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From software architecture to analysis models and back: Model-driven refactoring aimed at availability improvement

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ABSTRACT

Context: With the ever-increasing evolution of software systems, their architecture is subject to frequent changes due to multiple reasons, such as new requirements. Appropriate architectural changes driven by non-functional requirements are particularly challenging to identify because they concern quantitative analyses that are usually carried out with specific languages and tools. A considerable number of approaches have been proposed in the last decades to derive non-functional analysis models from architectural ones. However, there is an evident lack of automation in the backward path that brings the analysis results back to the software architecture.

Objective: In this paper, we propose a model-driven approach to support designers in improving the availability of their software systems through refactoring actions.

Method: The proposed framework makes use of bidirectional model transformations to map UML models onto Generalized Stochastic Petri Nets (GSPN) analysis models and vice versa. In particular, after availability analysis, our approach enables the application of model refactoring, possibly based on well-known fault tolerance patterns, aimed at improving the availability of the architectural model.

Results: We validated the effectiveness of our approach on an Environmental Control System. Our results show that the approach can generate: (i) an analyzable availability model from a software architecture description, and (ii) valid software architecture models back from availability models. Finally, our results highlight that the application of fault tolerance patterns significantly improves the availability in each considered scenario.

Conclusion: The approach integrates bidirectional model transformation and fault tolerance techniques to support the availability-driven refactoring of architectural models. The results of our experiment showed the effectiveness of the approach in improving the software availability of the system.

1. Introduction

In order to succeed in new market segments, organizations have constantly been increasing the use of software in systems over the last decades. Nowadays, due to continuous evolution, software architecture is subject to changes induced by decisions taken along the overall software lifecycle [1]. Indeed, as the earliest artifact that evolves along the process, a software architecture model can support different tasks, such as test case generation [2], traceability [3], and non-functional validation [4].

Appropriate architectural changes driven by non-functional requirements are particularly challenging to identify, mainly because non-functional analysis is based on specific languages and tools (e.g., Petri Nets, Markov Models) that are different from typical software architecture notations like Architecture Description Languages (e.g., ACME [5]). In fact, very few ADLs embed constructs that enable the specification of non-functional attributes (e.g., AADL [6]) and even fewer ones are equipped with solvers leading non-functional indices out of an architecture specification (e.g., Palladio [7]). Hence, even in cases where the analysis tools help to identify suitable architectural changes that may overcome non-functional problems, these changes need to be brought back within the architecture description language and environment. This step may prove to be particularly complex, as it subsumes a change of notation that might alter the semantics of identified architectural changes.

With the introduction of Model Driven Engineering (MDE) [8] techniques in the software lifecycle, the analysis of quality attributes has become more effective by means of automated transformations from software artifacts to analysis models [9]. Hence, in order to validate non-functional requirements on a software architecture, a number of approaches, mostly based on model transformations, have been proposed

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in the last decades to generate non-functional models from software architectural descriptions [10,11]. There is instead a clear lack of automation in the backward path that basically consists in the interpretation of the analysis results and the generation of architectural feedback to be propagated back to the software architecture.

The goal of this paper is to introduce a model-driven approach that works on the forward and backward path of a round-trip software process to support designers in improving the availability of their software architecture. In particular, we introduce JASA (JTL-based[1] framework for Availability analysis of Software Architecture), which makes use of bidirectional model transformations to map architectural models and availability models in both forward and backward directions. By working with UML models, annotated with availability parameters, and Generalized Stochastic Petri Nets (GSPN), JASA is able both to derive an analysis model from a software architecture and, after the analysis, to propagate back on the software architecture the changes made on the analysis model. In addition, these changes can be based on well-known fault tolerance patterns that we have preventively modeled in GSPN to be easily applied to the model under analysis.

The main contributions of this paper are:

- the automated transformation of a software architecture (modeled in UML) into a GSPN analysis model,
- the refactoring of GSPN models (possibly based on well-known fault tolerance patterns), and
- the propagation of the changes performed on the GSPN models back to UML models.

In a previous paper [13], we presented a bidirectional model transformation between UML State Machines (SMs), annotated with availability parameters, and GSPN. Such transformation was aimed both to derive a GSPN availability model from a SM-based software architecture and, after the analysis, to propagate back on the UML model the changes made on the GSPN model. This paper is an extension of our previous paper stemming from the realization that it was restricted to consider only SMs. In fact, a deeper semantic comprehension of an UML model can be achieved if the dynamic behavior is modeled by using the Sequence Diagrams (SDs) in addition to SMs [14]. In fact, SMs describe the behavior of an object (that could be the instance of a particular component/class) depending on what state it is currently in, whereas SDs show the execution of use cases and the behavior of involved objects in terms of their interactions. Such modeling extension of behavioral aspects of software architectures impacts on the accuracy of availability analysis and on the introduction of well-known fault-tolerance refactoring techniques (e.g. error masking). Moreover, the back propagation of GSPN changes into UML models is improved by considering the interactions among components.

Furthermore, in this paper we introduce a catalog of refactoring patterns with the aim to drive the designers in their process. In particular, the patterns for fault tolerance presented in Saridakis [15] have been considered to generate the corresponding patterns in GSPN, that will be propagated in UML through the bidirectional model transformations defined in JASA. The overall approach has been implemented as a dedicated framework implemented within Eclipse.[2]

Finally, our approach has been evaluated on an Environmental Control System example application in order to address these points: (i) generation of analyzable availability models from software architecture models; (ii) back generation of valid software architecture models from availability models; (iii) ability to improve the availability of software architecture models.

The rest of the paper is organized as follows: Section 2 sets the background for this research work along with its contributions and relations with the authors' previous work. Section 3 describes the JASA methodology and its implementation. Section 4 illustrates the application of JASA to the Environmental Control System (ECS) example application. Section 5 provides the evaluation of the results obtained by applying JASA. Section 6 describes related approaches, and finally Section 7 concludes the paper.

[1] The transformation engine is based on JTL [12].

[2] Eclipse Platform: https://projects.eclipse.org/projects/eclipse.platform.

2. Background

In the following, we describe the background of this research work and its contributions in terms of non-functional analysis and refactoring process leveraged for the definition of JASA. Also, we detail the contributions presented in this paper and put them in relation to the authors' previous work.

2.1. Round-trip non-functional analysis process

In order to validate non-functional requirements on a software architecture, some approaches, mostly based on model transformations, have been proposed in the last decades to generate *non-functional models* from *software architectural descriptions* [10,11]. This generation step is also called *forward path*, and it is represented by the topmost steps of Fig. 1. However, the solution of generated models does not necessarily produce indices that satisfy the requirements, thus an iterative process is often required to refactor the generated model on the basis of solution results. This process (hopefully) ends up when satisfactory indices are produced, and it is represented by the rightmost step of Fig. 1.

Thereafter, changes applied to non-functional models, for the sake of requirement satisfaction, have to be propagated back to the software architecture, and this is represented by the bottom-most step of Fig. 1, also called *backward path*. However, analysis results do not straightforwardly suggest what changes have to be made on the software architecture, hence this propagation is often based on the ability of experts that interpret the results. This clear lack of automation in the backward path represents a heavy limitation towards the construction of a round-trip process for non-functional validation of a software architecture. In this paper, we consider this general round-trip non-functional analysis process in the availability analysis context.

2.2. Model-based availability analysis

Availability can be defined as the system readiness to provide correct service. It corresponds to the probability that the system is working within its specifications at a given instant [16]. In particular, the steady state availability can be expressed as the ratio between the value of MTTF (Mean Time To Failure) and the sum of MTTF and MTTR (Mean Time To Repair) values.

Stochastic Petri Nets (SPN) are a well-established formalism for modeling systems availability [11]. In this paper, we consider an extension of SPN, called Generalized Stochastic Petri Nets (GSPN) [17]. Transitions defined in GSPN can be either immediate, when firings take no time, or timed, when associated delays are exponentially distributed. Immediate transitions fire with priority over timed transitions, and different priority levels can be defined over them. A weight is also associated to each immediate transition. When two or more immediate transitions are in conflict (e.g., because they have the same priority), the selection of the one that fires first is made using the associated weights. The delay associated with a timed transition is a random variable, distributed as a negative exponential, with a defined rate. When two or more timed transitions are in conflict, the selection of the one that fires first is made according to the race policy.

In this work, availability analysis is conducted on a GSPN derived from a software architecture modeled in UML [18].

Since UML does not natively provide support for availability modeling, we rely on the "Dependability Analysis and Modeling" (DAM) profile [19] to enhance UML models with availability annotations. DAM was designed on top of the standard MARTE profile [20], which extends

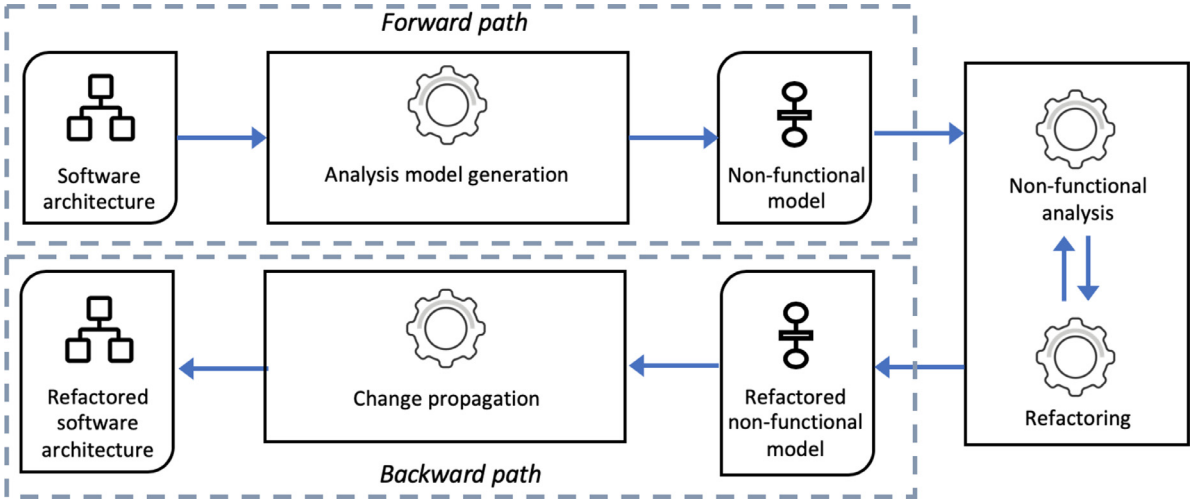


Fig. 1. Round-trip non-functional analysis process.

