Exploiting Traceability Uncertainty between Software Architectural Models and Extra-Functional Results

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Abstract

Deriving extra-functional properties (e.g., performance, security, reliability) from software architectural models is the cornerstone of software development as it supports the designers with quantitative predictions of system qualities. However, the problem of interpreting results from quantitative analysis of extra-functional properties is still challenging because it is hard to understand how the analysis results (e.g., response time, data confidentiality, mean time to failure) trace back to the architectural model elements (i.e., software components, interactions among components, deployment nodes).

The goal of this paper is to automate the traceability between software architectural models and extra-functional results, such as performance and security, by investigating the uncertainty while bridging these two domains. Our approach makes use of extra-functional patterns and antipatterns, such as performance antipatterns and security patterns, to deduce the logical consequences between the architectural elements and analysis results and automatically build a graph of traces, thus to identify the most critical causes of extra-functional flaws. We developed a tool that jointly considers SOftware and Extra-Functional concepts (SoEfTraceAnalyzer), and it automatically builds model-to-results traceability links. This paper demonstrates the effectiveness of our automated and tool supported approach on three case studies, i.e., two academic research projects and one industrial system.

Keywords:
Traceability, Uncertainty, Software Modelling, Extra-Functional Results.

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1. Introduction

In the software development domain there is a very high interest in the early validation of extra-functional requirements because this ability avoids late and expensive repairs to consolidated software artifacts [1]. One of the proper ways to manage software quality is to systematically predict the extra-functional properties of the software system throughout the development process. It is thus possible to make informed choices among architectural and design alternatives; and knowing in advance if the software will meet its extra-functional objectives [2].

Advanced Model-Driven Engineering (MDE) techniques have successfully been used in the last few years to introduce automation in software quality modeling and analysis [3]. Nevertheless, the problem of interpreting extra-functional results is still quite challenging. A large gap exists between the representation of extra-functional analysis results and the software architectural model provided by the engineers. In fact, the former usually contains numbers (e.g., throughput variance, vulnerability level, mean time to failure, etc.), whereas the latter embeds architectural choices (e.g., software components, interaction among components, deployment nodes). Today, the interpretation of extra-functional results is mostly based on the analysts' experience and therefore its effectiveness often suffers from lack of automation [4].

In [5] we proposed a language capable of capturing model-to-code traceability while considering typical uncertainties in its domain. For example, the engineer knows that some given piece of code may implement an architectural element; however, not whether this piece of code also implements other architectural elements; or whether this architectural element is also implemented elsewhere (other code). This paper adapts this language to provide model-to-results traceability links while considering typical uncertainties from the extra-functional analysis domain. We presume that engineers know when a given extra-functional result is affected by an architectural element. However, they may not know whether this extra-functional result is also affected by other architectural elements or whether other extra-functional results are also affected by this architectural element.

Further knowledge can be considered to better understand the relationship between architectural elements and extra-functional results, in particular extra-functional patterns and antipatterns [6, 7] represent best and bad practices in architectural models affecting extra-functional properties. A pattern specification [6] includes solutions to commonly occurring problems, e.g., security patterns [8] encapsulate knowledge and expertise to improve security properties such as confidentiality, integrity, etc. An antipattern definition [7] includes the description of bad practices occurring in the architectural model along with the solution that can be applied to avoid negative consequences, e.g., performance antipatterns [9] collect domain-expert knowledge to react against performance flaws such as low response time, high network utilization, etc.

This paper is an extension of [10] where we focused on performance analysis results and we used sofware performance antipatterns to reduce model-to-results traceability uncertainties. The contribution of this paper is to provide support in the process of identifying the architectural model elements that most likely contribute to the violation of multiple extra-functional requirements by jointly considering knowledge from engineers and extra-functional patterns and antipatterns. To this end, we developed a tool, namely SoEfTraceAnalyzer [11], that jointly considers Software and Extra-Functional concepts: it takes as input a set of statements specifying the relationships between software elements and extra-functional properties, and provides as output model-to-results traceability links. The language defined in [5] is extended by adding a weighting methodology that quantifies the extra-functional requirements' violation, thus to highlight the criticality of model elements despite extra-functional properties. The key feature of our tool is that the knowledge of extra-functional patterns and antipatterns can be embedded in the specification of uncertainties to deduce the logical consequences between architectural elements and analysis results, thus to disambiguate the limited knowledge of engineers.

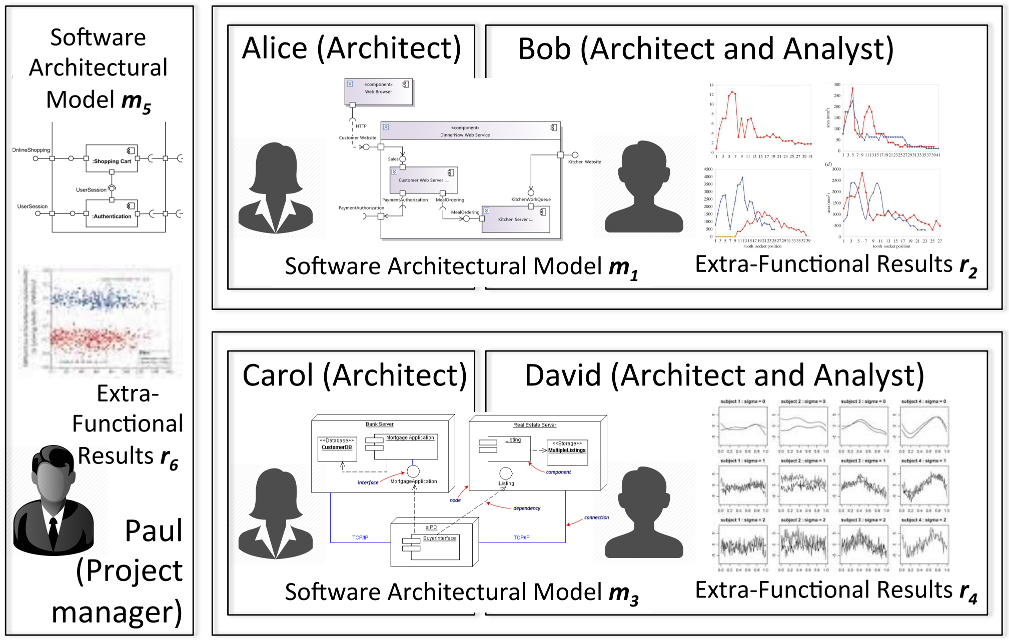
Our approach is not limited, in principle, to specific extra-functional properties. However, to investigate the effectiveness of traceability links, in this paper we decided to focus on performance and security, and we make use of security patterns [8] and performance antipatterns [9] to reduce traceability uncertainty. This choice is driven by the fact that security has a "direct" overhead on performance, whereas other extra-functional properties may not. For example, it is well known that introducing security mechanisms, such as encryption of data, inevitably consume system resources influencing the system performance, even affecting its full operability. On the contrary, increasing system reliability may mean to create copies of software components off-line without any impact on the system performance.

The paper is organized as follows: Section 2 describes an illustrative example; Section 3 discusses the relationships between sofware development artifacts and extra-functional properties; Section 4 describes our approach; Section 5 illustrates the validation of the approach on three case studies (i.e., two academic research projects and one industrial system); Section 6 discusses the threats to validity of the approach; Section 7 presents related work; Section 8 concludes the paper.

2. Illustrative Example

In this section we illustrate the *DesignSpace*, an academic research project aimed at building an engineering infrastructure to integrate diverse development artifacts and their relations [12]. It is an engineering platform for the exchange, linking, and validation of the knowledge across different artifacts. It supports distributed collaboration, a wide range of tools and development, maintenance, and evolution of services including incremental consistency checking and transformation. There are three main challenges: (i) how the knowledge created and manipulated by engineers in their respective single-user tools is being made available to other engineers; (ii) how this knowledge is interconnected to express cross-tool dependencies; (iii) how engineers benefit from analysis and transformation techniques.

Figure 1 provides a high-level overview of the DesignSpace system [12] to illustrate some examples of the involved artifacts and their traceability, thus to demonstrate the need of our approach. Figure 1a provides a high-level representation of the users and artifacts involved in a system. There are five engineers: Alice is an architect and collaborates with Bob on the modeling of a subpart of the system reported in the software architectural model m_1. Bob is also an analyst and checks if the extra-functional results r_2 of this subsystem are fulfilling the stated requirements. Similarly, Carol is an architect and collaborates with David on the modeling of an other subpart of the system reported in the model m_3. David is also an analyst and checks the results r_4 of this last subsystem. Finally, Paul is a project manager and manages the software architectural model m_5 modeling the whole system, and the global extra-functional results r_6. Examples of both functional and extra-functional requirements are reported in Figure 1b: R_1 is a functional requirement through which the architectural models are updated, e.g., changes to model m_1 require modifications to m_5 but not to m_3; R_2


Software Architectural Model m_5
Extra-Functional Results r_6
Paul (Project manager)
Alice (Architect)
Bob (Architect and Analyst)
Software Architectural Model m_1
Extra-Functional Results r_2
Carol (Architect)
David (Architect and Analyst)
Software Architectural Model m_3
Extra-Functional Results r_4

(a) Overview.

Req. ID	Description	Property
R_1	Update model m_5 automatically after modifying model m_1	Functional
R_2	Three seconds max to load a model	Extra-Functional (Performance)
R_3	Only authorized users get access to models	Extra-Functional (Security)

(b) Requirements.

Figure 1: DesignSpace system.

is a performance requirement requesting a maximum delay of three seconds when loading the models; R_3 is a security requirement regulating the users access to models under authorization, e.g., Alice can access to model m_1 only, David can access to model m_3 and results r_4, whereas Paul can access to all artifacts, i.e., all models and extra-functional results.

As stated in [13], when analyzing trade-offs among these requirements, the developer must understand how the requirements affect each other. The goal of our approach is to trace extra-functional results to architectural model artifacts thus to support software designers in the task of identifying the most suitable model elements responsible for bad properties, if any.

3. Software Architectural Models and Extra-functional Properties

Common practice for software engineers is to document architectural descriptions, however it is less common to document how such architectural elements (e.g., software components, dynamic scenarios, deployment nodes, etc.) are related to extra-functional properties (e.g., performance, security). Knowing about traceability is important to understand what are the architectural elements contributing to extra-functional properties and deriving the most suitable refactoring actions to improve such properties. The goal of this work is to support software designers in the task of identifying the relationships between software architectural models and extra-functional results.

We refer to specific software architectural elements where the granularity of an architectural element is entirely user-definable. An architectural element could be a software component, a service built on top of several components, or any other logical grouping (e.g., a hardware device hosting several software components). We will discuss the implications of different granularity choices later.

We refer to specific extra-functional properties, such as performance (e.g., response time, throughput, utilization) and security (e.g., security level/risk). Here also the granularity is arbitrary user definable. For example, we could trace all the stated software components to system extra-functional properties or we could trace its individual model elements and their corresponding extra-functional properties.

The relationship between architectural elements and extra-functional properties is bidirectional. We expect that a single model element is contributing in multiple extra-functional properties (one-to-many mapping), for example a software component may affect the response time of a service and the utilization of its hosting hardware device. Similarly, an extra-functional property is affected by multiple model elements, but it may happen that the architectural specification is incomplete either by choice or by omission. For example, system response time and/or security level are two properties that may span the entire system, and they can be affected by parts of the system architecture that are not included as modelling artifacts. Consequently, it becomes very difficult to select specific model elements, besides others, that are not contributing to system properties.

4. Our approach

Figure 2 illustrates the process we envisage to automate the traceability between architectural model elements and extra-functional results. Ovals in the figure represent operational steps whereas square boxes represent input/output data. Four main phases are identified in the process.

Phase ①: Requirements. We assume that a set of extra-functional *requirements* is defined. Some examples of performance requirements are as follows: the response time of a service has to be less than 3 seconds, the throughput of a service has to be greater than 10 requests/second, the utilisation of a hardware device shall not be higher than 80%, etc. Some examples of security requirements are: a message exchanged between two components might require encryption depending on whether the communication channel between the components is a wireless one or not, the completion of a certain software operation needs to be verified by a certification authority, etc. All extra-functional (e.g., performance and security) requirements will be used to build the software architectural model and interpret the results obtained from the model-based analysis [14].

Phase ②: Modeling. In the *modeling* phase, an annotated[1] software architectural model is built. Such model embeds the stated extra-functional requirements, e.g., to enable reliability properties some software components need to be duplicated, or to achieve a certain security level some software services have to be protected (e.g., a software component requiring a certain service must be authenticated before allowing its usage).

