sum()/current->size()
endif
```

C.1.5 avoidedUnavailability():Real

This operation calculates the avoided unavailability based on the Noisy-OR model from [17]. The model originally gives the avoided unavailability as

$$A(\mathbf{X}_p) = 1 - P(y|\mathbf{X}_p) = (1 - p_0) \prod_{i:X_i \in \mathbf{X}_p} \frac{(1 - p_i)}{(1 - p_0)} \quad (10)$$

where $A(\mathbf{X}_p)$ is the avoided unavailability of an architecture lacking the best practice factors listed in the vector $\mathbf{X}_p$. The p_i variables are the ones given in Table 1. In this implementation, each factor to the right of the product sign is calculated using the operation `noisyOrFactor`.

```
--Leakage 1%
let p0 : Real = 0.01 in
--Grand unified Noisy-OR product
(1-p0)*
noisyOrFactor(0.0997315262,getBestPractice-
  PhysicalEnvironmentAndInfrastructureRedundancy(self),p0)*
noisyOrFactor(0.2524557957,getBestPractice-
  RequirementsAndProcurement(self),p0)*
noisyOrFactor(0.2299924070,getBestPractice-
  Operations(self),p0)*
noisyOrFactor(0.2807783956,getBestPractice-
  ChangeControl(self),p0)*
noisyOrFactor(0.0695945946,getBestPractice-
  TechnicalSolutionOfBackup(self),p0)*
noisyOrFactor(0.0357142857,getBestPractice-
  ProcessSolutionOfBackup(self),p0)*
noisyOrFactor(0.0955186161,getBestPractice-
  DataAndStorageArchitectureRedundancy(self),p0)*
noisyOrFactor(0.1685845800,getBestPractice-
  AvoidanceOfInternalApplicationFailures(self),p0)*
noisyOrFactor(0.0865984930,getBestPractice-
  AvoidanceOfExternalServiceFailures(self),p0)*
noisyOrFactor(0.0760578279,getBestPractice-
  NetworkRedundancy(self),p0)*
noisyOrFactor(0.1828929068,getBestPractice-
  AvoidanceOfNetworkFailures(self),p0)*
noisyOrFactor(0.0334905660,getBestPractice-
  PhysicalLocation(self),p0)*
noisyOrFactor(0.0364864865,getBestPractice-
  ResilientClientServerSolutions(self),p0)*
noisyOrFactor(0.2614035088,getBestPractice-
  ComponentMonitoring(self),p0)
```

C.1.6 noisyOrFactor(Real,Real,Real):Real

This operation calculates factors for the `avoidedUnavailability` operation. In the formulation given in Eq. 10, each best practice factor is either present or not (i.e. listed in the vector $\mathbf{X}_p$, or not). However, `noisyOrFactor` allows factors to be present probabilistically, i.e. be present with a probability q and absent with a probability $1 - q$. A causal factor being present means that it is not listed in the index set $\mathbf{X}_p$, which is equivalent to `noisyOrFactor` returning 1, i.e. the multiplicative identity. This consideration gives `noisyOrFactor` the following form:

```
q*1+(1-q)*(1-p)/(1-p0)
```

`noisyOrFactor` takes three arguments; p, q, and p_0. $p_0 = 1\%$ [17], p is the appropriate p_i from Table 1, and q is the value returned from the appropriate `getBestPractice`*`CausalFactor`*.

It is a feature of Noisy-OR models as such that the impact of the systemic causal factors is multiplicatively separable. This allows the probabilistic presence of each factor to be treated independently from the rest, as in `noisyOrFactor`.

D Appendix: OCL code for metamodel invariants

A number of OCL invariants are included in the metamodel, in order to express constraints that cannot be expressed in a regular entity-relationship diagram.

D.1 BehaviorElement

D.1.1 baselineCheck

This invariant requires that the `AvoidedUnavailabilityBaseline` $\in [0, 1)$. It cannot be unity, since the Noisy-OR model behind *AvoidedUnavailability* has leakage and cannot be unity.

```
if
  (AvoidedUnavailabilityBaseline >= 1
  or AvoidedUnavailabilityBaseline < 0)
then false
else true
endif
```

D.1.2 mostOneType

This invariant requires that a `BehaviorElement` is at most connected to one gate through the `gateToService` relation or to one `ActiveStructureElement` through the `assigned` relation, but not to both. Being connected to both would lead to a conflict in the calculation of architectural availability.

```
(gateToServiceInv->notEmpty() implies assigned->isEmpty())
  and (assigned->notEmpty() implies gateToServiceInv->isEmpty())
```

D.2 Node

D.2.1 onlyInfrastructureService

This invariant requires that only an `InfrastructureService`, and no other type of `BehaviorElement` can be `assigned` to a `Node`.

```
assignedInv->forAll(s: BehaviorElement |
  s.oclIsTypeOf(InfrastructureService))
```

D.3 ApplicationComponent

D.3.1 onlyFunction

This invariant requires that only an `ApplicationFunction`, and no other type of `BehaviorElement` can be `assigned` to an `ApplicationComponent`.

```
assignedInv->forAll(s: BehaviorElement |
  s.oclIsTypeOf(ApplicationFunction))
```

D.4 CommunicationPath

D.4.1 onlyInfrastructureService

This invariant requires that only an `InfrastructureService`, and no other type of `BehaviorElement` can be `assigned` to a `CommunicationPath`.

```
assignedInv->forAll(s: BehaviorElement |
  s.oclIsTypeOf(InfrastructureService))
```