UML to annotate models with schedulability and performance analysis information. Despite the ability to annotate behavioral models with availability properties, UML-DAM lacks the execution semantics to be formally analyzed. This is the reason why DAM-annotated UML models need to be transformed (e.g., in GSPN) for the sake of analysis.

2.3. Fault tolerance refactoring techniques

Nowadays, software has strong influence on system availability. Since defects inherently occur in software design and coding for several reasons (e.g., software complexity, changing requirements, time pressures), software fault tolerance is even more important.

Among the well-known fault tolerance refactoring techniques that may improve the software availability, we consider the techniques that deal with error masking [15], i.e.: *Passive Replication, Semi-Passive Replication, Active Replication* and *Semi-Active Replication*.

Error masking techniques aim at isolating the subsystem in which an error is detected by relying on some form of redundancy to resume the processing that the system was performing when the error occurred. Replicas of system components and checkpoints can be employed, even in combination, to implement such techniques. *Passive Replication* and *Semi-Passive Replication* patterns provide error masking by saving the state of a component (checkpoint) before it receives the input, so that, if an error occurs during processing, an identical replica of the component can be activated to restart the processing from the saved checkpoint. While in the *Passive Replication* pattern the checkpoint is stored in a separate *Storage* component, *Semi-Passive Replication* requires that the checkpoint is directly stored in the replica. On the other hand, *Active Replication* and *Semi-Active Replication* patterns require a group of replicas to be always active during input processing. In the *Active Replication* pattern, the replicas provide the output to a *Comparator* component that performs a majority vote before forwarding it to the rest of the system. In contrast, in the *Semi-Active Replication* pattern, a replica provides the output to the system only when an error occurs in the original component. The patterns mentioned above, as well as refactoring inspired by them, will be presented in detail in Section 3.3.

3. The JASA approach

In this section we introduce JASA, a model-driven framework for supporting the round-trip availability analysis process and software architectural refactoring. The approach aims at supporting designers in their availability analysis process that involves the back propagation of results as refactoring actions on the software architecture. In particular, JASA leverages the interplay of UML and GSPN and provides automation for their mapping by means of a bidirectional model transformation mechanism [12]. In fact, the bidirectional engine provides the possibility to automate round-trip process by applying the transformation rules in both ways, from right to left domains and vice versa. In addition, JASA provides a set of refactoring actions that can be used by the designer to improve the availability of the system.

In the following, we introduce the used technologies, we present the process underlying our approach, and we provide a catalog of availability patterns that can be applied on GSPN models. Then, we describe the implementation of the approach based on bidirectional model transformations. The complete implementation of JASA is available online.[3]

3.1. Using model driven techniques

Model Driven Engineering (MDE) [8] leverages domain knowledge and business logic from source code into high-level specifications enabling more accurate analyses. In general, an application domain is consistently analyzed and engineered by means of a *metamodel*, i.e., a coherent set of interrelated concepts. A model is said to *conform* to a metamodel: it is expressed by the concepts encoded in the metamodel. Constraints are expressed at the meta-level, and model transformations are based on source and target metamodels. With the introduction of model-driven techniques in the software lifecycle, the analysis of quality attributes has become effective by means of automated transformations from software artifacts to analysis models [10].

The proposed approach makes use of bidirectional model transformations [21] to map architectural models and analysis models in both forward and backward directions. In contrast to unidirectional languages, bidirectional approaches allow describing both forward and backward transformations simultaneously, so that the consistency of the transformation can be guaranteed by construction [22].

3.2. From availability assessment to architecture improvements

The proposed approach is realized on top of JTL (Janus Transformation Language) [12,23], that is a constraint-based model transformation framework specifically tailored to support bidirectionality and change propagation.[4] JASA has been implemented within the Eclipse framework and mainly exploits the Eclipse Modeling Framework (EMF).[5] As a

[3] JASA: https://github.com/SEALABQualityGroup/JASA.
[4] JTL: http://jtl.univaq.it/.
[5] Eclipse Modeling Framework: https://www.eclipse.org/modeling/emf/.

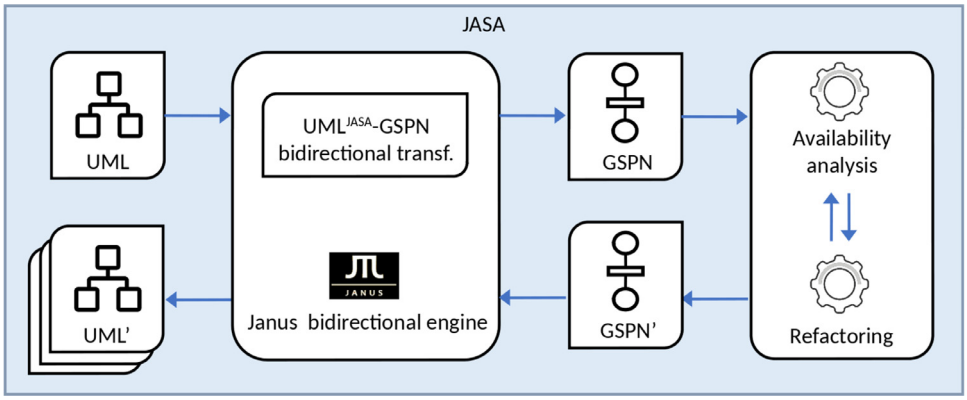


Fig. 2. The JASA overall approach.

consequence, the environment supports any language defined as a metamodel conforming to Ecore (i.e., the EMF metamodel). In this work, we focus on GSPN-based analysis models, whereas, the software architecture is modeled by means of UML. In particular, for the behavioral aspects, State Machines (SM) and Sequence Diagrams (SD) annotated via DAM are considered, whereas for the static aspects, Component Diagrams (CD) are considered. In the rest of the paper, we use UML^{JASA} to refer to the considered UML diagrams, that are UML^{SM}, UML^{SD} and UML^{CD}.

The JASA overall approach is reported in Fig. 2. As said, the *Bidirectional engine* relies on JTL to enable the execution of bidirectional model transformations in both forward and backward directions. The UML^{JASA}-GSPN bidirectional transformation maps UML models to GSPN and vice versa. In particular, in order to execute the transformation in the forward direction, a DAM-annotated UML model is taken as input to the engine, and the correspondent GSPN model is produced as output. The generated GSPN model is solved in order to obtain a set of indices that have to be interpreted (see *Availability analysis* in the figure). Thereafter, the GSPN model is iteratively modified until availability requirements are satisfied (see *Refactoring* in the figure). In order to propagate changes applied to the GSPN model back to the UML model, the bidirectional transformation is executed in the backward direction. In our case, the engine takes as input the modified GSPN model and produces as output a DAM-annotated UML model representing the software architecture that embeds the changes made on the GSPN to solve arisen availability problems.

3.3. A catalog of availability patterns

In this section, we present a set of patterns that can be used to improve the availability of a system. These patterns employ error masking techniques, based on replicas and checkpoints, that can be applied to a system designed by means of a GSPN. For each pattern, we show how a GSPN can be refactored to mask errors coming from a component without altering its original functionality.

Although, at the current stage, the refactoring activity is performed manually, the GSPN refactoring patterns we introduce in this section are designed to support automation. In particular, each pattern is equipped with anchor points that are used to properly insert it on a specific point of a GSPN modeling the original behaviour of a software component. Potentially, an automated tool can take as inputs the original GSPN, the pattern to be inserted and the specific point where it has to be applied, and it returns the GSPN refactored with the pattern.

Once applied on the GSPN model, the refactoring patterns will be propagated backwards through the transformation that will be presented in Section 3.4.

3.3.1. Passive replication

In this pattern, an error is masked by saving the state of a system component (a checkpoint) before it starts processing the input. If an error is detected, a backup replica of the same component is activated and the checkpoint restored. Hence, the backup will restart the processing of the input from the last state in which the system was behaving correctly. A Component Diagram of this pattern is reported in Fig. 3a, where components represent roles in the pattern and interfaces are used to depict the actions that are required for coordination. Fig. 3b shows the implementation of this pattern in GSPN. For the sake of presentation, three vertical dots are used to visually compress sequences of places and transitions without branching points, whereas surrounding boxes are used to highlight the roles of GSPN subnets in the pattern. Grey boxes (e.g., *Primary Behavior* and *Backup Behavior* in the figure) are introduced to show where the original behavior of components will fit into the pattern.

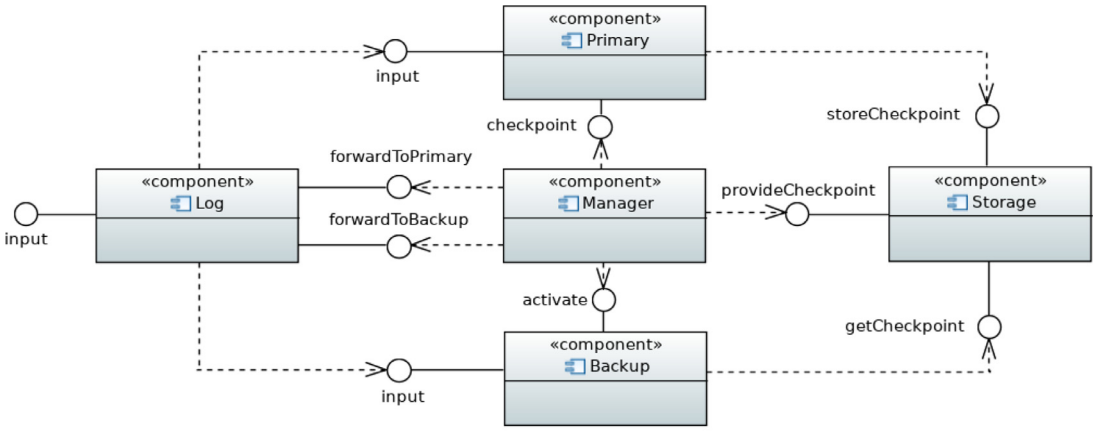
In order to implement the Passive Replication pattern, the following additional components should be added to the system:

- The *Backup*, that is identical to the original (*Primary*) component of which we want to mask errors. This replica is not started during error-free executions;
- The *Log*, which is able to record and forward inputs to the *Primary* as well as send the recorded inputs again to the *Backup* in case of error;
- The *Storage*, that is responsible for storing checkpoints and sending them to *Backup* upon request from the *Manager*. We assume that the *Storage* is not subject to errors;
- The *Manager*, that has the tasks of (i) asking the *Primary* to save a checkpoint, (ii) activating the backup in the presence of errors and (iii) requesting from the *Storage* to provide the last saved checkpoint.