Phase ③: Analysis. In the *analysis* phase, extra-functional model(s) are obtained through model transformation, and such models (e.g., queuing networks for performance [15], and fault-trees for reliability [16]) are solved to obtain the results of interest. Some extra-functional requirements (e.g., security) consist in the addition of appropriate mechanisms implementing the corresponding requirement in the software architectural model. As an example, if a security requirement specifies that data integrity must be guaranteed for a certain service, an additional pattern with the steps needed for the data integrity mechanism must be introduced in the architectural model wherever the service is invoked. All these additions are included into extra-functional model(s), thus to get results reflecting them.

[1]Annotations are aimed at specifying information to execute performance analysis such as the incoming workload, service demands, hardware characteristics, etc.

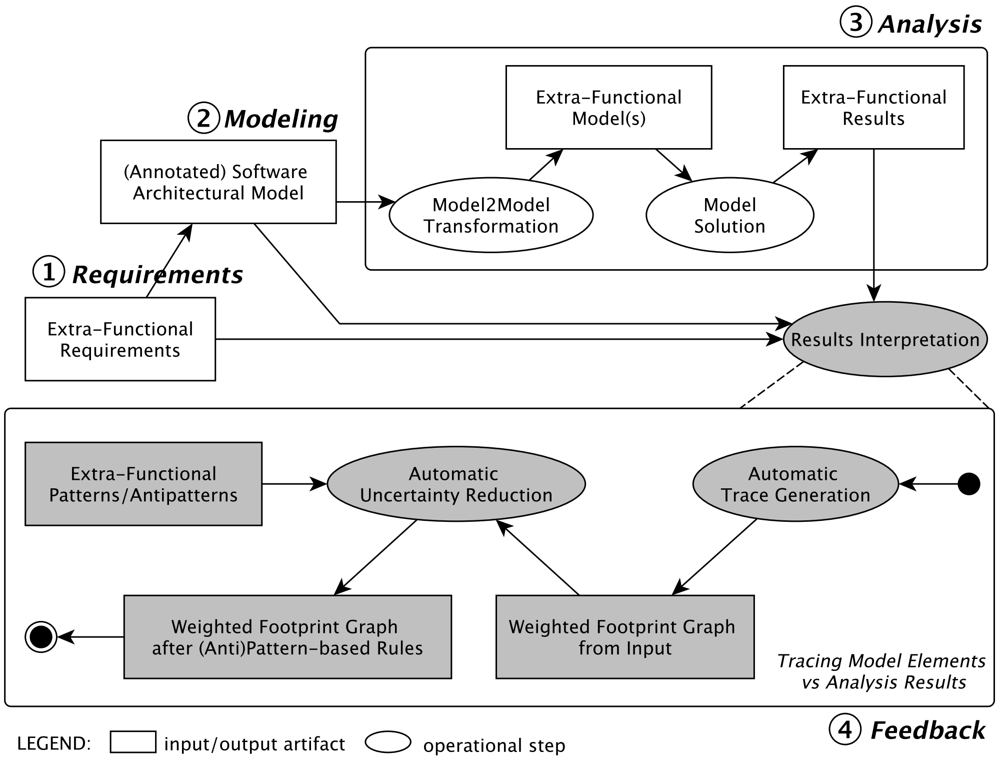

③ Analysis
② Modeling
① Requirements
(Annotated) Software Architectural Model
Extra-Functional Model(s)
Extra-Functional Results
Model2Model Transformation
Model Solution
Extra-Functional Requirements
Results Interpretation
Extra-Functional Patterns/Antipatterns
Automatic Uncertainty Reduction
Automatic Trace Generation
Weighted Footprint Graph after (Anti)Pattern-based Rules
Weighted Footprint Graph from Input
Tracing Model Elements vs Analysis Results
④ Feedback
LEGEND:
input/output artifact
operational step

Figure 2: Deriving automatically model-to-results traceability links by means of extra-functional patterns/antipatterns.

Phase ④: Feedback. The focus of this paper is on the *feedback* phase where the extra-functional requirements must be interpreted in order to detect, if any, extra-functional flaws[2]. Such flaws may be of different nature and several refactoring actions can be introduced to improve the corresponding violated property. For example, to increase the reliability of a software component the number of its replications can vary, or to increase the security of a software service the key size of the encryption algorithm can be modified. This leads to a trade-off analysis that is conducted by implementing the available refactorings as new software architectural models that undergo the same process shown in Figure 2.

The goal of our approach is to trace architectural model elements vs extra-functional results (see shaded boxes of Figure 2), thus to highlight the architectural model elements contributing to extra-functional flaws. It starts with an automatic trace generation operational step that provides as output a weighted footprint graph (from input), i.e., a graph containing a node for every result element (called RE nodes) and a node for each model element (called ME nodes). The connections between these nodes describe the certainties of the input (trace or no-trace), and are refined with an automatic uncertainty reduction operational step aimed at generating a weighted foot print graph, i.e., after (anti)pattern-based rules. This latter step is supported by extra-functional patterns/antipatterns, because they suitably fit with our goal. In [10] we used performance antipatterns [9] to deduce the logical consequences of the uncertainties, and we found that they nicely contribute to automatically generate traces joining architectural elements and performance results. In this paper we further consider *security patterns* [17] to enable a trade-off analysis among these two extra-functional properties.

4.1. Automatic Trace Generation

The automatic trace generation operational step (see Figure 2) takes as input: (i) extra-functional requirements, (ii) annotated software architectural model, and (iii) extra-functional results. It provides as output a weighted footprint graph.

Extra-functional requirements are classified on the basis of the property (e.g., performance, security) they address and the level of abstraction they

[2]A flaw originates from a set of unfulfilled requirement(s), such as "the estimated average response time of a service is higher than the required one", or "the achieved security level of a service is lower than the required one".

apply. In general, it is very challenging to quantify security-related properties, hence we leave to engineers the decision of associating pre-defined security levels (`SEC`), i.e., low, medium, and high. For performance we consider the requirements that refer to the following performance indices[18]: *Response time* (`RT`) is defined as the time interval between a user request of a service and the response of the system; *Throughput* (`TH`) is defined as the rate at which requests can be handled by a system, and is measured in requests per unit of time; *Utilization* (`U`) is defined as the ratio of busy time of a resource and the total elapsed time of the measurement period; *Queue length* (`QL`) is defined as the number of users waiting for a resource; *Waiting time* (`WT`) is defined as the time interval required to access to a resource starting from when the resource is required up to when it is accessed.

Usually, RT requirements are upper bounds defined in "business" requirements by the end users of the system. TH requirements can be both "business" and "system" requirements, they can represent either an upper or a lower bound. U, QL and WT requirements are upper bounds defined in "system" requirements by system engineers on the basis of their experience, scalability issues, or constraints from other concurrent software systems.

Various levels of abstraction can be defined for a requirement: system, processor, etc. However, we do not consider all possible combinations of indices and levels of abstraction, we focus on the most common ones that are: `SEC`, `RT`, and `TH` of services, `U`, `QL`, and `WT` of hardware devices.

Extra-functional results represent the analysis values of the indices we consider for traceability. Note that such values are affected by a set of features such as system workload and operation profile that represent how the software system is used [18].

Annotated software architectural models may be constituted by elements belonging to different views [19]: *Static/Software View* (SW) includes the software elements, e.g., operations (`SWop`), components (`SWcomp`), services, and the static relationships among them; *Dynamic/Interaction View* (DY) includes the specification of the interaction, e.g., messages (`DYmsg`), that occurs between the software components to provide services; *Deployment/Hardware View* (HW) includes the hardware devices, e.g., processing nodes (`HWnode`), and communication networks (`HWnet`), and the mapping of software components and iteractions onto hardware devices. Summarizing, `SWop`, `SWcomp`, `DYmsg`, `HWnode`, and `HWnet` represent the architectural elements we consider for traceability.

4.1.1. Language for expressing traceability

This paper adapts the language for model-to-code traceability introduced in [5] and extends it to express model-to-results traceability considering some of the unique aspects of this domain. The main benefit of our approach is that our language allows the engineer to express uncertainty constructs to the level of detail she or he is comfortable with. As drawback, neither correctness nor completeness are guaranteed.

Each construct is defined as $\{m^*\}$ relationship $\{r^*\}$ where $\{m^*\}$ is the set of model elements and $\{r^*\}$ is the set of results elements. The star symbol (*) expresses multiplicity in that m* stands for multiple model elements and r* for multiple results elements. The relationship term declares how the first set is related to the second one.

We distinguish between three major relationships: affectAtLeast, affectAtMost, affectExactly.

1) AffectAtLeast Construct: the input {m*} affectAtLeast {r*} defines that the model elements in {m*} affect all of the result elements in {r*} and possibly more. This input has a correctness constraint ensuring that every model element in {m*} individually must be affecting a subset of {r*}. One example of this relationship is provided by the software components $SWcomp$ and the subset of operations $SWop$ involved in a service S that affect at least the security level (SEC), the response time (RT) and the throughput (TH) of the service S.

Input: {`SWop`*, `SWcomp`*} affectAtLeast {`SEC`, `RT`, `TH`}

2) AffectAtMost Construct: the input {m*} affectAtMost {r*} defines that the model elements in {m*} affect some of the result elements in {r*} but certainly not more. This input expresses the certainty that every other model element not in {m*} must not affect any result element in {r*}. One example of this relationship is provided by the software components $SWcomp$ and the subset of operations $SWop$ involved in a service S as well as the deployment nodes $HWnode$ where the $SWcomp$ components are deployed that affect at most the security level (SEC), the response time (RT) and the throughput (TH) of the service S.

Input: {`SWop`*, `SWcomp`*, `HWnode`*} affectAtMost {`SEC`, `RT`, `TH`}

3) AffectExactly Construct: the input {m*} affectExactly {r*} defines that every model element in {m*} affects one or more result elements in {r*} and that the results elements in {r*} are not affected in any other model element not in {m*}. This input defines no-trace between each result

element in {r*} and each model element in the remaining M-{m*} (where M is the set of all input model elements), since each model element in {m*} affects only a subset of {r*}. However, this does not mean that these result elements could not be affected by other model elements in M-{m*}. One example of this relationship is provided by an hardware device *HWnode* and the performed operations *SWop* that affect exactly its utilization (U).
Input: {`SWop*, HWnode`} affectExactly {`U`}

4.1.2. Weighted footprint graph

The language we provided to express the uncertainty constructs between a set of architectural model elements and a set of analysis results elements is very flexible. Listing 1 reports one abstract example for the specification of the input. For example, the hardware devices `HWnode` and `HWnet` affect exactly the performance indices related to them, i.e., utilization (U), queue length (QL), and waiting time (WT). As another example, the software components *SWcomp* and the subset of operations *SWop* involved in a service *S* affect at least the security level (SEC), the response time (RT) and the throughput (TH) of the service *S*.

```
{HWnode, HWnet} affectExactly {U, QL, WT};
{SWop, SWcomp} affectAtLeast {SEC, RT, TH};
{SWop, DYmsg} affectAtMost {SEC, RT, TH, QL};
{SWcomp, DYmsg} affectAtMost {SEC, RT, TH, QL};
```

Listing 1: Input to trace generation.

The goal of our SoEfTraceAnalyzer tool [11] is to interpret these traceability expressions and automatically build (certainties and uncertainties) in a graph structure, which we call the weighted footprint graph (from input).

Figure 3 reports one abstract example of this graph and it refers to the input specified in Listing 1. The graph contains a node for every result element (called RE nodes) and a node for each model element (called ME nodes). RE nodes are: response time (`RT`), throughput (`TH`), utilization (`U`), queue length (`QL`), waiting time (`WT`), and security level (`SEC`). ME nodes are: software operations (`SWop`), software components (`SWcomp`), dynamic interactions (`DYmsg`), hardware nodes (`HWnode`), and communication networks (`HWnet`).