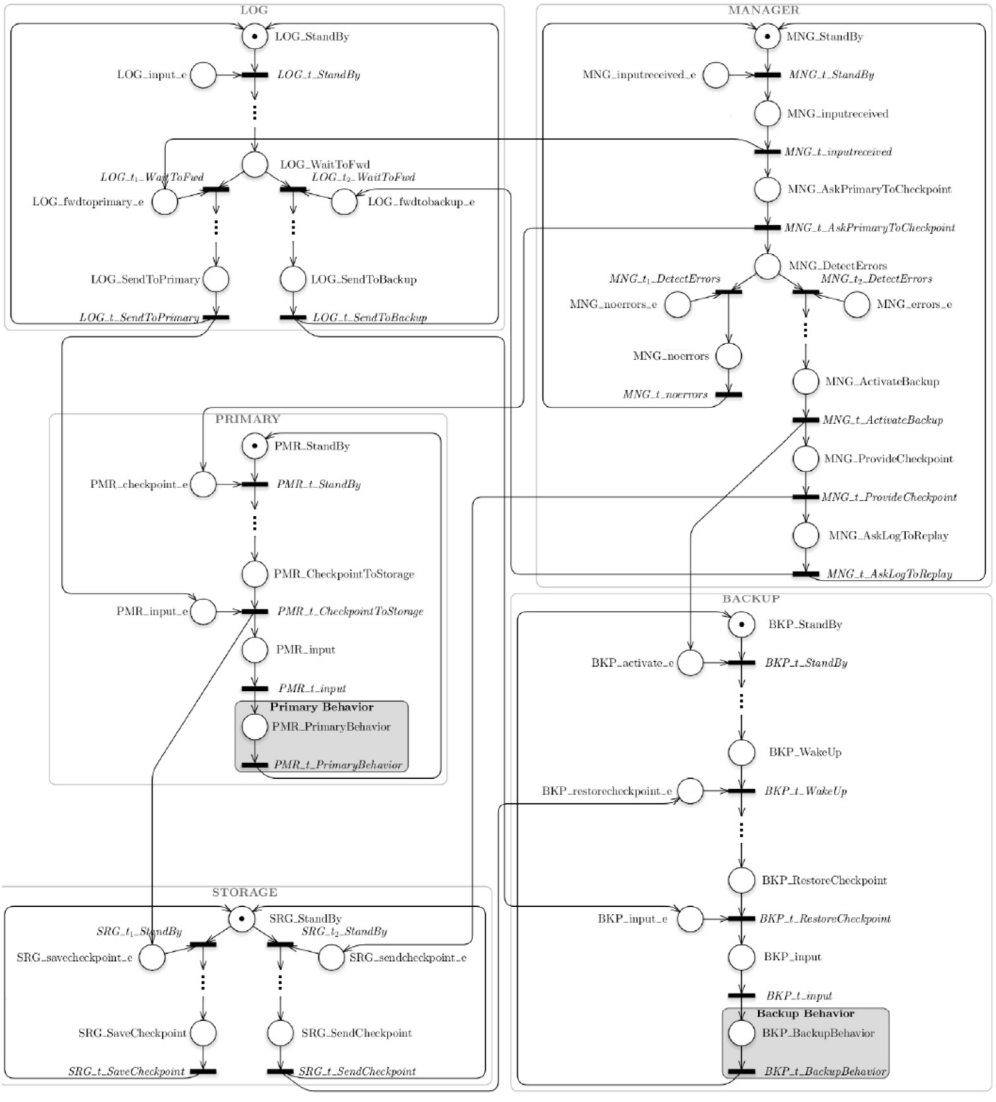
Primary, *Backup*, and *Manager* must be deployed to different units of failure.

3.3.2. Semi-passive replication

The *Semi-Passive Replication* pattern is able to mask errors in a similar way to the *Passive Replication* pattern, but without requiring a storage dedicated to checkpoints. The Component Diagram of this pattern is shown in Fig. 4a. The *Primary* component saves the checkpoint by sending it directly to the *Backup*. *Log* and *Manager* components are still required to implement the pattern. The *Log* stores and forward the input to the *Primary* which, before processing it, sends a checkpoint to the *Backup*. When an error occurs, the *Manager* activates the *Backup* and asks the *Log* to forward the input to it. The *Backup* restores its state using the saved checkpoint before starting to process the input. *Primary* and *Backup* must be deployed to different units of failure.

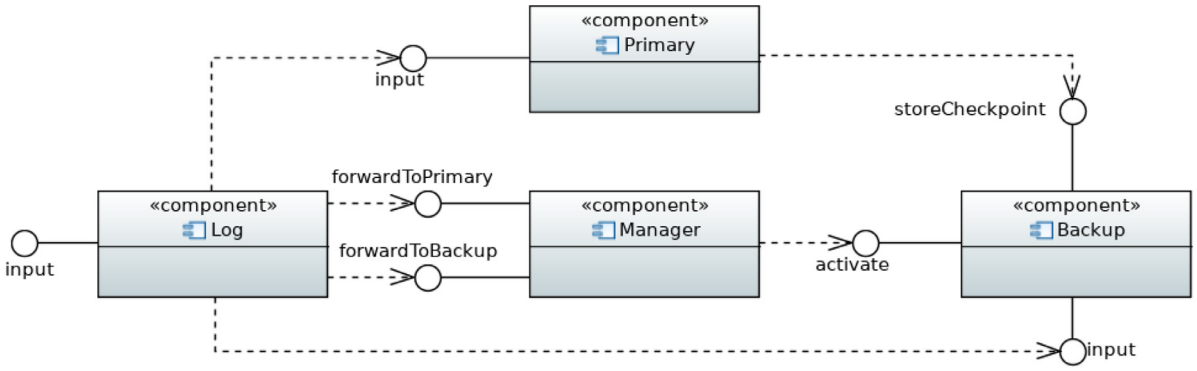


(a) Component Diagram of the *Passive Replication* pattern

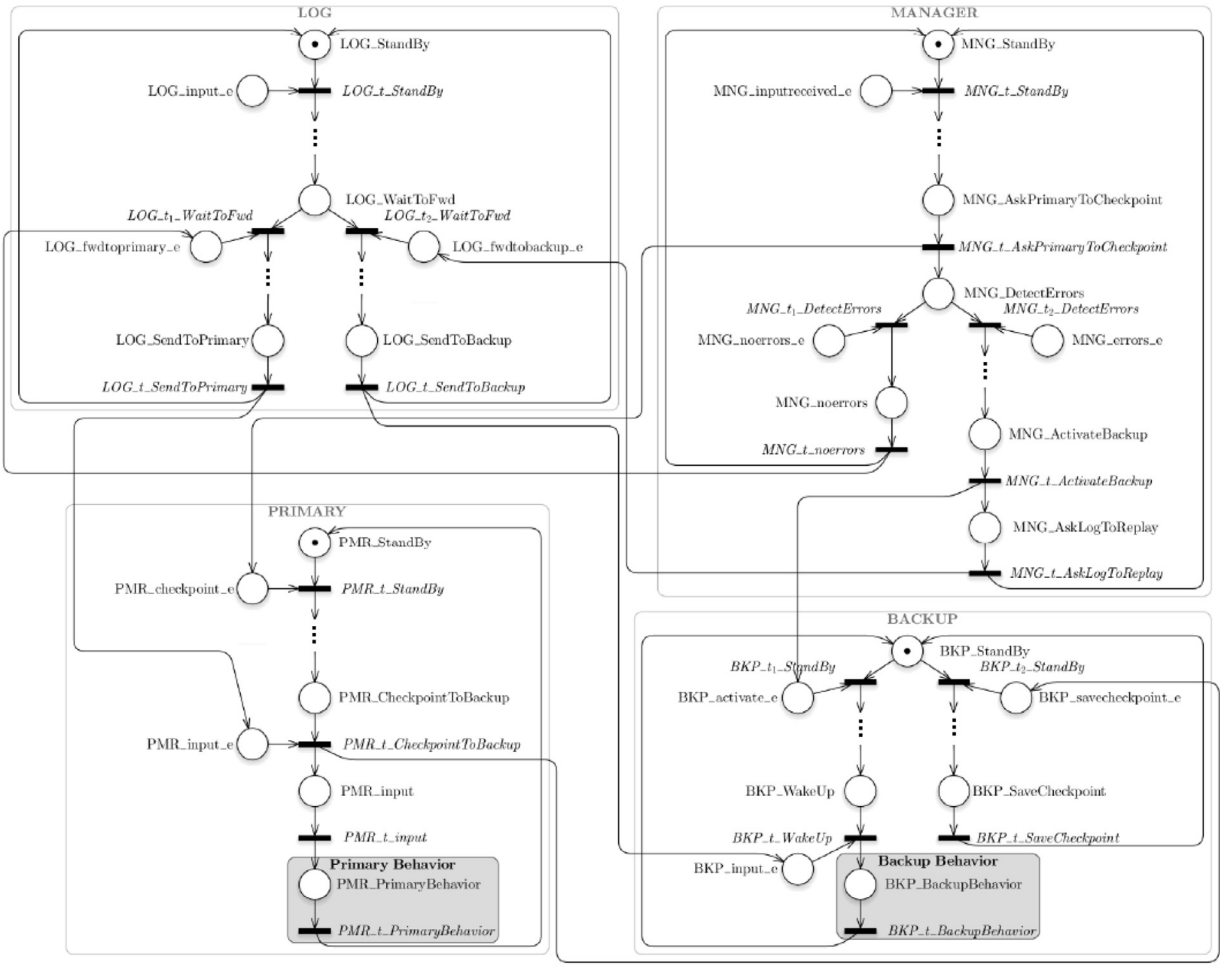


(b) GSPN of the *Passive Replication* pattern

Fig. 3. The *Passive Replication* pattern.