The connections between RE nodes and ME nodes describe the certainties of the input (trace or no-trace) which are generated out of the logical consequences of the uncertainties. A trace (m, r) is depicted by a bold line between the ME node of m and the RE node of r. In figure 3 no such lines

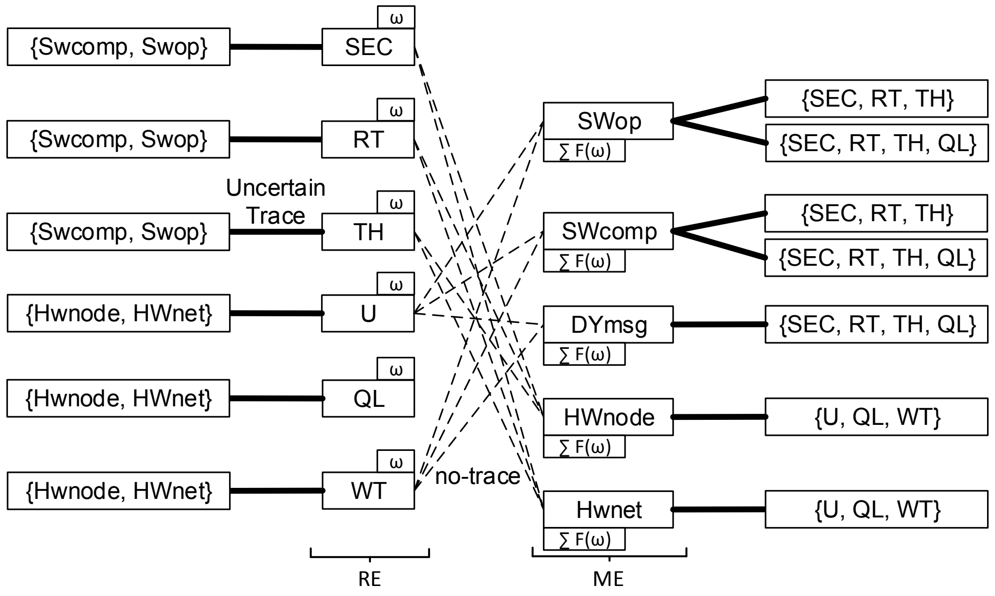


Figure 3: Weighted Footprint Graph, from Input.

are depicted because the logical interpretation of the input did not yield any traces. On the contrary, no-traces are depicted by dashed lines. Furthermore, the graph contains nodes to capture model element groups (MEG nodes) and results element groups (REG nodes). These two kinds of nodes describe the uncertainties of the input.

Note that each result element node *RE* has a weight (ω) that represents a value indicating how much the requirement is far from the analysed index, whereas each model element node *ME* has a weight that is a function ($\sum$ F(ω)) indicating how much the architectural element is critical for the violated requirements. Our language allows to set the weights for *RE* nodes and their guilt estimates vs *ME* nodes, thus to quantify how much extra-functional results are affected by architectural elements. Listing 2 reports a simple example for the specification of weight and guilt estimates: the response time (`RT`) and security (`SEC`) results are violated by 0.5 and 0.33, respectively; the software component (`SWcomp`) participates to both results with different guilt estimates, i.e., 0.42 and 0.15 for `RT` and `SEC`, respectively. The numerical values provided as weight estimates come from the evaluation of stated extra-functional requirements, e.g., if the response time of a service is required to be not larger than 8 sec, but the performance analysis reveals that the actual value is 12 sec, then 0.5 represents the percentage of requirement' violation. For security results it is indeed challenging to provide weights expressing requirement' violation, hence we assume that security concerns can be discretized in a set of samples on the basis of their severity and numerical values are associated to these samples (e.g., security levels may be: high $\rightarrow$ 0.75, medium $\rightarrow$ 0.5, and low $\rightarrow$ 0.25). In this way, similarly to performance, we can report the estimation of requirement' violation expressed as percentage among the specified values.

```
set weight : RT = 0.5;
set weight : SEC = 0.33;
set guilt : RT -> SWcomp = 0.42;
set guilt : SEC -> SWcomp = 0.15;
```

Listing 2: Specification of weight and guilt estimates.

Guilt estimates for performance results are assigned by using the guilt-based approach we validated in our previous work [20]. In particular, each model element is ranked on the basis of how much it contributes to the performance index under analysis: we calculate the index of the corresponding model element and we estimate how much it is contributing. For security results it is indeed challenging to provide guilt estimates, hence we assume that security concerns can be associated to a set of model elements and numerical values are associated by ranking them, similarly to performance.

Figure 4 shows the weighted footprint graph that is generated from input (see Listing 1) augmented with weight and guilt estimates specification reported in Listing 2. Note that the weights for *RE* nodes are directly derived from their specification, whereas weights for *ME* nodes are calculated while taking into account traceability information. If there exists a trace (m, r) then we assume that m fully participates to the weight of r, whereas if there is an uncertain trace then guilt estimates are used to scale the weight of r. Weights of model elements are obtained by summing up all traces and uncertain ones. In our example the `SWcomp` node is weighted by the following calculation: 0.5 * 0.42 + 0.33 * 0.15 = 0.26, in fact that node is involved with uncertain traces in both `SEC` and `RT` results.

Different heuristics (ω) and functions ($\sum$ F(ω)) can be used to weight RE and ME nodes in footprint graphs. Furthermore, the human intervention of engineers may help to add priorities to extra-functional properties and to specify legacy constraints for architectural elements.

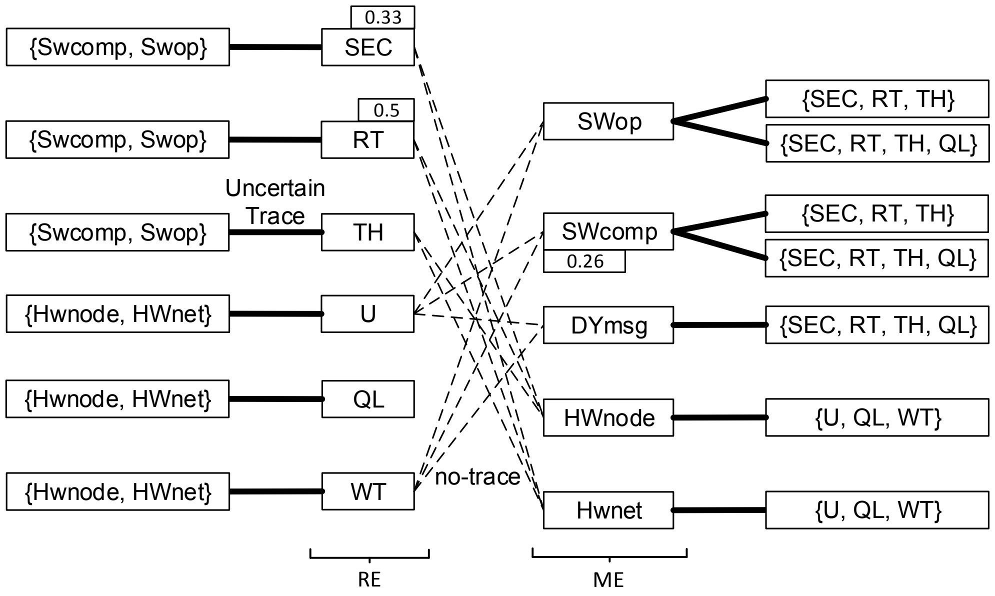


Figure 4: Weighted Footprint Graph, from Input, weight and guilt estimates.

4.2. Automatic Uncertainty Reduction

The weighted footprint graph is the foundation for automatic trace generation, and several propagation rules can be introduced to reduce the initial uncertainty. Our approach makes use of performance antipatterns [21] and security patterns [22] to deduce the logical consequences between architectural elements and analysis results.

(Anti)patterns represent a well-known technique to express domain-independent knowledge and expertise in a reusable way. Architectural and design patterns constitute solid solutions that can be employed in order to solve known and recurrent problems. (Anti)patterns provide the main advantage of including benefits and drawbacks in their specification, and they can be taken into account while sketching their solution.

4.2.1. Performance Antipatterns

Performance antipatterns deal with the performance issues of software systems. In literature, the main source of performance antipatterns is the work done across years by Smith and Williams [9] that have ultimately defined a number of 14 notation- and technology- independent antipatterns. The benefit of using these antipatterns is that they offer solutions in forms of alternative architectures to performance flaws, and several works recently have demonstrated their usefulness [23, 24, 25, 26].

In our previous work [27] we provided a logic-based representation of performance antipatterns that supports the specification of further input to trace generation. Listing 3 reports the traceability rules while considering the specification of some performance antipatterns, i.e., Concurrent Processing Systems (CPS), Pipe & Filter (P&F), God Class/Component (BLOB), Extensive Processing (EP), Empty Semi Trucks (EST), One-Lane Bridge (OLB), and The Ramp (TR), respectively.

```
CPS: {HWnode} affectExactly {QL, U};
BLOB: {SWop, DYmsg} affectAtLeast {U};
P&F: {SWop, DYmsg} affectAtLeast {TH, U};
EP:  {SWop, DYmsg} affectAtLeast {RT, U};
EST: {DYmsg} affectAtLeast {RT, U};
OLB: {SWcomp, SWop, DYmsg} affectAtMost {RT, WT};
TR:  {SWop} affectExactly {RT, TH};
```

Listing 3: Performance Antipattern-based rules to reduce model-to-results uncertainty.

For example, detecting a CPS antipattern indicates that `HWnode` affects exactly `QL` and `U`. This rule comes from the logic-based formula of the CPS antipattern that has been defined in [27], and an excerpt is reported in Equation (1) where $\mathbb{P}$ represents the set of all the hardware devices.

$$\begin{aligned} \exists P_x \in \mathbb{P} \mid F_{maxQL}(P_x) \geq Th_{maxQL} \wedge \\ F_{maxHwUtil}(P_x) \geq Th_{maxUtil} \end{aligned} \tag{1}$$

CPS is an antipattern that occurs when processes cannot make effective use of available hardware devices to a non-balanced assignment of tasks. The *over-utilized* hardware devices are detected by checking if the queue length and the utilization overcome pre-defined thresholds[3].

4.2.2. Security Patterns

Security patterns deal with the security properties of software systems. In literature, security patterns have gained significant attention by the research community after the seminal work in [17] that have defined a catalog of 7 patterns collaborating to provide the necessary security within an application.

[3]A specific characteristic of performance antipatterns is that they contain numerical parameters representing thresholds (e.g., *high* utilization, *excessive* number of messages). For further details refer to [27].

The benefit of using these patterns is that software systems should result in a 'more secure' design, i.e., they should expose fewer security flaws at the design level, and several works recently have demonstrated their usefulness [28, 29, 8].

Listing 4 reports the traceability rules while considering the specification of some security patterns [17], i.e., Authorization (AUTH), Role-based Access Control (RBAC), Limited View (LV), and Session (SES), respectively. These rules come from our understanding of the pattern specification in [17]. In particular, for each pattern we defined the model elements (i.e., `SWcomp`, `SWop`, `DYmsg`, `HWnode`) that most likely affect their security level (`SEC`). To further extend their specification we also consider the performance indices related to that specific element (i.e., `RT`, `TH`, `U`, `QL`, `WT`).

```
AUTH:  {DYmsg} affectAtLeast {SEC, RT, TH};
RBAC:  {SWop, DYmsg} affectAtLeast {SEC, RT, TH};
LV:  {SWcomp, SWop, DYmsg} affectAtLeast {SEC, RT, TH};
SES: {HWnode} affectAtMost {SEC, U, QL, WT};
```

Listing 4: Security Pattern-based rules to reduce model-to-results uncertainty.

For example, introducing a Session (SES) pattern indicates that `HWnode` needs to verify system accesses thus to prevent malicious users, hence it affects at most its security level (i.e., `SEC`) and all performance indices related to that specific model element (i.e., `U`, `QL`, and `WT`). In all the traceability rules we do not use the *affectExactly* construct, since we assume that model elements involved in security properties may affect other result elements. In this way we do not restrict model elements in their involvement to further extra-functional properties.