(a) Component Diagram of the *Semi-Passive Replication* pattern



(b) GSPN of the *Semi-Passive Replication* pattern

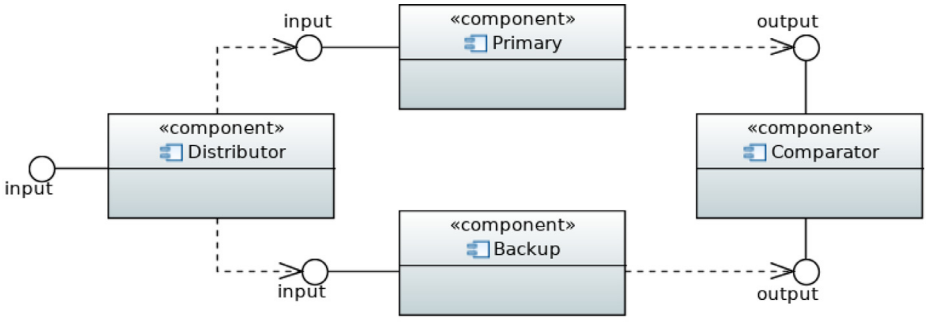
Fig. 4. The *Semi-Passive Replication* pattern.

3.3.3. Active replication

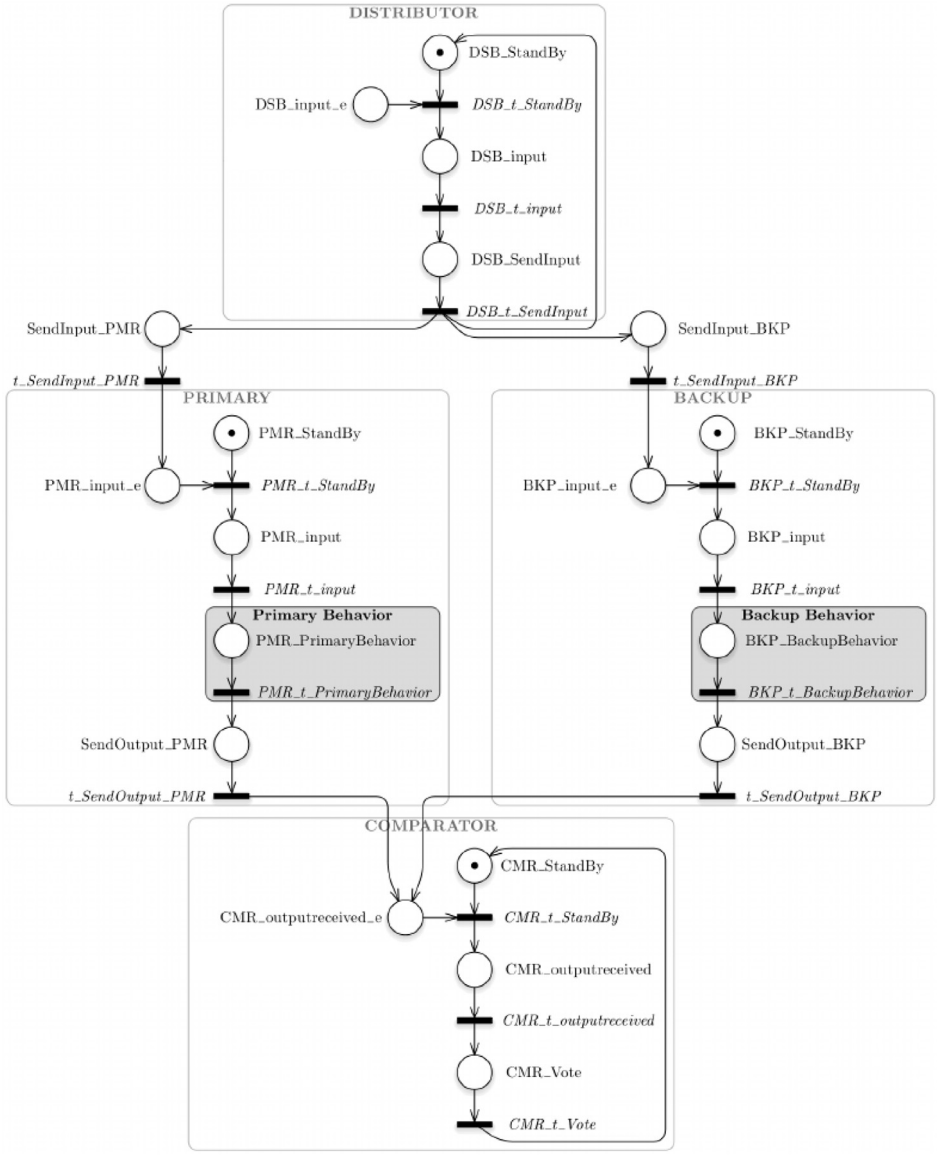
The *Active Replication* pattern is considered the most effective error masking technique but also the most expensive. This pattern employs a group of replicas actively receiving and processing every input intended for the component of which we want to mask errors. According to this pattern, we need to introduce two new components:

- The *Distributor*, which receives the input intended for the original component and forward it to all the replicas in the group;
- The *Comparator*, that is responsible for comparing the output computed by the replicas and deciding (by majority voting) what will be the final output of the system.

Fig. 5a shows the Component Diagram of this pattern when the group of replicas is composed by (i) a *Primary* component, representing the original component of which we want to mask errors, and (ii) a *Backup* component, that is an identical replica of



(a) Component Diagram of the *Active Replication* pattern



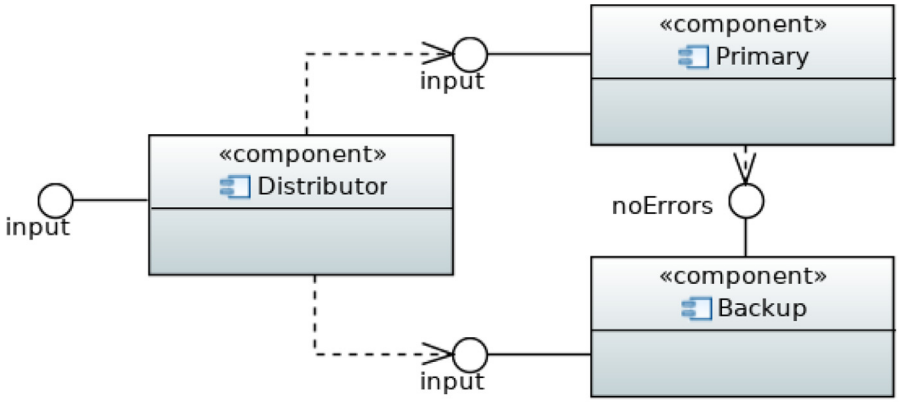
(b) GSPN of the *Active Replication* pattern

Fig. 5. The *Active Replication* pattern.

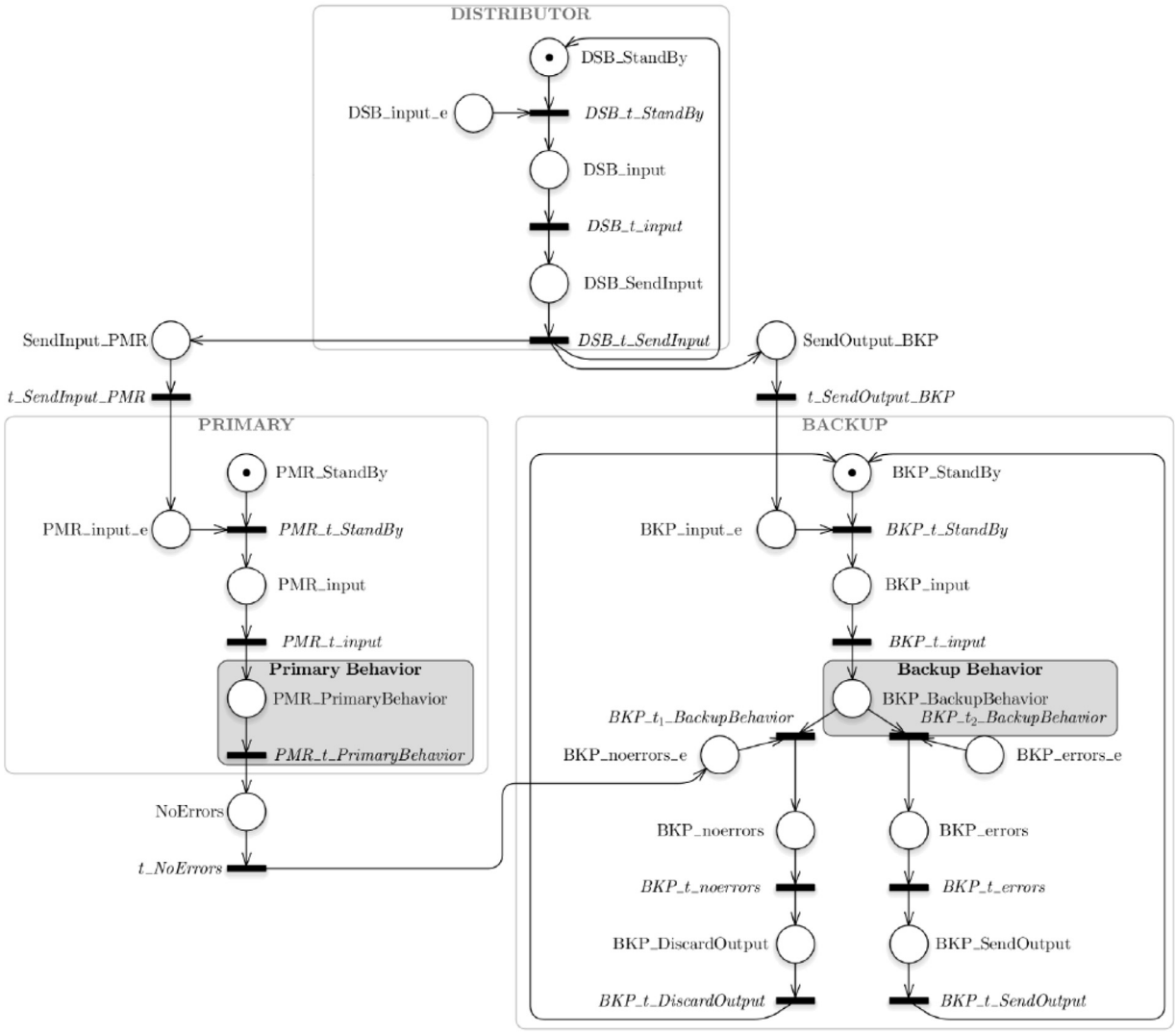
Primary. For the reason that all the replicas are continuously active, the structure of this pattern does not contain a different path that the system will follow in case of errors. *Primary, Backup*, and *Comparator* components must be mapped to different units of failure.