Figure 5 reports the weighted footprint graph, after introducing performance and security (anti)pattern-based rules. For figure readability, it is built considering: (i) CPS and TR performance antipattern-based rules (see Listing 3); (ii) AUTH and SES security pattern-based rules (see Listing 4). The inclusion of these performance antipatterns and security patterns generates nine additional traces (bold lines) and three no-traces (dashed lines) between MEs and REs. In fact, the weighted footprint graph from input (see Figure 3) shows 0 traces (T), 12 no-traces (N), and 18 uncertain traces (TN), whereas the weighted footprint graph, after (anti)pattern-based rules (see Figure 5), shows 9 traces (T), 15 no-traces (N), and 6 uncertain traces (TN). Note that the newly generated traceability information triggers the modification of weights associated to model elements. Figure 6 shows the weighted footprint graph that is obtained after antipattern-based rules aug-

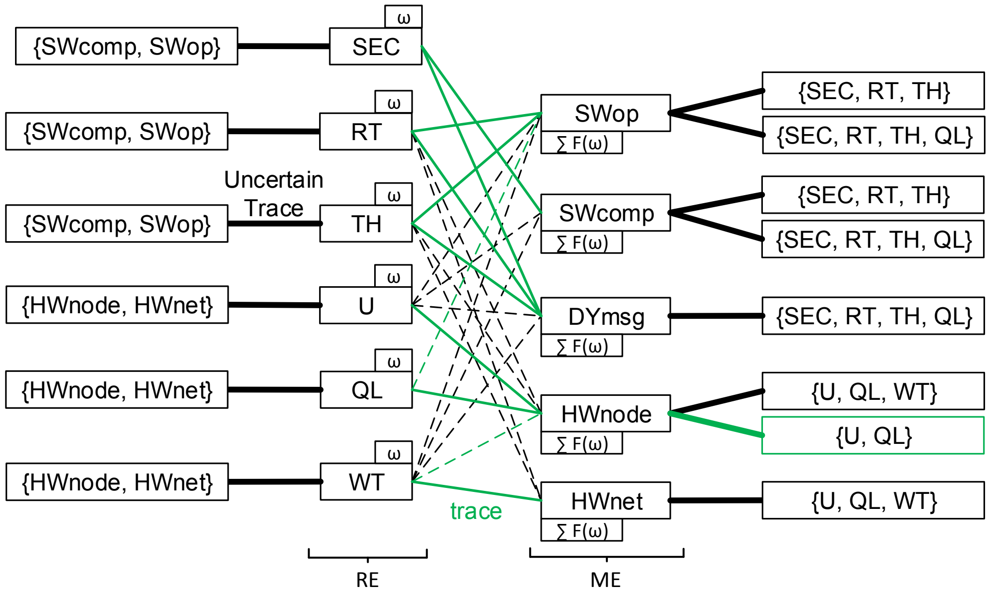


Figure 5: Weighted Footprint Graph, after (Anti)pattern-based Rules.

mented with weight and guilt estimates reported in Listing 2, where weights of RE nodes are modified accordingly. For example, the `SWcomp` node is here weighted by the following calculation: $0.5 * 0.42 + 0.33 * 1 = 0.54$, in fact this node is involved in the (`SWcomp`, `SEC`) trace. Further nodes are weighted: the (`SWop`, `RT`) trace leads to assign the weight equal to 0.5 to the `SWop` node; the (`DYmsg`, `RT`) and (`DYmsg`, `SEC`) traces produce a weight equal to $0.5 + 0.33 = 0.83$ for the `DYmsg` node.

Note that the specification of performance and security (anti)pattern-based rules may also keep unchanged or even increase the overall uncertainty of the system since no logical consequences can be deduced while considering the addition of these further constructs.

5. Validation

Our approach enables the specification of traceability between architectural model elements and extra-functional results. In the following we report the experimental results on three different case studies, i.e., two academic research projects (i.e., ECCO and DesignSpace) and one production system (i.e., PermissionSystem). All the case studies share the same experimental setting, as discussed hereafter.

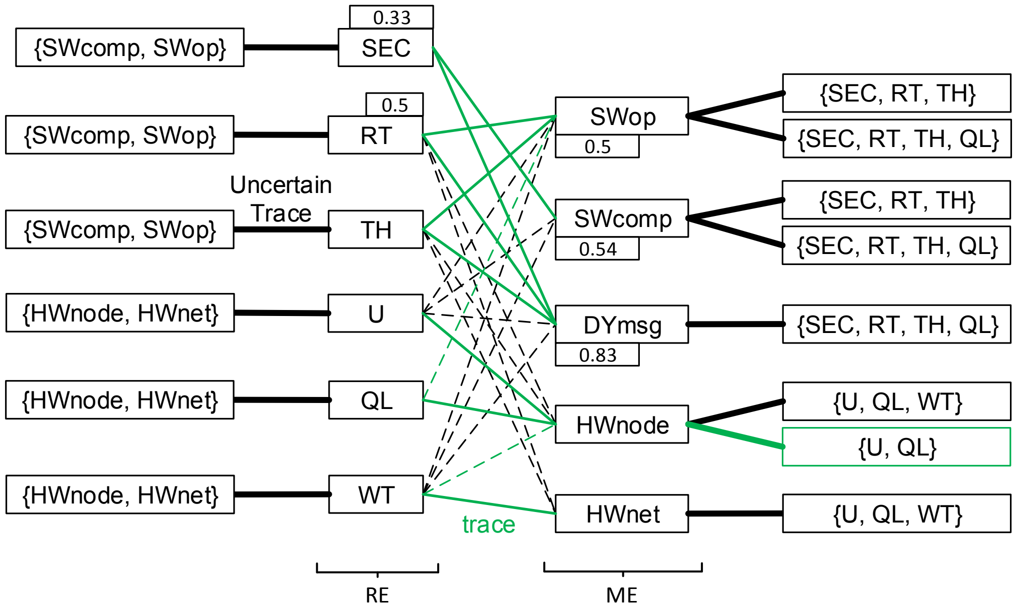


Figure 6: Weighted Footprint Graph, after (Anti)pattern-based Rules, weight and guilt estimates.

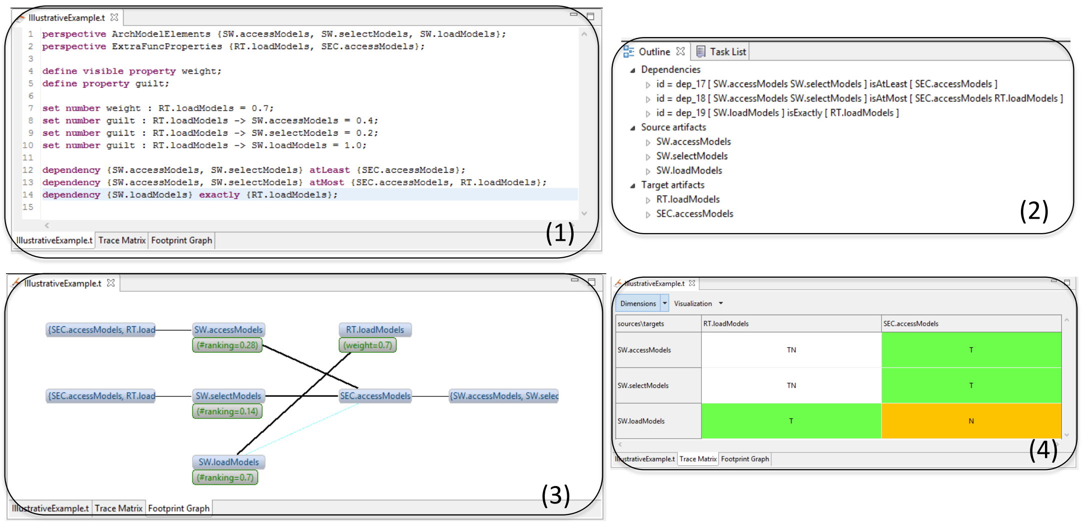
5.1. Experimental Setting

Our approach is implemented in a tool called SoEfTraceAnalyzer [11] that is built on the Eclipse platform to improve its usability. Figure 7 shows the screenshot of the tool used to model our DesignSpace illustrative example (see Section 2). It highlights four different input views:

(1) the textual input view includes the specification of perspectives along with its constituent elements, and dependencies (i.e., *affectAtLeast*, *affectAtMost*, and *affectAtMost*) among the elements that are regulated with our language for expressing traceability;

(2) the outline view lists source (i.e., *SW.accessModels*, *SW.selectModels*, and *SW.loadModels*) and target (i.e., *RT.loadModels*, and *SEC.accessModels*) artifacts. Note that target artifacts match the R_2 and R_3 extra-functional properties reported in Table 1b as performance and security requirements, respectively;

(3) the footprint graph view depicts the source and target artifacts in the middle of the graph as nodes, dependencies are reported as arcs where bold lines denote traces and dashed lines indicate no-traces;



```
perspective ArchModelElements {SW.accessModels, SW.selectModels, SW.loadModels};
perspective ExtraFuncProperties {RT.loadModels, SEC.accessModels};

define visible property weight;
define property guilt;

set number weight : RT.loadModels = 0.7;
set number guilt : RT.loadModels -> SW.accessModels = 0.4;
set number guilt : RT.loadModels -> SW.selectModels = 0.2;
set number guilt : RT.loadModels -> SW.loadModels = 1.0;

dependency {SW.accessModels, SW.selectModels} atLeast {SEC.accessModels};
dependency {SW.accessModels, SW.selectModels} atMost {SEC.accessModels, RT.loadModels};
dependency {SW.loadModels} exactly {RT.loadModels};
```

```
Dependencies
    id = dep_17 [ SW.accessModels SW.selectModels ] isAtLeast [ SEC.accessModels ]
    id = dep_18 [ SW.accessModels SW.selectModels ] isAtMost [ SEC.accessModels RT.loadModels ]
    id = dep_19 [ SW.loadModels ] isExactly [ RT.loadModels ]
Source artifacts
    SW.accessModels
    SW.selectModels
    SW.loadModels
Target artifacts
    RT.loadModels
    SEC.accessModels
```

sources\targets	RT.loadModels	SEC.accessModels
SW.accessModels	TN	T
SW.selectModels	TN	T
SW.loadModels	T	N

Figure 7: Screenshot of the SoEfTraceAnalyzer tool.

(4) the trace matrix view reports source and target artifacts; an entry (i, j) of the matrix indicates the relationship between the i-th source elements vs the j-th target element, where labels T, N, TN mean 'trace', 'no-trace', and 'uncertain trace', respectively.

Our experimentation is conducted by using the input provided by engineers, and adding further knowledge about patterns and antipatterns. Specifically, security patterns are explicitly stated in the system specification, whereas detection of performance antipatterns is performed by means of our rule-based engine [27]. Both security patterns and performance antipatterns are translated with our traceability language and may contribute to reduce uncertainty. As anticipated in Section 4.1.2, two further properties can be defined for this goal, i.e., weight and guilt estimates that allow to quantify violations of extra-functional results and how much architectural elements contribute to requirements' violations, respectively.

To investigate the effectiveness of traceability links, provided as output by our tool, we conducted the following experimentation. If a performance/security flaw is identified we apply a set of refactoring actions (e.g., substitute a software component with a faster/lower one, re-deploy a certain software component) to quantify the impact of such heuristics on performance/security results. Specifically, without traces we verify the impact of the refactoring by modifying all architectural elements contributing to that performance/security flaw one-by-one. On the contrary, with traces we restrict the refactoring to the subset of model elements indicated by the traceability links. This leads to quantify the effectiveness of our output graph as support to software designers since it provides guidelines to modify specific architectural elements with the goal to fulfill extra-functional requirements.

5.2. Selection of extra-functional properties

As stated in Section 1, our approach is not limited, in principle, to specific extra-functional properties. However, to investigate the effectiveness of traceability links we decided to focus on performance and security since this latter property has a "direct" overhead on the former. Besides this, performance and security trade-offs have been considered in our previous work [30, 31] where we introduced a framework to support the analysis of performance degradation due to the introduction of different security mechanisms. Such framework is able to quantify the system performance degradation while varying the adopted security strategies. Hence, we used this framework to translate (annotated) software architectural models, enriched with security annotations, to obtain a performance model, i.e., a Queueing Network (QN) [15], that embeds the stated security requirements.

As drawback, QN models only provide performance results, and they do not allow to estimate the achieved security level. In fact, it is very challenging to estimate the security of a software component, service, a hardware device, a firewall, etc. To this end, we leave to engineers the decision of associating architectural model elements with pre-defined security levels, i.e., low, medium, and high. To increase/decrease such levels we expect that the corresponding operation has a larger/lower demand in terms of computational resources and we reflect this change into the performance model.

The performance analysis has been conducted by solving the QN model with two well-assessed techniques [18], i.e., mean value analysis (MVA) and simulation. Both solution techniques are supported by Java Modeling Tools (JMT) [32].

5.3. Case Study 1: ECCO

ECCO is an academic research project that aims to reuse existing software and customize it to meet customer-specific needs [33, 34]. The name stands for Extraction and Composition for Clone-and-Own, and it is a framework enabling the automated systematic reuse of existing arbitrary development artifacts. The workflow consists of three main operational steps: (i) *extraction* that locates and extracts desired reusable artifacts (e.g., code) from existing variants; (ii) *composition* where the selected artifacts are pasted/edited to create the new product; (iii) *completion* where the new product variant is adapted to account for needs that did not exist previously.

Figure 8 reports an excerpt of the ECCO software architectural model. It is constituted by 17 software components (i.e., SC_i, with $i \in [1, \ldots, 17]$) among which 2 components have been intentionally added to model the security patterns that are $AUTH$ and $RBAC$. Software components are labelled with the stereotype *artifact* since they are deployed on five different hardware machines labelled with the stereotype *GaExecHost* meaning the execution hosts. Hardware platforms communicate through different networks, i.e., wide and local area networks, labelled with the stereotype *GaCommHost* that indicates communication hosts.

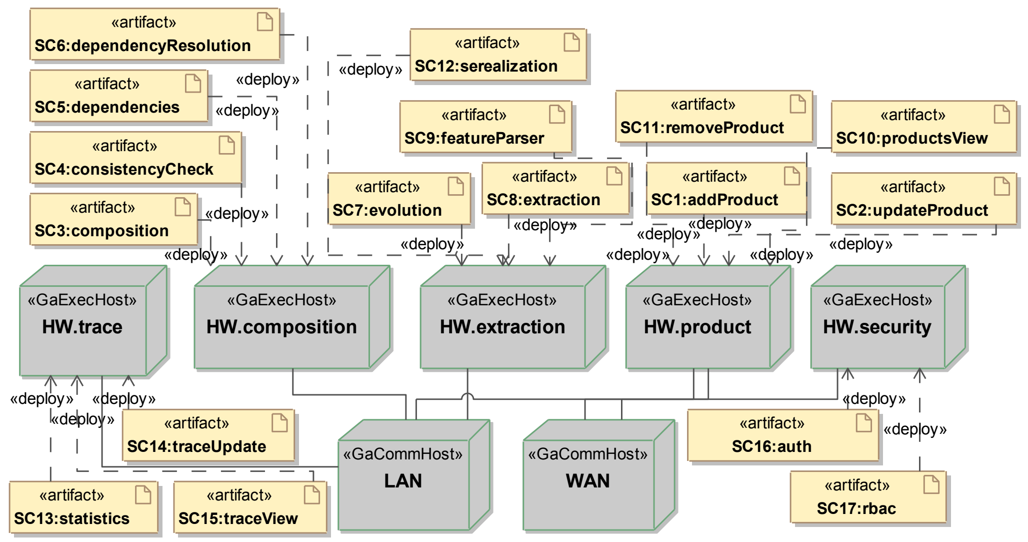

«artifact» SC6:dependencyResolution
«artifact» SC5:dependencies
«artifact» SC4:consistencyCheck
«artifact» SC3:composition
«artifact» SC12:serealization
«artifact» SC9:featureParser
«artifact» SC11:removeProduct
«artifact» SC10:productsView
«artifact» SC7:evolution
«artifact» SC8:extraction
«artifact» SC1:addProduct
«artifact» SC2:updateProduct
«deploy»
«GaExecHost» HW.trace
«GaExecHost» HW.composition
«GaExecHost» HW.extraction
«GaExecHost» HW.product
«GaExecHost» HW.security
«artifact» SC14:traceUpdate
«artifact» SC13:statistics
«artifact» SC15:traceView
«GaCommHost» LAN
«GaCommHost» WAN
«artifact» SC16:auth
«artifact» SC17:rbac

Figure 8: An excerpt of the ECCO software architectural model.

The system workload is assumed to be closed with a population of 1500 users and an average thinking time of 1 second. The performance requirements that we consider, under the stated workload, are: (i) RT: the average response time of the *composition* service has to be less than 5 ms; (ii) TH: the throughput of the *extraction* service has to be greater than 0.3 requests/ms. Security requirements indicate that there is a critical service (i.e., *addProduct*) that require a *high* security level (SL).

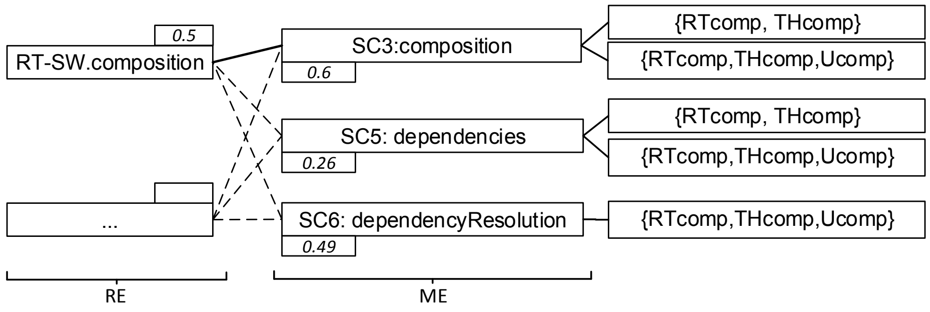


Figure 9: An excerpt of the ECCO Weighted Footprint Graph after (anti)pattern-based rules.

While solving the QN built for ECCO we found that all the requirements are not fulfilled. In particular, the average response time (RT) of the *composition* service has been estimated to be 10.09 ms, the throughput of the *extraction* service has been evaluated to be 0.16 requests/ms. Also the security requirement is not fulfilled since the *addProduct* service is annotated in the software architectural model with the *medium* security level.

Performance antipatterns have been detected by means of our rule-based engine [27], and we found the following two instances: (i) The Ramp (TR) antipattern, i.e., the response time of the *composition* service is quite unstable along simulation time; (ii) Pipe & Filter (P&F) antipattern, i.e., the throughput of the *extraction* service suffers from the *consistencyCheck* and *dependencyResolution* slow filters.

Figure 9 reports an excerpt of the ECCO Weighted Footprint Graph after (anti)pattern-based rules, where we can notice that the response time (RT) of the *composition* service shows traces with SC_3, SC_5, and SC_6 software components. In particular, the weight reported on the $RTcomposition$ result element represents the observed requirement violation (0.5), i.e., the overhead of the predicted value (10.09 ms) with respect to the requirement (5 ms). The guiltness values associated to the software components indicate that they contribute to that specific performance flaw at a certain extent, specifically with the following estimates: SC_3 (0.6), SC_5 (0.26), and SC_6 (0.49).

Figure 10 depicts the response time of the *composition* service, where the horizontal bold line indicates the performance requirement. The leftmost side of the figure reports the initial system and we can see that the service is provided in 10.09 ms. The middle part of the figure reports the response times observed while refactoring the software components one-by-one, without the support of traces. In this case software components are replaced with ones two times faster to understand at which extent response times may improve. In the figure we can notice that there are few results showing a reasonable improvement whereas all other predicted values are very similar to the initial system. In particular, the refactorings associated to the software components suggested by our weighted footprint graph (see Figure 9) show a certain improvement for the software system, in fact modifying SC_3, SC_5 and SC_6 we get 6.48 ms, 8.31 ms, and 7.43 ms, respectively. It is worth to notice that guilt estimates are also reflected in the experimental results: SC_3 shows the highest guilt value (0.6, see Figure 9) and its refactoring actually improves the response time of the *composition* service (from 10.09 ms to 6.48 ms), whereas SC_5 shows the lowest guilt value (0.26, see Figure 9) and the performance improvement is lower (from 10.09 ms to 8.41 ms). The rightmost side of the figure shows the response time obtained while jointly refactoring SC_3, SC_5, and SC_6 software components. This leads to a response time equal to 2.81 ms, thus allowing the fulfillment of the stated requirement.

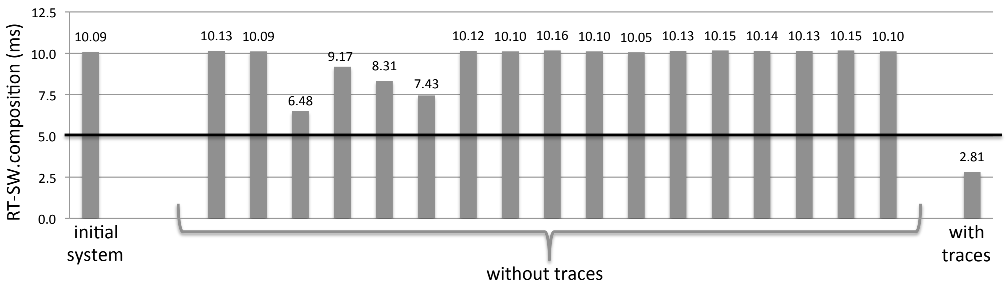


Figure 10: Response time of the *composition* service.

Figure 11 depicts the throughput of the *extraction* service. Similarly to Figure 10, the horizontal bold line indicates the performance requirement. The leftmost side of the figure reports the initial system and we can see that 0.16 reqs/ms are served. The middle part of the figure reports the throughputs observed while modifying the software components one-by-one, without the support of traces. Also in this case software components are replaced with ones two times faster to understand at which extent throughputs may improve. We can notice that the best improvement makes the system to serve 0.25 reqs/ms. The rightmost side of the figure shows the throughput obtained while using the traces, i.e., the SC_4, SC_6, SC_7, and SC_8 software components are jointly refactored. This leads to a throughput equal to 0.33 reqs/ms, thus allowing the fulfillment of the stated requirement.

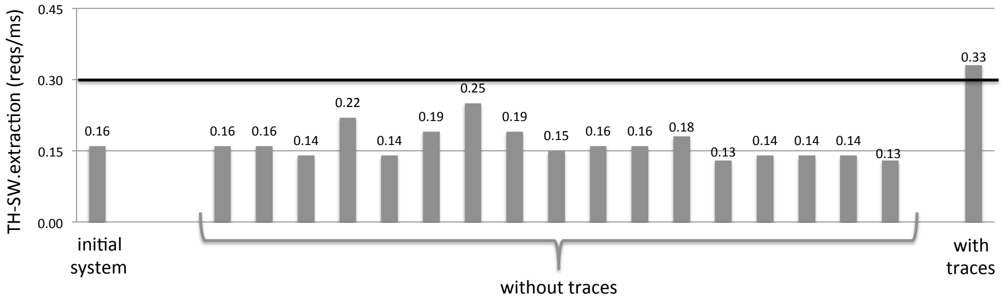


Figure 11: Throughput of the *extraction* service.

To increase the security level (SL) of the *addProduct* service from *medium* to *high* we modify the ECCO system by replacing the software component providing the associated security mechanism (i.e., SC_{16}) with one component two times slower to understand at which extent performance may degrade. In this case traceability information is used to refactor all the other software components contributing to that service that are not providing security strategies (i.e., SC_2, SC_{10}). These last components are replaced with ones two times faster to quantify their impact on the overall service provisioning.

Extra-Functional Requirements	Performance Analysis			Improve-ment (%)
	initial system	without traces	with traces	
RT(*SW.composition*) $\leq$ 5 ms	10.09 ms	6.48 ms	2.81 ms	56.6
TH(*SW.extraction*) $\geq$ 0.3 reqs/ms	0.16 reqs/ms	0.25 reqs/ms	0.33 reqs/ms	24.2
SL(*addProduct*) $\equiv$ high RT(*addProduct*)	medium 2.06 ms	high 2.95 ms	high 2.47 ms	16.27

Table 1: Performance improvement gained with the model-to-results traces in the ECCO case study.

Table 1 compares the experimental results with and without the traceability information. The first column reports the stated requirements, the second column shows the results from the analysis of the initial system, the third column reports the results without traces, and the fourth column shows the results obtained while using the traceability information. In the last column of the table we report the percentage of improvement gained with traceability links vs without such information. For example, in the first row of the table we can see that the *RT* of the *composition* service improves from 10.09 ms to 6.48 ms (without traces) up to 2.81 ms (with traces). Hence, with traceability links, an improvement of 56.6% is achieved. Last row of table reports the security requirement and the refactoring enables to increase the security level from *medium* to *high*. In this case the *RT* of the *addProduct* service degrades from 2.06 ms to 2.95 ms, hence traceability links lead to get 2.47 ms, i.e., 16.27% of improvement.

5.4. Case Study 2: DesignSpace

DesignSpace is an academic research project [12] that has been illustrated in Section 2. It implements two security patterns. First, the *Limited View* (LV) allows to restrict the visibility of artifacts under development to a restricted number of users belonging to some ad-hoc groups. Second, the *Role-based Access Control* (RBAC) enables permissions of adding, modifying, and deleting artifacts on the basis of user roles, such as programmers, project managers, etc.

We omit the graphical representation of the software architectural model, however it includes eighteen software components ($SC_1, \ldots, SC_{18}$) and one hardware device (*HW.propertyManagement*).