3.3.4. Semi-active replication

Similarly to the previous pattern, the *Semi-Active Replication* pattern employs a group of replicas that are always active. However, unlike the *Active Replication* pattern, only one replica will deliver the output. Fig. 6a reports the Component Diagram of this pattern with the group



(a) Component Diagram of the *Semi-Active Replication* pattern



(b) GSPN of the *Semi-Active Replication* pattern

Fig. 6. The *Semi-Active Replication* pattern.

of replicas composed by *Primary* and *Backup*. A *Distributor* component is still needed to forward the input to all the replicas. In an error-free execution, the *Primary* component directly delivers the output to the environment and then reports to the *Backup* that no errors occurred so that the output computed by the *Backup* can be discarded. If an error occurs on the *Primary*, then the *Backup* takes over the responsibility to deliver the output. *Primary, Backup* must be deployed to different units of failure.

3.4. The UML^{JASA}-GSPN bidirectional transformation

JTL adopts a textual syntax (that is inspired to QVT-R [24]) and allows a declarative specification of relationships between MOF models. The mechanism of transformation is rule-based. The language supports object pattern matching, and implicitly creates trace instances to record what occurred during a transformation execution. A transformation between candidate models is specified as a set of *relation*s that must hold for the transformation to be successful: in particular, it is defined by two *domain*s and includes a pair of *when* and *where* predicates that specify the pre- and post- conditions that must be satisfied by elements of the candidate models. When a bidirectional transformation is invoked for the enforcement, it is executed in a specific direction by selecting one of the candidate models as the target by means of a run configuration. The implementation relies on the Answer Set Programming (ASP) [25], which is a form of declarative programming oriented towards difficult (primarily NP-hard) search problems and based on the stable model (answer set) semantics of logic programming. The JTL engine finds and generates, in a single execution, all possible models that are consistent with the transformation rules by a deductive process.

The implementation of the UML^{JASA}-GSPN bidirectional transformation includes the definitions of the following tasks:

- Mapping UML^{SM} to GSPN models and vice versa (UML^{SM}-GSPN),
- Composing GSPN subnets by mapping UML^{SD} to GSPN models and vice versa (UML^{SD}-GSPN),
- Updating the static view of the architecture (UML^{CD}).

We remark that the considered UML diagrams are linked together in accordance with the UML specifications [18]. As a consequence, the coordination between execution semantics of related machines is realized by considering the relationships between transitions and operations. More in detail, each transition has a reference to an event that, in turn, refers to an operation already defined in the Component diagram. For instance, in the State Machine diagrams in Fig. 10, the *getTemperatureData* transitions in *TemperatureSensor* and *GreenhouseController* refer to the very same homonymous operation.

Specifically, with regard to the elements involved in the transformation, a single `State Machine` is defined for each `Component`, and `Transition` elements in the State Machine Diagram are linked to `Operation` elements in the Component Diagram by means of the `trigger.event.operation` reference. The same elements of `Operation` type are also linked to `Message` elements in Sequence Diagrams through the `signature` reference. Additionally, Sequence Diagrams are linked to Component Diagrams through the `Lifeline` elements that refer to `Component` elements by using the `represents.type` reference.

In the rest of this section, we present a detailed discussion of each of the above mentioned tasks. The complete implementation of the UML^{JASA}-GSPN bidirectional transformation is available online.[6]

3.4.1. UML^{SM}-GSPN

The first part of the transformation maps UML^{SM} and GSPN; it is characterized by a one-to-pattern element mapping, meaning that a UML^{SM} element is mapped to a pattern of GSPN elements. In particular, starting from UML^{SM} the corresponding patterns in GSPN are generated and vice versa. Such implementation considers the formal definition of the unidirectional translation of UML^{SM} in GSPN provided in Bernardi and Merseguer [26]. Starting from the latter, the relationships between UML^{SM} and GSPN are deduced and then completed in order to define the bidirectional mapping between the notations. The complexity of the latter task is high because the unique bidirectional transformation has to guarantee the syntactic and semantic consistency of source and target models in both directions.

For the sake of detailed illustration, a fragment of the UML^{SM}-GSPN bidirectional transformation implemented via JTL is depicted in Listing 1. In the following listings, three dots are used in place of repetitive sections of code.

As said, the transformation is specified by means of a set of *relations* among elements of the two involved *domains*; they represent the transformation rules that can be executed in both directions. The first line of the listing declares the variable `uml` that matches models conforming to the UML^{SM} metamodel and the variable `pn` that matches models conforming to the GSPN metamodel (based on the standard Petri Net Markup Language (PNML) [27]). The main relations specified in the transformation are described as follows:

- `StateMachine2PetriNet` (lines 3–18) generates a container element of type `PetriNet` with attribute `id` from an element of type `StateMachine` with attribute `name`, and vice versa in the opposite direction. Moreover, the correspondence between the reference `region` of type `Region` and the reference `pages` of type `Page` is defined.
- `State2Pattern` (lines 20–41) maps simple states to a specific pattern. Since a single element in the UML^{SM} domain induces the creation of a list of elements in the GSPN domain, the relation enforces multiple patterns. In particular, for each UML^{SM} `State` in a `Region` (see the reference `subvertex`), the following GSPN elements (see the references `objects`) are created: an element `s` of type `Place`, an element `s1` of type `Transition` (of kind "immediate", marking an immediate GSPN transition), and an element `s2` of type `Arc` that links `s` and `s1`. In the opposite direction, for each occurrence of the described GSPN pattern a correspondent `State` is generated;
- `StateActivity2Pattern` (lines 43–72) considers states that involve elements of type `Activity` and add a pattern of elements to the base pattern defined for simple states. In particular, the following elements are added: `s3` of type `Place`, `s4` of type `Arc` that links the previously created transition `s2` and the place `s4`, `s5` of type `Transition` (of kind "exponential", marking an exponential GSPN transition), and `s6` of type `Arc` that links `s4` and `s5`. In the opposite direction, for each occurrence of the described GSPN pattern a correspondent `State` is generated;
- `Transition2Pattern` (lines 74–120) relates transitions to a specific pattern. In particular, for each UML^{SM} `Transition` in a `Region` (see the reference `transition`), the following GSPN elements (see the references `objects`) are created: an element `t` of type `Place`, an element `t1` of type `Transition` (of kind "immediate"), an element `t2` of type `Arc` that links `t` and `t1`, an element `t3` of type `Arc` that links `t` and the transition `s1` (created from a simple state), an element `t4` of type `Place`, an element `t5` of type `Arc` that links `s1` and `t4`, an element `t6` of type `Transition` (of kind "immediate"), and an element `t7` of type `Arc` that links `t4` and `t6`. In the opposite direction, for each occurrence of the described GSPN pattern a correspondent `Transition` is generated;
- `TransitionDaStep2Pattern` (lines 122–146) relates UML^{SM} transitions annotated with the stereotype `DaStep` from the profile DAM and GSPN transitions (of kind "immediate"). Moreover, the value of the attribute `occurrenceProb` is mapped to attribute `weight`, and vice versa.

[6] UML^{JASA}-GSPN: https://github.com/SEALABQualityGroup/JASA/blob/master/JTL/transformations/UMLGSPN.jtl.

```
1  transformation UMLGSPN (uml:umlsm, pn:
       ptnet) {
2   ...
3   top relation StateMachine2PetriNet {
4    name: String;
5    enforce domain uml statemachine:umlsm
         ::StateMachine {
6     name=name,
7     region=r:umlsm::Region {}
8    };
9    enforce domain pn petrinet:ptnet::
         PetriNet {
10    id=name,
11    pages=p:ptnet::Page {}
12   };
13   where {
14    State2Pattern(r, p);
15    StateActivity2Pattern(r, p);
16    Transition2Pattern(r, p);
17   }
18  }
19
20  relation State2Pattern {
21   enforce domain uml r:umlsm::Region {
22    subvertex=s:umlsm::State {}
23   };
24   enforce domain pn p:ptnet::Page {
25    objects=s:ptnet::Place {}
26   };
27   enforce domain pn p:ptnet::Page {
28    objects=s1:ptnet::Transition {
29     transitionKind="immediate"
30    }
31   };
32   enforce domain pn p:ptnet::Page {
33    objects=s2:ptnet::Arc {
34     source=s:ptnet::Place {}
35     target=s1:ptnet::Transition {}
36    }
37   };
38   where {
39    s.doActivity.oclIsUndefined()
40   }
41  }
42
43  relation StateActivity2Pattern {
44   enforce domain uml r:umlsm::Region {
45    subvertex=s:umlsm::State {
46     doActivity=a:umlsm::Activity {}
47    }
48   };
49   enforce domain pn p:ptnet::Page { ...
         };
50   enforce domain pn p:ptnet::Page { ...
         };
51   enforce domain pn p:ptnet::Page { ...
         };
52   enforce domain pn p:ptnet::Page {
53    objects=s3:ptnet::Place {}
54   };
```

Listing 1. A fragment of the UML^{JASA}-GSPN bidirectional transformation.