The system workload is assumed to be closed with a population of 1800 users and an average thinking time of 1 second. The performance requirements that we consider, under the stated workload, are: (i) TH: the throughput of the *createArtifact* service has to be greater than 0.5 requests/ms; (ii) U: the utilization of the *HW.propertyManagement* hardware device has to be lower than 70%. Security requirements indicate that there is a critical service (i.e., *commit*) that require a *medium* security level (SL).

While solving the QN built for the DesignSpace we found that all the performance requirements are not fulfilled. In particular, the average throughput (*TH*) of the *createArtifact* service has been estimated to be 0.1 reqs/ms, and the *HW.propertyManagement* hardware device has an utilization equal to 81%. Also the security requirement is not fulfilled since the *commit* service is annotated with *low* security level.

Detection of performance antipatterns provides as output the following three instances: (i) Blob antipattern, i.e., the *getWorkspace* software component is managing most of the application's business logics; (ii) Extensive Processing (EP) antipattern, i.e., the demand of the *showArtifactDetails* service is much larger than *createArtifact* service; (iii) Empty Semi Trucks (EST) antipattern, i.e., the software components *startValidation* and *showValidation* communicate with a large number of messages of low size.

Figure 12 depicts the throughput of the *createArtifact* service, where the horizontal bold line indicates the performance requirement. The leftmost side of the figure reports the initial system and we can see that 0.1 reqs/ms are served. The middle part of the figure reports the throughputs observed while modifying the software components one-by-one, without the support of traces. In this case software components are replaced with ones ten times faster to understand at which extent performance may improve. We report all values in the figure and we can notice that the best improvement makes the system to serve 0.38 reqs/ms. The rightmost side of the figure shows the throughput obtained while using the traces, i.e., the SC_7, SC_{10}, SC_{12}, and SC_{13} software components are jointly refactored. This leads to a throughput equal to 0.52 reqs/ms, thus allowing the fulfillment of the stated requirement.

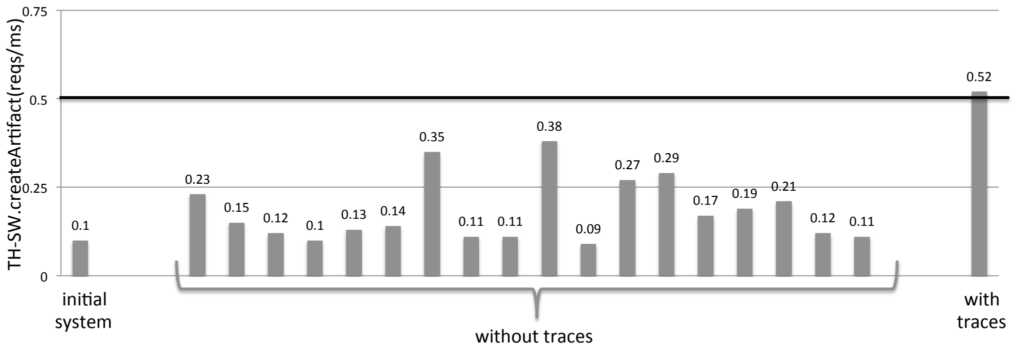


Figure 12: Throughput of the *createArtifact* service.

Figure 13 depicts the utilization of the *propertyManagement* hardware device, where the horizontal bold line indicates the performance requirement. The leftmost side of the figure reports the initial system and we can see that the utilization is 0.81 %. The middle part of the figure reports the utilization values while modifying the software components one-by-one, without the support of traces. In this case software components are replaced with ones ten times faster to understand at which extent utilization may improve. We can see in the figure that the best value is achieved while refactoring the SC_7 component that leads to an utilization of 0.71 %. The rightmost side of the figure shows the utilization obtained while using the traces, i.e., the SC_7 and

SC_{10} software components are jointly refactored. This leads to an utilization equal to 0.61%, thus allowing the fulfillment of the stated requirement.

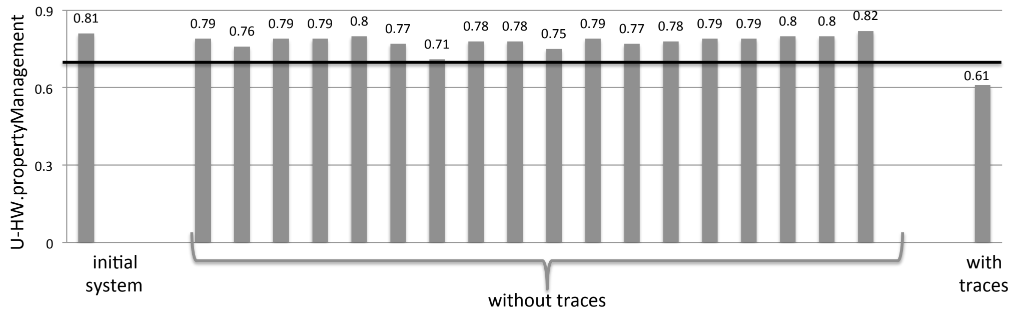


Figure 13: Utilization of the *propertyManagement* hardware device.

To increase the security level (SL) of the *commit* service from *low* to *medium* we modify the DesignSpace system by replacing the software component providing the associated security mechanism (i.e., SC_6) with one two times slower to understand at which extent performance may degrade. In this case traceability information is used to refactor all the other software components contributing to that service that are not providing security strategies (i.e., SC_5, SC_7, SC_8). These last components are replaced with ones two times faster to quantify their impact on the overall service provisioning.

Similarly to Table 1, Table 2 summarizes the experimental results with and without the traceability information. For example, in the first row of the table we can see that the TH of the *createArtifact* service improves from 0.1 reqs/ms to 0.38 reqs/ms (without traces) up to 0.52 reqs/ms (with traces). Last row of table reports the security requirement and the refactoring increases the security level from *low* to *medium*. In this case the RT of the *commit* service inevitably degrades, in particular it goes from 0.82 ms to 1.63 ms. Traceability information leads to get 1.46 ms, i.e., 9.81% of improvement. We also report the percentage of improvement while comparing the results with and without the traceability information, and we can notice an improvement up to 26.92% among all requirements.

5.5. Case Study 3: PermissionSystem

PermissionSystem is an industrial system developed to manage security permissions in a content management system. It is designed to meet multiple security patterns on content and users at the same time. In its actual version

Extra-Functional Requirements	Performance Analysis			Improve-ment (%)
	initial system	without traces	with traces	
TH($SW.createArtifact$) $\geq$ 0.5 reqs/ms	0.1 reqs/ms	0.38 reqs/ms	0.52 reqs/ms	26.92
U($HW.propertyManagement$) $\leq$ 0.7	0.81	0.71	0.61	14.08
SL($commit$) $\equiv$ medium RT($commit$)	low 0.82 ms	medium 1.63 ms	medium 1.46 ms	 9.81

Table 2: Performance improvement gained with the model-to-results traces in the DesignSpace case study.

the PermissionSystem implements three security patterns. First, it provides direct permissions (authorization pattern) assigned to content entities and/or users. For instance the administrator of a software product may mark an entity as visible for all users. In such case the entity will be visible for every user regardless of his/her account in the system. The administrator may also assign the permission to a user account, allowing it to view all entities under a given structure. Second, the PermissionSystem implements the session security pattern, which is mostly needed to store permissions assigned to user accounts at runtime. This is also a performance optimization as it allows for faster evaluation of user permissions. Third, a role based access control (RBAC) pattern is implemented to support more sophisticated permissions. In this pattern, a mapping between user accounts groups and their respective permissions are created. This feature allows the integration of PermissionSystem with other heterogeneous systems (e.g., active directory).

We omit the graphical representation of the software architectural model, however it includes eight software components ($SC_1, \ldots, SC_8$) and two hardware devices (*HW.permissions*, *HW.accesses*).

The system workload is assumed to be closed with a population of 80 users and an average thinking time of 1 second. The performance requirements that we consider, under the stated workload, are: (i) *RT*: the average response time of the *permissionOnEntities* service has to be less than 5 ms; (ii) *U*: the utilization of the *HW.permissions* hardware device has to be lower than 90%. Security requirements indicate that there are some critical services (i.e., *accessPermission* and *checkPermission*) that require a *high* security level (*SL*).

While solving the QN built for the PermissionSystem we found that all the performance requirements are not fulfilled. In particular, the average response time (RT) of the *permissionOnEntities* service has been estimated to be 15.72 ms, and the *HW.permissions* hardware device has an utilization equal to 100%. Also the security requirements are not fulfilled since the *checkPermission* is annotated with *medium* security level.

Detection of performance antipatterns provides as output the following two instances: (i) Concurrent Processing System (CPS) antipattern, i.e., *HW.permissions* hardware device is over-utilized; (ii) One-Lane Bridge (OLB) antipattern, i.e., the response time of the *permissionOnEntities* service suffers from the low multi-threading enabled in the database while verifying permissions.

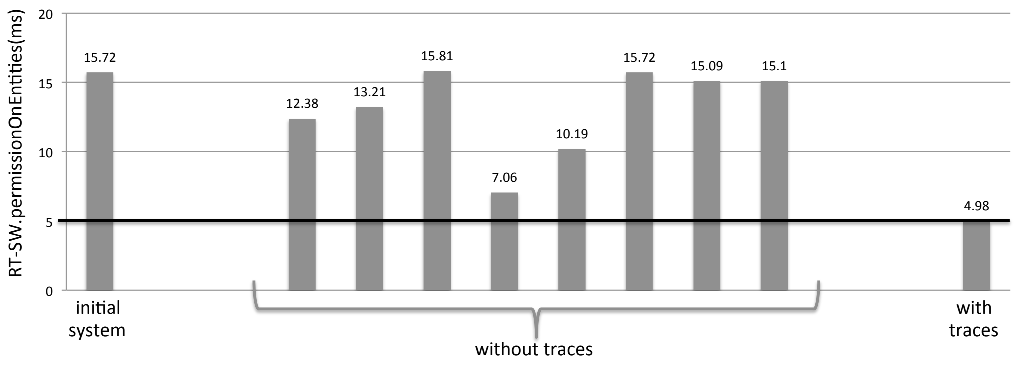


Figure 14: Response time of the *permissionOnEntities* service.

Figure 14 depicts the response time of the *permissionOnEntities* service, where the horizontal bold line indicates the performance requirement. The leftmost side of the figure reports the initial system and we can see that the service is provided in 15.72 ms. The middle part of the figure reports the RT observed while modifying the software components one-by-one, without the support of traces. In this case software components are replaced with ones ten times faster to understand at which extent performance may improve. The best value is obtained while refactoring the SC_4 software component, in fact the response time slows down to 7.06 ms. The rightmost side of the figure shows the response time obtained while using the traces, i.e., the SC_4 and SC_5 software components are jointly refactored. This leads to a response time equal to 4.98 ms, thus allowing the fulfillment of the stated requirement.

Figure 15 depicts the utilization of the two hardware devices (i.e., *HW.permissions*, *HW.accesses*), where the horizontal bold line indicates the performance requirement. The leftmost side of the figure reports the initial system and we can see that the utilization of *HW.permissions* device is 100%, whereas the utilization of *HW.accesses* device is 39%. The middle part of the figure reports the utilization values while redeploying the software components one-by-one, without the support of traces. We can see in the figure that the best value is achieved while moving the SC_8 component that leads to an utilization of 26% for the *HW.accesses* device. The rightmost side of the figure shows the utilization obtained while using the traces, i.e., the SC_2, SC_5 and SC_8 software components are jointly redeployed from *HW.permissions* to *HW.accesses*. This leads to an utilization equal to 81% for *HW.permissions* device, but the hosting node shows an increasing utilization (from 39% to 84%). However, both devices fulfill the stated requirement.

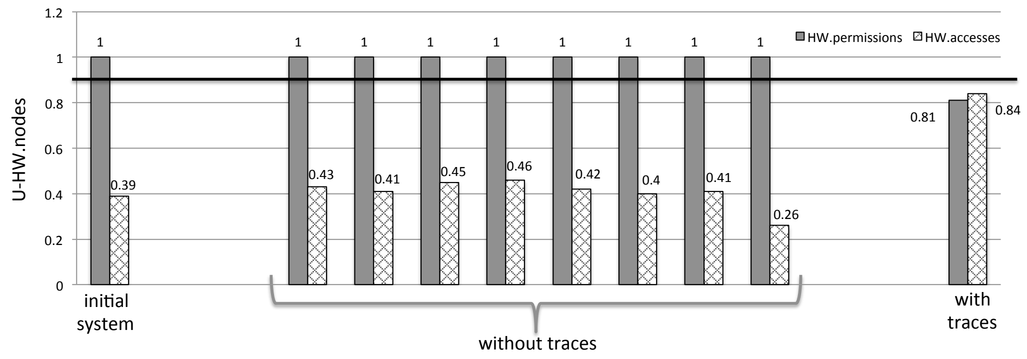


Figure 15: Utilization of *HW.permissions* and *HW.accesses* hardware devices.