3.4.2. GSPN subnets composition

The UML^{SM}-GSPN transformation in the previous section generates a separate GSPN for each UML^{SM}. The set of GSPNs obtained in this way does not represent the entire system as their behavior is not properly connected. These GSPNs can be considered to be subnets of the final system. It is therefore necessary to compose such subnets by connecting them, so that the resulting GSPN represents a system scenario. In this approach, we derive the composition of GSPN subnets from messages exchanged in UML^{SD}.

Specifically, we need to consider two cases: when messages represent a *synchronous* or *asynchronous* call. In case of a synchronous call, as depicted in Fig. 7a, we need to connect the GSPN immediate transition of the state in which the caller component is currently positioned to the GSPN place of the state in which the called component is positioned when receiving the message. The *reply* message resulting from a synchronous call connects the last GSPN immediate transition representing the end of the called component behavior to the GSPN immediate transition on which a token was waiting for the reply message. In the asynchronous case, shown in Fig. 7b, the call is represented similarly to the synchronous case with the important distinction that no token will wait for a reply message as none is expected.

The mapping of UML^{SD} to GSPN is characterized by a one-to-pattern element mapping, meaning that a UML^{SD} element is mapped to a pattern of GSPN elements. In particular, starting from UML^{SD}, the corresponding GSPN is generated and vice versa. Such implementation considers the formal definition of the unidirectional translation of UML^{SD} in GSPN provided in Bernardi et al. [28]. With respect to the latter, we only consider *instantaneous* messages (non delayed).

For the sake of detailed illustration, a fragment of the UML^{SD}-GSPN bidirectional transformation implemented via JTL is depicted in Listing 2.

The main relations specified in the transformation are described as follows:

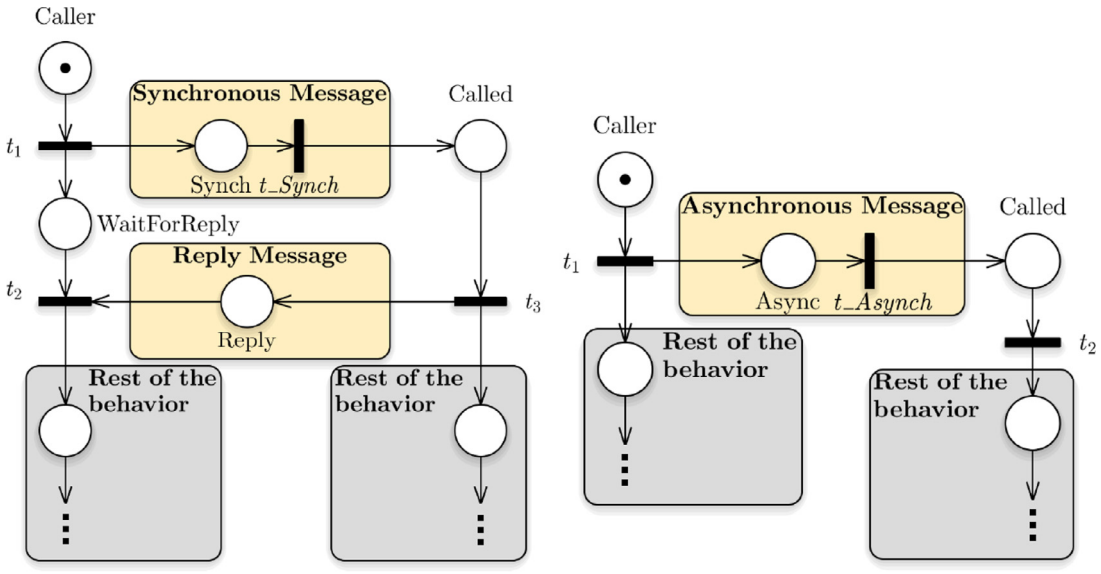
- `MessageSynch2Pattern` (lines 2–36) maps messages to a specific pattern. Since a single element in the UML^{SD} domain induces the creation of a list of elements in the GSPN domain, the relation enforces multiple patterns. In particular, for each UML^{SD} `Message` generated with a synchronous type of communication action (messageSort = “synchCall”, marking a synchronous message), the following GSPN elements (see the references `objects`) are created: an element `s` of type `Place`, an element `s1` of type `Transition` (of kind “immediate”), an element `s2` of type `Arc` that links `s` and `s1`, an element `s3` of type `Arc` that links `c` (that represent the caller transition) and `s`, and an element `s4` of type `Arc` that links `s1` () and `r` (that represent the receiver place). The elements `c` and `r` are mapped by calling the relation `State2Pattern` (from Listing 1) in the `when` clause. In the opposite direction, for each occurrence of the described GSPN pattern a correspondent synchronous `Message` is generated;
- `MessageAsynch2Pattern` (lines 38–48) maps UML^{SD} `Message` generated with an asynchronous type of communication action (messageSort = “asynchCall”, marking an asynchronous message) to a specific pattern, similarly to the previous relation; In the opposite direction, for each occurrence of the described GSPN pattern a correspondent asynchronous `Message` is generated;

```
 enforce domain pn p:ptnet::Page {
  objects=s4:ptnet::Arc {
   source=s1:ptnet::Transition {}
   target=s3:ptnet::Place {}
  }
 };
 enforce domain pn p:ptnet::Page {
  objects=s5:ptnet::Transition {
   transitionKind="exponential"
  }
 };
 enforce domain pn p:ptnet::Page {
  objects=s6:ptnet::Arc {
   source=s3:ptnet::Place {}
   target=s5:ptnet::Transition {}
  }
 };
}

relation Transition2Pattern {
 enforce domain uml region:umlsm::
      Region {
  transition=t:umlsm::Transition {
   source=s:umlsm::State {}
  }
 };
 enforce domain pn page:ptnet::Page {
  objects=t:ptnet::Place {}
 };
 enforce domain pn page:ptnet::Page {
  objects=t1:ptnet::Transition {
   transitionKind="immediate"
  }
 };
 enforce domain pn page:ptnet::Page {
  objects=t2:ptnet::Arc {
   source=t:ptnet::Place {}
   target=t1:ptnet::Transition {}
  }
 };
 enforce domain pn page:ptnet::Page {
  objects=t3:ptnet::Arc {
   source=t:ptnet::Place {}
   target=s1:ptnet::Transition {}
  }
 };
 enforce domain pn page:ptnet::Page {
      ... };
 enforce domain pn page:ptnet::Page {
      ... };
 enforce domain pn page:ptnet::Page {
  objects=t4:ptnet::Place {}
 };
 enforce domain pn page:ptnet::Page {
  objects=t5:ptnet::Arc {
   source=s1:ptnet::Transition {}
   target=t4:ptnet::Place {}
  }
 };
 enforce domain pn page:ptnet::Page {
  objects=t6:ptnet::Transition {
  transitionKind="immediate"
  }
 };
 enforce domain pn page:ptnet::Page {
  objects=t7:ptnet::Arc {
   source=t4:ptnet::Place {}
   target=t6:ptnet::Transition {}
  }
 };
}

relation TransitionDaStep2Pattern {
 name:String;
 prob:String;
 enforce domain uml region:umlsm::
      Region {
  transition=t:umlsm::DaStep {
   name=name,
   occurrenceProb=prob,
   source=s:umlsm::State {}
  }
 };
 enforce domain pn page:ptnet::Page {
      ... };
 enforce domain pn page:ptnet::Page {
  objects=t1:ptnet::Transition {
   id=name,
   weight=prob
   transitionKind="immediate"
  }
 };
 enforce domain pn page:ptnet::Page {
      ... };
 enforce domain pn page:ptnet::Page {
      ... };
      ... };
 enforce domain pn page:ptnet::Page {
      ... };
}
...
```

Listing 1. Continued



(a) A synchronous message in GSPN (b) An asynchronous message in GSPN

Fig. 7. GSPN subnets composition.

- `MessageReply2Pattern` (lines 50–73) considers UML^{SD} reply messages (messageSort = "reply", marking a reply message) and generate a pattern of elements in the GSPN domain. In particular, the following elements are added: `s` of type `Place`, `s1` of type `Arc` that links the receiver transition `r` and the place `s`, and `s2` of type `Arc` that links the transition `s1` and the caller place `c`. The elements `c` and `r` are mapped by calling the relation `State2Pattern` (from Listing 1) in the `when` clause. In the opposite direction, for each occurrence of the described GSPN pattern a correspondent reply `Message` is generated;

3.4.3. Static view (UML^{CD}) update

After the refactoring and analysis steps are performed on the GSPN, the execution in backward direction of the transformation propagates the changes from GSPN to UML. This back propagation also affects the static view of the system, that is represented by a UML Component Diagram (UML^{CD}). For example, when a replica of a sensor is created in GSPN, the corresponding new component should be automatically generated in the UML^{CD}. In order to achieve this, we introduce additional relations updating the static view of the system, as reported in the Listing 3.

The main relations specified in the transformation are described as follows:

- `Component2Page` (lines 2–10) maps a UML `Component` to a GSPN `Page`. Following the design assumption that a State Machine is created to describe the behaviour of a Component, this relation creates a correspondence between a `Component` in UML and a GSPN subnet enclosed in a `Page` that contains the behaviour defined in a State Machine. When executed in the backward direction, this relation generates a new `Component` for each new `Page` added by the refactoring in GSPN.
- `Interface2Pattern` (lines 12–63) maps a UML pattern composed of an `Interface`, its realization and usage to a GSPN pattern defining a call operation between components. Specifically, the UML pattern is composed of an `Interface`, its `ownedOperation` and two `Components`, one receiving the call (`receiver`) and the other performing it (`caller`). On the GSPN side, the relation matches the pattern corresponding to a call operation between components (the pattern matches both synchronous and asynchronous calls as they are differentiated only by the presence of a reply message). The `when` clause is used to ensure that the matched components have been mapped to different pages. In order to guarantee that the matched call is happening between two components, the `where` clause contains two constraints requiring that `source` and `target` references of the `Arcs` `s3` and `s4` point to different `Pages`.