To increase the security level (SL) of the *checkPermission* service from *medium* to *high* we modify the PermissionSystem by replacing the software component providing the associated security mechanism (i.e., SC_7) with one ten times slower to understand at which extent performance may degrade. In this case traceability information is used to refactor the software components contributing to that service that are not providing security strategies (i.e., SC_1, SC_2, SC_3). These last components are replaced with ones ten times faster to quantify their impact on the overall service provisioning.

Similarly to Table 2, Table 3 summarizes the experimental results with and without the traceability information. For example, in the first row of the table we can see that the RT of the *permissionOnEntities* service improves from 15.72 ms to 7.06 ms (without traces) up to 4.98 ms (with traces), i.e., 29.49% of improvement. Last row of table reports the security requirement and the refactoring enables the security level to increase from *medium* to *high*. In this case we report the RT of the *checkPermission* service that

Extra-Functional Requirements	Performance Analysis			Improve-ment (%)
	initial system	without traces	with traces	
RT(*permissionOnEntities*) $\leq$ 5 ms	15.72 ms	7.06 ms	4.98 ms	29.46
U(*HW.permissions*) $\leq$ 0.9	1.0	1.0	0.81	19
SL(*checkPermission*) $\equiv$ high	medium	high	high	
RT(*checkPermission*)	1.86 ms	3.45 ms	3.05 ms	11.59

Table 3: Performance improvement gained with the model-to-results traces in the PermissionSystem case study.

degrades from 1.86 ms to 3.45 ms. Traceability information indicates refactorings leading to 3.05 ms, i.e., 11.59% of improvement. While comparing the results with and without the traceability information, we can observe an improvement up to 29.46% among the three requirements.

5.6. Users feedback

To investigate the usefulness of our approach, we conducted an experiment with users to collect their feedback, with the goal to answer the following two research questions:

RQ_1: Do trace uncertainties for architectural models vs extra-functional results exist and are relevant in practice?

RQ_2: Do security patterns and performance antipatterns help in the reduction of uncertainty?

Our experiment was performed by contacting the 3 owners of the presented case studies, plus 9 PhD students involved in the Computer Science program at the Gran Sasso Science Institute (GSSI), Italy. All the PhD students had been exposed to software architecture modelling and extra-functional analysis topics in their courses. Hence, the subjects involved in the experiment were 12 users aware of the domain.

The outcome of our user study is that: 100% of the subjects confirmed that there are uncertainties while bridging architectural model elements with extra-functional results by answering the RQ_1 question positively, and this high percentage confirms our claim that uncertainties exist and are relevant in practice; 83% of the subjects expressed a positive opinion on the addition of patterns and antipatterns knowledge, however 2 users over 12 were skeptical for the RQ_2 question, and they provided the following motivations:

- patterns and antipatterns are application-dependent, i.e., their usefulness might be strongly related to the case study under analysis, hence they might not lead to a better interpretation of results in some cases;
- patterns and antipatterns are granularity-related, i.e., their usefulness is affected by the granularity used in the specification of architectural model elements and extra-functional results, hence if they are expressed on different levels of granularity they become useless.

We agree with these motivations and we think that, even if the usefulness of patterns and antipatterns cannot be always guaranteed, in our case studies their usage resulted to provide a consistent uncertainty reduction. To further investigate this point, we asked all users to provide their own traceability links for the three case studies under analysis, and we quantified their outputs by evaluating the average percentage of uncertainty reduction (see Table 4). Further discussion on this experimentation is reported in Section 5.7.

Besides this, we also asked for further comments on the approach and on the used tool, thus to understand the difficulties of users in the assigned tasks. One user pointed out that it could be useful to identify architectural elements and extra functional properties that share the same names and automatically produce their traceability links, leaving the opportunity to the user to modify or delete such links afterwards. Another user complained about the typing of the uncertainties, it may take too much time and it may be an error-prone task, i.e., a smarter code completion and a GUI could be helpful. Both these points represent our future work.

5.7. Afterthoughts

The experimentation conducted on three different case studies supports the idea of exploiting traceability information in the field of extra-functional analysis. We showed that with traces we are able to get a certain performance improvement across all the presented case studies. Specifically, our approach allows to derive quantitative evaluations of performance and security trade-offs, and it is suitable for decision making while refactoring software architectures. As feedback to software designers we are able to identify the root causes of performance/security flaws and to point out the most promising model elements for the refactoring process by means of traceability links.

Table 4 provides an overview of the presented case studies, where rows report some system features, and columns list the three analyzed systems:

two academic research projects (i.e., ECCO and DesignSpace) and one production system (i.e., PermissionSystem). For each considered case study, in the upper part of the table we report: (i) the number of architectural model elements; (ii) the number of extra-functional properties; (iii) the size of trace matrix that basically represents $\#rows * \#columns$ entries. In the lower part of the table we report: (i) detected performance antipatterns; (ii) specified security patterns; (iii) the uncertainty reduction is quantified in terms of number of traces (T), no-traces (N), and their sum (T+N) that we have in the transition matrix before and after (anti)patterns knowledge. Uncertainty reduction is reported by evaluating the traceability links provided by the owners of the three case studies, and also calculating the average of the traceability links specified by all the other participants involved in our user study. These average estimations inevitably result in decimal numbers for both the number of traces and no-traces.

		ECCO	DesignSpace	PermissionSystem
	ArchModel Elements	43	30	16
	ExtraFunc Properties	70	94	58
	Size of TM	3010	2820	928
	Performance Antipatterns	TR, P&F	BLOB, EP, EST	CPS, OLB
	Security Patterns	AUTH, RBAC	LV, RBAC	AUTH, SES, RBAC
Uncertainty reduction	owners	T: 48 → 60 N: 713 → 781 T+N: 761 → 841	T: 72 → 87 N: 1941 → 1941 T+N: 2013 → 2028	T: 27 → 44 N: 252 → 420 T+N: 279 → 464
	other participants	T: 29.8 → 36.8 N: 133.9 → 185.0 T+N: 163.7 → 221.8	T: 21.8 → 31.1 N: 57.9 → 57.9 T+N: 79.7 → 89	T: 24.4 → 34.1 N: 46.3 → 208.8 T+N: 70.7 → 242.9

Table 4: Overview of the presented case studies.

For example, in the last column of the table, we can see that for the PermissionSystem we have 16 architectural model elements, 58 extra-functional properties obtaining a matrix $16 * 58 = 928$ entries. While adding performance antipatterns (i.e., CPS and OLB) and security patterns (i.e., AUTH, SES, and RBAC) traces from the owner of the case study go from 27 to 44, whereas no-traces go from 252 to 420. Both information allowed to reduce the initial uncertainty ($928 - 279 = 649$ TN) of a considerable amount

$(928 - 464 = 464$ TN), i.e., 28.5% of uncertainty reduction. From the other participants we found that traces go from an average value of 24.4 to 34.1, whereas no-traces go from an average value of 46.3 to 208.8. Both information allowed to reduce the initial uncertainty $(928 - 70.7 = 857.3$ TN) of a substantial amount $(928 - 242.9 = 685.1$ TN), i.e., 20.1% of uncertainty reduction. It is worth to remark that even if the absolute values of traces and no-traces from the owners is higher than the ones provided by the other participants, our experimentation provides evidence that (anti)patterns are helpful for the uncertainty reduction.

As stated in Section 4.2, the specification of performance and security (anti)pattern-based rules does not guarantee to decrease the overall uncertainty of the system. In fact, in Table 4 we can notice that the DesignSpace case study shows an unchanged number of no-traces (i.e., 1941), whereas traces rather increase (from 72 to 87) while considering the specification of traceability links from the owners of the case study. Interestingly, looking at the average values from the other participants we also found an unchanged number of no-traces (i.e., 57.9). Even if the absolute value is much lower in this last case, the experimentation shows that (anti)patterns were not useful for the understanding of no-traces in this case study. In fact, for the DesignSpace case study the initial uncertainty $(2820 - 2013 = 807$ TN) is reduced of a small amount $(2820 - 2028 = 792$ TN), i.e., 1.9% of uncertainty reduction. Indeed uncertainty reduction strongly depends from the initial input provided by software engineers, however in our experimentation across three different case studies we found that most likely (anti)pattern-based rules lead to reduce the initial uncertainty.

As stated in Section 5.6, the usefulness of our approach has been validated with a user study involving the 3 owners of the case studies plus 9 external users. We found that 100% of the subjects confirmed that there are uncertainties while bridging architectural model elements with extra-functional results, and 83% of the subjects expressed a positive opinion on the addition of patterns and antipatterns knowledge. These high percentage values support our claim that uncertainties are commonly encountered by software engineers and our technique is helpful to support them in understanding the root causes of extra-functional flaws.

The scalability of our approach for handling traceability links has been evaluated in our previous work [5]. As the automated part of this work is in essence an application of our previous approach, we assume that the same scalability evaluation does apply for this work either. In [5] we assessed the scalability of our approach by measuring the ratio between the size of uncertainty input and the time required to solve it. As input we used three case study systems (i.e., Gantt, JHotDraw, and ReactOS Explorer) and we automatically generated 597 possible inputs of different sizes and complexity. After running our approach against all these inputs, we measured the time required to solve the uncertainty, and each of the 597 possible inputs was resolved in less than one second. More details on the scalability evaluation are reported in the evaluation section 7.2 from [5].

In this paper, the scalability evaluation is conducted on tree case studies (i.e., ECCO, DesignSpace, and PermissionSystem) of different (i) sizes, in fact the traceability matrix varies from 928 to 3010 entries, and (ii) complexity as the sum of traces and no-traces varies from 279 to 2028, as shown in Table 4. We measured the time required to solve the uncertainty for the provided inputs and it is less than one second with all the different inputs. Practically we never noticed the computation time as the tool runs almost instantly when new input is provided.

Summarizing, the proposed technique and toolset is aimed to improve the ability of software engineers in the identification of critical architectural model elements and their refactorings. Differently from design space exploration approaches [35, 36, 37] that look for optimal trade-offs by evaluating all feasible architectural alternatives with the risk that the design space may be huge and its exploration may be time-consuming, our objective is to limit the number of architectural alternatives and to quickly converge towards a system configuration suitable to overcome extra-functional flaws. As drawback, our approach builds upon heuristic evaluations (i.e., patterns and antipatterns) hence extra-functional improvements are not guaranteed.

6. Threats to validity

Besides inheriting all limitations of the underlying software quality engineering and model-driven traceability techniques [38, 39], our approach exhibits the following threats to validity.

Correctness: input is given by the engineer that defines uncertainty constructs to the level of detail she or he is comfortable with. This means that not every input combination is valid and it becomes increasingly unlikely that the input remains consistent, especially if the input is provided by different engineers. An important aspect of future work is to provide correctness checks based on the consistency of the input, in fact consistency does not imply correctness. We can identify the input that is responsible for incorrectness and granularity problems, and provide support to engineers for resolving the detected issues.

Granularity: it is difficult to establish at what level of granularity traces between model and results should be generated. Extra-functional properties can be estimated at different levels of granularity, e.g. the response time performance index or the security level can be evaluated at the level of a cpu device, or at the level of a service that spans on different devices. Then, the engineer has the choice to establish traceability between the model elements and it is unrealistic to keep under control all performance and security properties at all levels of abstraction.

Selection of extra-functional properties: our current experimentation is focused on performance and security flaws, but many other extra-functional properties can be tackled as well. The rationale of selecting these two is that there exists a trade-off relationship among them: the raising of the security level implies a performance degradation that can be mitigated with model-to-results traces. In the near future we plan to integrate larger set of extra-functional properties, such as reliability, along with other methods, such as fault-tree analysis [16], to derive further extra-functional results (e.g., mean time to failure, mean time to repair) and deeply investigate the traceability benefits in this domain.