Next section shows how the approach is applied to an example scenario.

4. JASA at work

In this section, we present the approach in practice with the aim of illustrating the JASA process and how it can be replicated by potential researchers and practitioners that would like to follow the same process on their own architecture.

The experiment is conducted by applying the approach to the Environmental Control System (ECS) system example (as described in Section 4.1). First, the system has been modelled by means of UML annotated with the MARTE DAM profile (as described in Section 2). Then, in order to be used in the EMF environment, the involved models have been specified in their Ecore format. The approach has been executed within the JTL framework; in particular, the UML^{JASA}-GSPN bidirectional transformation has been run in the forward direction to generate the GSPN models (as described in Section 4.2); after performing the GSPN analysis, a set of refactoring actions have been performed on the GSPNs on the basis of the obtained results (as described in Section 4.3). Finally, the UML^{JASA}-GSPN bidirectional transformation has been run in the backward direction to propagate the changes and generate the updated UML architecture (as described in Section 4.4).

4.1. Environmental control system (ECS) modeling

The approach presented in the previous sections has been applied to a software system for the environmental control of a botanical garden. The Environmental Control System (ECS) is responsible for the automated management of the artificial habitat preserved in greenhouses. A network of sensors periodically checks air temperature, air humidity and soil humidity inside greenhouses. When sensors detect values exceeding the thresholds defined for a given greenhouse, the system automatically restores the environment conditions activating irrigation and air conditioning systems as required.

```
...
 relation MessageSynch2Pattern {
  enforce domain uml m:umlsm::Message {
   messageSort="synchCall"
  };
  enforce domain pn p:ptnet::Page {
   objects=s:ptnet::Place {}
  };
  enforce domain pn p:ptnet::Page {
   objects=s1:ptnet::Transition {
    transitionKind="immediate"
   }
  };
  enforce domain pn p:ptnet::Page {
   objects=s2:ptnet::Arc {
    source=s:ptnet::Place {}
    target=s1:ptnet::Transition {}
   }
  };
  enforce domain pn p:ptnet::Page {
   objects=s3:ptnet::Arc {
    source=c:ptnet::Transition {}
    target=s:ptnet::Place {}
   }
  };
  enforce domain pn p:ptnet::Page {
   objects=s4:ptnet::Arc {
    source=s1:ptnet::Transition {}
    target=r:ptnet::Place {}
   }
  };
  when {
   State2Pattern(c, c);
   State2Pattern(r, r);
  }
 }

 relation MessageAsynch2Pattern {
  enforce domain uml m:umlsm::Message {
   messageSort="asynchCall"
  };
  enforce domain pn p:ptnet::Page {
       ...  };
  enforce domain pn p:ptnet::Page {
       ...  };
  enforce domain pn p:ptnet::Page {
       ...  };
  enforce domain pn p:ptnet::Page {
       ...  };
  enforce domain pn p:ptnet::Page {
       ...  };
  when {  ... }
 }

 relation MessageReply2Pattern {
  enforce domain uml m:umlsm::Message {
   messageSort="reply"
  };
  enforce domain pn p:ptnet::Page {
   objects=s:ptnet::Place {}
  };
  enforce domain pn p:ptnet::Page {
   objects=s1:ptnet::Arc {
    source=r:ptnet::Transition {}
    target=s:ptnet::Place {}
   }
  };
  enforce domain pn p:ptnet::Page {
   objects=s2:ptnet::Arc {
    source=s1:ptnet::Transition {}
    target=c:ptnet::Place {}
   }
  };
  when {
   State2Pattern(r, r);
   State2Pattern(c, c);
  }
 }
...
```

Listing 2. A fragment of the UML^{JASA}-GSPN bidirectional transformation.

ECS consists of seven software components: *GreenhouseController* is responsible for checking environment conditions; *TemperatureSensor, AirHumiditySensor* and *SoilHumiditySensor* respectively measure air temperature, air humidity and soil humidity; *Database* is queried to retrieve the thresholds defined for each monitored condition; *AirConditioner* can raise or decrease the air temperature inside a greenhouse; *MobileApp* notifies the user about certain events such as conditions exceeding the defined thresholds.

We consider three use case scenarios of ECS, for which we provide the respective UML Sequence Diagrams: *Monitoring Conditions*, in Fig. 9a, in which a timer periodically activates a procedure to check environment conditions, *Remote Monitoring*, in Fig. 9b, in which the air humidity is continuously monitored and the *GreenhouseController* notifies the user when the value exceeds the corresponding threshold, and *Managing Temperature*, in Fig. 9c, that defines the procedure for the activation of the air conditioner when required. We assume that the complexity of a message parameters and return types, as well as the width of their ranges, do not affect the behaviour following that message.

Moreover, the internal behavior of each software component is described by a State Machine that is consistent with the interactions defined in the Sequence Diagrams. The resulting State Machine diagram is shown in Fig. 8.

UML *Transition* and *Message* elements that may fail are annotated with the *DaStep* stereotype from DAM, as depicted in Figs. 8 and 9, respectively. This stereotype is used here to define system failure modes and the probabilities of failures occurring in a scenario, as follows: attribute *kind* is set to *failure*, as a consequence, the attribute *failure* can be used to set the failure probability as the *occurrenceProb* real value.

The considered models, specified in UML, are available online.[7]

[7] ECS UML models: https://github.com/SEALABQualityGroup/JASA/tree/master/UML.

```
...
relation Component2Page {
 name:String;
 enforce domain uml c:umlsm::Component
      {
  name=name
 };
 checkonly domain pn p:ptnet::Page {
  id=name
 };
}

relation Interface2Pattern {
 enforce domain uml i:umlsm::Interface
      {
  ownedOperation=o:umlsm::Operation {}
 };
 enforce domain uml receiver:umlsm::
      Component {
  interfaceRealization=ir:umlsm::
       InterfaceRealization {
   supplier=i:umlsm::Interface {},
   contract=i:umlsm::Interface {}
  }
 };
 enforce domain uml caller:umlsm::
      Component {
  packagedElement=d:umlsm::Dependency
       {
   client=caller:umlsm::Component {},
   supplier=i:umlsm::Interface {}
  }
 };
 enforce domain pn p:ptnet::Page {
  objects=s:ptnet::Place {}
 };
 enforce domain pn p:ptnet::Page {
  objects=s1:ptnet::Transition {
   transitionKind="immediate"
  }
 };
 enforce domain pn p:ptnet::Page {
  objects=s2:ptnet::Arc {
   source=s:ptnet::Place {}
   target=s1:ptnet::Transition {}
  }
 };
 enforce domain pn p1:ptnet::Page {
  objects=s3:ptnet::Arc {
   source=c:ptnet::Transition {}
   target=s:ptnet::Place {}
  }
 };
 enforce domain pn p2:ptnet::Page {
  objects=s4:ptnet::Arc {
   source=s1:ptnet::Transition {}
   target=r:ptnet::Place {}
  }
 };
 when {
  Component2Page(caller, p1);
  Component2Page(receiver, p3);
 }
 where {
  s3.source.containerPage.id <>
     s3.target.containerPage.id;
  s4.source.containerPage.id <>
     s4.target.containerPage.id;
 }
...
```

Listing 3. A fragment of the UML^{JASA}-GSPN bidirectional transformation.

4.2. Analysis model generation

The first operational step of our approach consists in the execution (in the forward direction) of the transformation presented in Section 3.4 (UML^{JASA}-GSPN) within the JTL framework. For each scenario, from a Sequence Diagram and the set of involved State Machines, this execution generates a GSPN. The transformation UML^{SM}-GSPN in Section 3.4.1 creates a GSPN subnet for each State Machine. As an example, Fig. 11 shows a fragment of the GSPN obtained for the *Managing Temperature* scenario (Fig. 9c). The GSPN subnets visible in the figure are generated from the *TemperatureSensor, AirConditioner* and *GreenhouseController* State Machines in Fig. 10, where colours are used to outline the subnets generated from the corresponding State Machines. Such subnets are connected on the basis of the transformation UML^{SD}-GSPN in Section 3.4.2.

In general, the composition of subnets obtained from this step is based on interactions among components, as appearing in Sequence Diagrams. In particular, synchronous and asynchronous messages are mapped to the corresponding patterns presented in Section 3.4.2.[8]

[8] The GSPNs generated for each scenario are available at https://github.com/SEALABQualityGroup/JASA/tree/master/GSPN.

4.3. Analysis results and refactoring

In this section, first we play with a simple case for checking whether patterns induce differences in the system availability. Thereafter, we apply patterns to components on the basis of current practices and component role, as it will be explained in detail at the end of the section. The result of patterns application is a unique static architecture that subsumes different SD, hence different availability results for different scenarios (in terms of operational profile and workload).

As a first step, we consider the GSPN obtained from the execution in the forward direction of the transformation to perform a steady state availability analysis. Given an initial marking of a GSPN, and provided that every place of the net is bounded, the reachability set is the set of all the markings reachable by sequences of transition firings from the initial one. The reachability graph associated to a GSPN is a directed graph whose nodes are the markings in the reachability set and each arc, connecting a marking M to a M' one, represents the firing of a transition enabled in M and leading to M'.