Complexity of architectural refactorings: to quantify the effectiveness of model-to-results traces we applied a set of refactoring actions (e.g., substitute a software component with another one that is x times faster/lower, re-deploy a certain software component) to the subset of model elements identified by traceability links. These refactorings are used for arguments sake to explore trade-offs and to demonstrate the usefulness of the weighted foot print graph, in fact we found that highly weighted architectural elements are the ones that actually contribute to higher performance benefits. However, such refactorings do not guarantee performance improvements a priori, because the entire process is based on heuristic evaluations. In fact, refactoring of architectural models is a very complex process [40], and it may also include the addition and deletion of other model elements that affect our footprint graph in its structure. This last point opens an interesting direction of research that we aim to investigate in the near future.

Complexity of security properties: it is very challenging to target security concerns because different types of attacks may occur and a single compromise can cause system failure. For sake of illustration, in our experimentation we considered pre-defined security levels (i.e., low, medium, and high), and the increase/decrease of such levels is regulated by larger/lower demand of computational resources, thus to explore security vs performance trade-offs. However, we plan to enable interoperability among extra-functional results, e.g., the occurrence of security flaws in architectural elements may lead to reset the performance results traced by such elements, thus to strengthen the security-related issues and explicitly include system reliability in the set of considered extra-functional results.

Specification of patterns and antipatterns: to reduce model-to-results uncertainty we use specific structures for the specification of performance antipatterns and security patterns, and these structures strictly conform to our interpretation of the literature [17, 9]. Indeed several other feasible interpretations of (anti)patterns can be provided due to their wide variety of implementation variants, which can lead to higher/lower accuracy. This unavoidable gap is an open issue, and requires a wider investigation to consolidate the (anti)patterns' specification in this domain.

Sufficiency of patterns and antipatterns: to build model-to-results traces we exploit performance antipatterns and security patterns since they are recognized to provide solid solutions to known and recurrent problems [41]. However, due to the complexity of real world systems their usage may not be sufficient for the detection of extra-functional problems. As future work, we plan to investigate further methodologies [42, 43] to catch extra-functional issues and integrate their output in our specification.

Uncertainty reduction: the addition of security patterns and performance antipatterns does not guarantee the uncertainty reduction a priori. As future work, we plan to integrate other approaches to derive model-to-results traceability links. For example, to achieve performance goals we can consider bottleneck analysis [44] and model optimization methods [35] to improve the uncertainty reduction.

Simulation accuracy: in our experimentation performance analysis results are obtained by simulating the QN model with JMT [32]. In particular, JMT performs an automatic stop of the simulation when all performance metrics are estimated with the required accuracy. We used the default values for the Confidence Interval Size of the solution and for the Max Relative Error of the greatest sample error that are 0.99 and 0.03, respectively, but they can be modified if more/less accurate results are required. Even if in literature some approaches have been proposed to combine QN prediction results with empirically found data to get more accurate QN-based models

[45], for our case studies (see Section 5) the numerical results are used to compare architectural refactorings applied to different model elements to validate if traceability links point out the most critical ones. Hence, we think that the considered simulation results cannot heavily affect the validation process, but we intend to investigate this aspect in the near future.

7. Related work

The work presented in this paper relates to two main research areas and builds upon our previous results in these areas: (i) software quality engineering, and (ii) model-driven traceability. We also discuss the state-of-art approaches in the context of uncertainty analysis and traceability research dealing with extra-functional properties of software systems.

7.1. Software quality engineering

Software quality represents the entire collection of engineering activities and related analyses used throughout the software development cycle, which are directed to meet extra-functional requirements [38]. In literature there are several approaches, surveyed in [14, 35], that tackle the problem of analyzing and optimizing software quality at the architectural level. Two main streams of research can be defined in this direction: (i) *qualitative* approaches provide exploratory insights into the problem, e.g., several analysis methods have been proposed in [46, 47, 48, 49]; (ii) *quantitative* approaches aim to generate numerical data to quantify architectural decisions, e.g., different design alternatives are evaluated in [50, 51, 52, 53]. Our approach belongs to quantitative approaches, in fact it aims to identify the contribution of architectural elements to extra-functional quantitative results. In literature few related works can be found dealing with the interpretation of extra-functional results, and most of them are based on monitoring techniques and therefore conceived to only act after software deployment. We are instead interested in model-based approaches that can be applied early in the software life-cycle to support design decisions. In this direction we identified two main categories of approaches: (i) rule-based methodologies that define a set of rules to overcome extra-functional problems [54, 55]; (ii) search-based approaches that explore the problem space by examining options to deal with extra-functional flaws [36, 37]. To achieve performance goals, our previous work focused on antipatterns [21] that are very complex (as compared to other software patterns) because they are founded on different characteristics of software systems related to architectural model elements (e.g., *many* usage dependencies, *excessive* message traffic) as well as to performance results (e.g., *high*, *low* utilization). Performance antipatterns represent effective instruments to tackle the issue of interpreting performance results, because they document: (i) common bad practices leading to performance problems and (ii) solutions in terms of architectural refactorings. Their effectiveness has been demonstrated, among others, by our recently consolidated results: (i) we formalized the representation of antipatterns by means of first-order logic rules that express a set of system properties under which an antipattern occurs [27]; (ii) we introduced a methodology to prioritize the detected antipatterns and solve the most promising ones [20]. To deal with security concerns, in our previous work [56, 30, 31] we developed a framework to support the specification of security strategies at the architectural level and their translation into QN performance models, thus to estimate security vs performance trade-offs. Moreover, in [30] we also demonstrated that QN prediction errors never exceeded 4% when compared with measurements on the real implementation of the system, thus to assess the accuracy of QN prediction results.

7.2. Model-driven traceability

Traceability has been defined as the ability to describe and follow the life cycle of software artifacts [57]. The current state of research and practice of traceability in requirements engineering and software development is discussed in [58], where model-driven techniques have been recognized of key relevance to support traceability concerns. In literature, there are many techniques exploiting the automatic recovery of different types of trace links, such as code and models [59, 60], code and documentation [61], code and features [62]. Results from existing empirical studies [63, 64, 65] demonstrate that traceability information has beneficial effects on the effectiveness and efficiency of understanding changes, performing requirements inspections, and evolving software artifacts. In our previous work [66] we introduced a language for expressing uncertainties in traceability relationships between models and code, which is the main benefit of this technique compared with other traceability approaches. Our recent work [5] out-passes these techniques by introducing a flexible methodology to express uncertainties, in fact we proved that the same uncertainty expressions could be applied to trace arbitrary kinds of software artifacts. Our approach makes use of this last achievement, in fact here we consider artifacts of different nature that are architectural elements and extra-functional results. This leads to broaden the scope of our research since we introduce a weighting methodology that gives a certain semantics to the involved artifacts: architectural elements are weighted on the basis of how much they contribute to the violation of extra-functional requirements.

7.3. Uncertainty analysis

The problem of dealing with uncertainty in early requirements and architectural decisions has been recognized by several works in literature. In [67] a taxonomy for classifying different types of uncertainties is provided, and three main dimensions are outlined: location, level and nature. The *location* of uncertainty refers to the place where the uncertainty manifests itself within the software artifacts; in this paper it consists of the relationships among architectural elements and extra-functional results. The *level* of uncertainty is the spectrum of its manifestation between deterministic knowledge and total ignorance; in this paper it is supported by our language and users specify the uncertainty at the level they are comfortable. The *nature* of uncertainty refers to whether it is due to the imperfection of the acquired knowledge or to the inherent variability of the phenomena being described; in this paper we consider the first nature of uncertainty, but we aim to consider the second type as future work. In [68] a language (i.e., RELAX) has been proposed to explicitly address uncertainty for specifying the behaviour of dynamically adaptive systems. Our approach differs from this work in the location and nature of uncertainty since [68] considers uncertain the system behaviour due to inherent variability of the execution environment. In [69] a tool (i.e., GuideArch) has been presented to guide the exploration of the architectural solution space under uncertainty. Our approach differs from this work in the location and level of uncertainty since [69] employs fuzzy mathematical methods to quantify uncertain architectural alternatives, but no levels can be explicitly specified to express higher/lower knowledge on such alternatives. In [70] a tool (i.e., Moda) has been introduced for multi-objective decision analysis by means of Monte-Carlo simulation and Pareto-based optimisation methods. Our approach differs from this work in the location and level of uncertainty since [70] models uncertainty in parameters' values as probability distributions that contribute to problem-specific goals, and the level of uncertainty is a discrete value that represents the attainment for each goal and its impact on risk. In our previous work [71, 72] we considered uncertainty in a different location (i.e., performance model parameters), and the analysis relied on lower/upper bounds provided by software architects. Besides the differences in the dimensions of uncertainty, all these works [68, 69, 70, 71, 72] do not explicitly consider extra-functional properties and their traceability with software architectural elements.

7.4. Traceability vs extra-functional properties

In literature there are some approaches that work towards the specification of traceability links between model elements and extra-functional properties. In [73] a mechanism to annotate performance analysis results back into the original performance models (provided by the domain experts) is presented. On the contrary, our approach includes the software models for traceability, and it supports the interpretation of analysis results by providing weights on the basis of requirements' violation. In [74] traceability links are maintained between performance requirements and Use Case Map (UCM) scenarios, however these links are used to build Layered Queueing Network (LQN) models only. On the contrary, our approach maps architectural elements with analysis results, thus to support software architects in the task of interpreting these results. In [75] traceability links are used to propagate the results of the performance model back to the original software model, however it applies to UML and LQN models only. In contrast to [75], our approach aims to automatically build model-to-results traceability links to point out the architectural elements affecting the stated requirements, with no reference to specific modelling languages. In [76] traceability links are maintained between the software design (i.e., UMLsec models [77]) and the implementation code (i.e., Java) to develop secure and dependable software systems. In particular, the traceability technique proposed in [76] is intended to find vulnerability bugs in the implementation of security protocols like SSL. On the contrary, our approach is aimed at tracing back security flaws to model elements and applying refactorings at the architectural level. In [78] authors extended their work by performing a run-time verification of traceability links from the design model to its implementation, i.e., the actual system is verified against the model while it executes. Our approach can be extended in a similar direction by considering extra-functional results as set of values obtained while changing run-time conditions. In [79] authors present an approach for adaptive information security in the cloud by using traceability as a mean to reason about the relationship between security requirements and the policies that satisfy those requirements. Traceability links are enriched with contextual information in order to support the adaptation of cloud applications to the environment they operate that was unknown or incomplete at design-time. As opposite to [79], our approach builds traceability links to make evident the architectural elements responsible for extra-functional flaws.

Summarizing, we found that some approaches [73, 74, 75] apply on early model abstractions like we do in our approach, whereas the remaining ones [76, 78, 79] work late in the development process (i.e., at the code level). Our motivation for dealing with early model abstractions is that extra-functional flaws are cheaper to fix [80], however as drawback the amount of information is limited and an obvious trade-off exists vs late analysis where the results are much more accurate but several constraints have been imposed on the structural and behavioral aspects of a software system. Concluding, to the best of our knowledge, there are no other works in literature that provided a tool-supported approach to derive weights for software artifacts on the basis of traceability uncertainties vs multiple extra-functional results, thus to support software engineers in their interpretation.

8. Conclusion

This paper presents a new approach to automate the traceability between architectural model elements and extra-functional results, thus to support software architects in the identification of the causes that most likely contribute to the violation of extra-functional requirements. To this end, we developed a tool (SoEfTraceAnalyzer) that is able to interpret a language capable of interpreting uncertainties while capturing model-to-results traceability links. The approach is validated by means of three different case studies, i.e., two academic research projects and one industrial system. The implemented tool and the case studies are publicly available for researchers and practitioners at [11].

The benefit of the tool is that it allows to automatically visualize the dependencies between modeling elements in architectural models (e.g., software components) and extra-functional properties (e.g., security level, response time, throughput, and utilization). As input the tool takes on the one hand possible influences already known to the domain expert, and on the other hand security patterns and performance antipatterns which express further such dependencies. The specification of extra-functional (anti)patterns is used to make the domain expert dependencies more precise, e.g., by ruling out certain influences.

We conducted a user study and we found that 100% of involved subjects confirmed the relevance of specifying uncertainties while bridging architectural model elements with extra-functional results, and 83% expressed a positive opinion on the addition of patterns and antipatterns knowledge. However, as future work we intend to further investigate the usability of our approach by exposing the developed tool [11] to users with higher levels of experience, such as experienced software architects and quality analysts. This wider experimentation will allow us to deeply investigate the usefulness of traceability links for developers in the context of mapping architectural model elements with extra-functional results.

9. Acknowledgements

We would like to thank the anonymous reviewers for constructive feedback that helped us to improve the paper and all participants of our user study.

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