In general, availability metrics of an GSPN model can be defined as reward functions on the reachability graph [29]. Let M^0 be the initial marking, and $r_M = \{1 \text{ if } M \in O,\ 0 \text{ if } M \in F\}$ be a state reward function that partitions the set of reachable markings $RS(M^0)$ into two sets: O, the

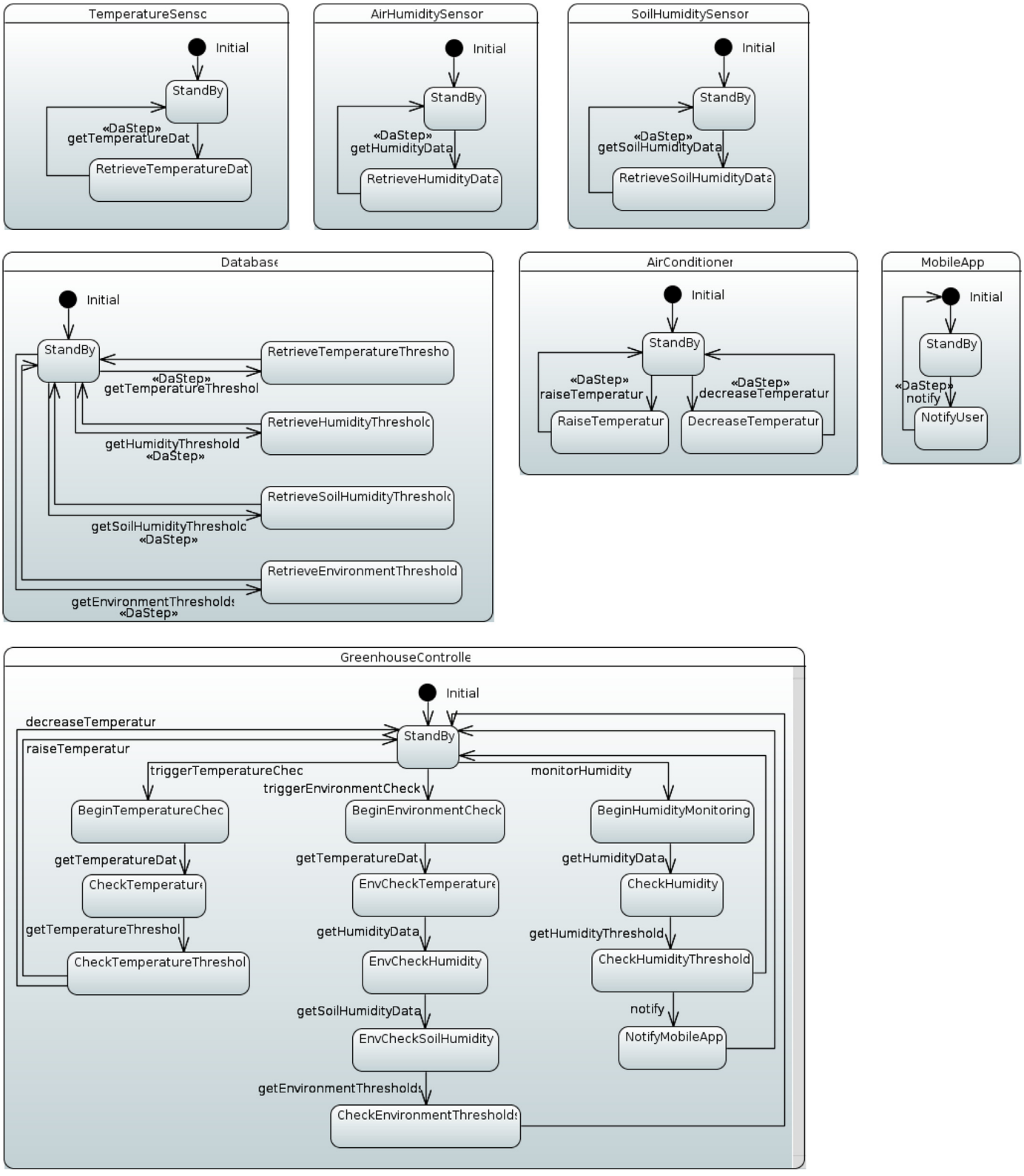
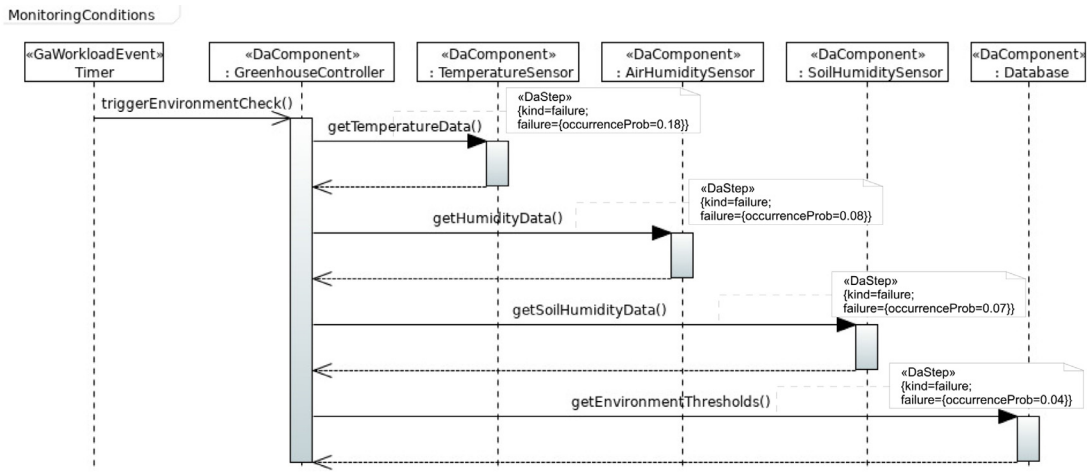


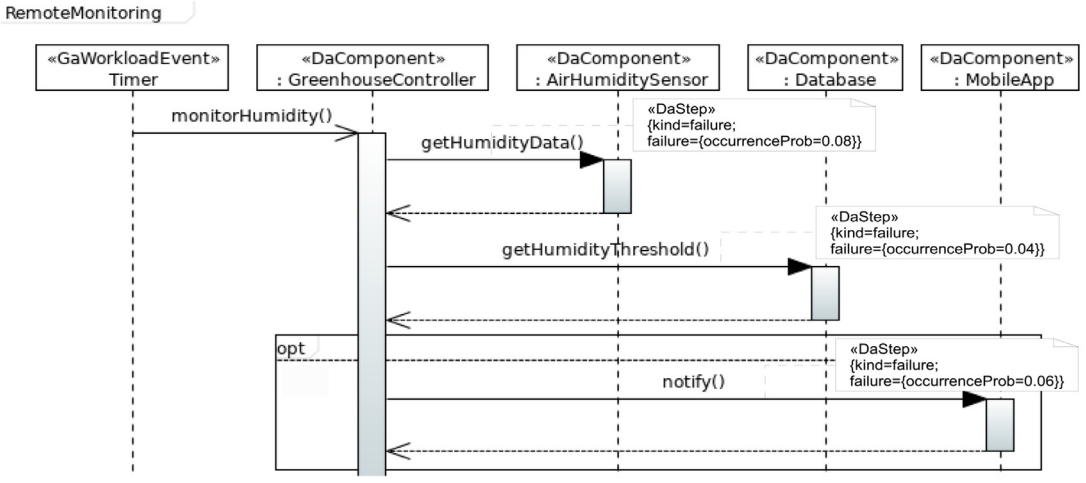
Fig. 8. UML State Machine Diagram of the ECS components.

set of operational system states, and F, the set of system failure states. The probability of the system being in marking M at time instant t can be expressed as $\sigma_M(t) = Pr\{X(t) = M\}$. Steady state probability can be computed as $\sigma_M = lim_{t\to\infty}\sigma_M(t)$, and it represents the probability of the system being in marking M at any time instant $t > 0$. The steady state availability of the GSPN is then defined taking into account the reward function and the steady state probabilities of individual markings introduced before, as follows: $A_\infty = \sum_{M\in RS(M_0)} r_M \sigma_M = \sum_{M\in O} \sigma_M$. The value of A_∞ is to be interpreted as the percentage of time the system is not in a failure state after running for a sufficiently long time.

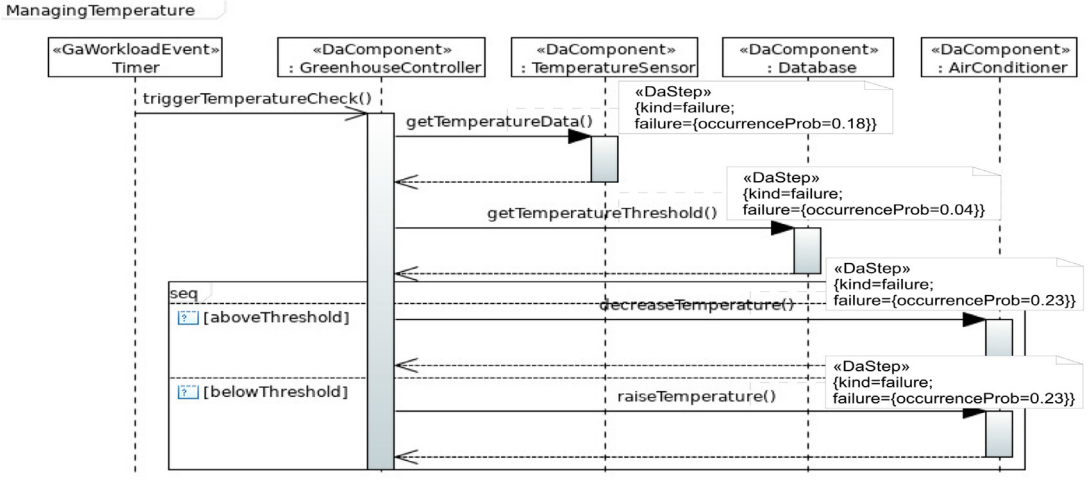
System failure mode needs to be defined in order to discern operational states from failure ones, and to exclusively assign the related markings to one among the O and F subsets of reachable markings. The system is considered to be in a failure state when any of the state tran-



(a) The *Monitoring Conditions* scenario



(b) The *Remote Monitoring* scenario



(c) The *Managing Temperature* scenario

Fig. 9. UML Sequence Diagrams of the ECS scenarios.

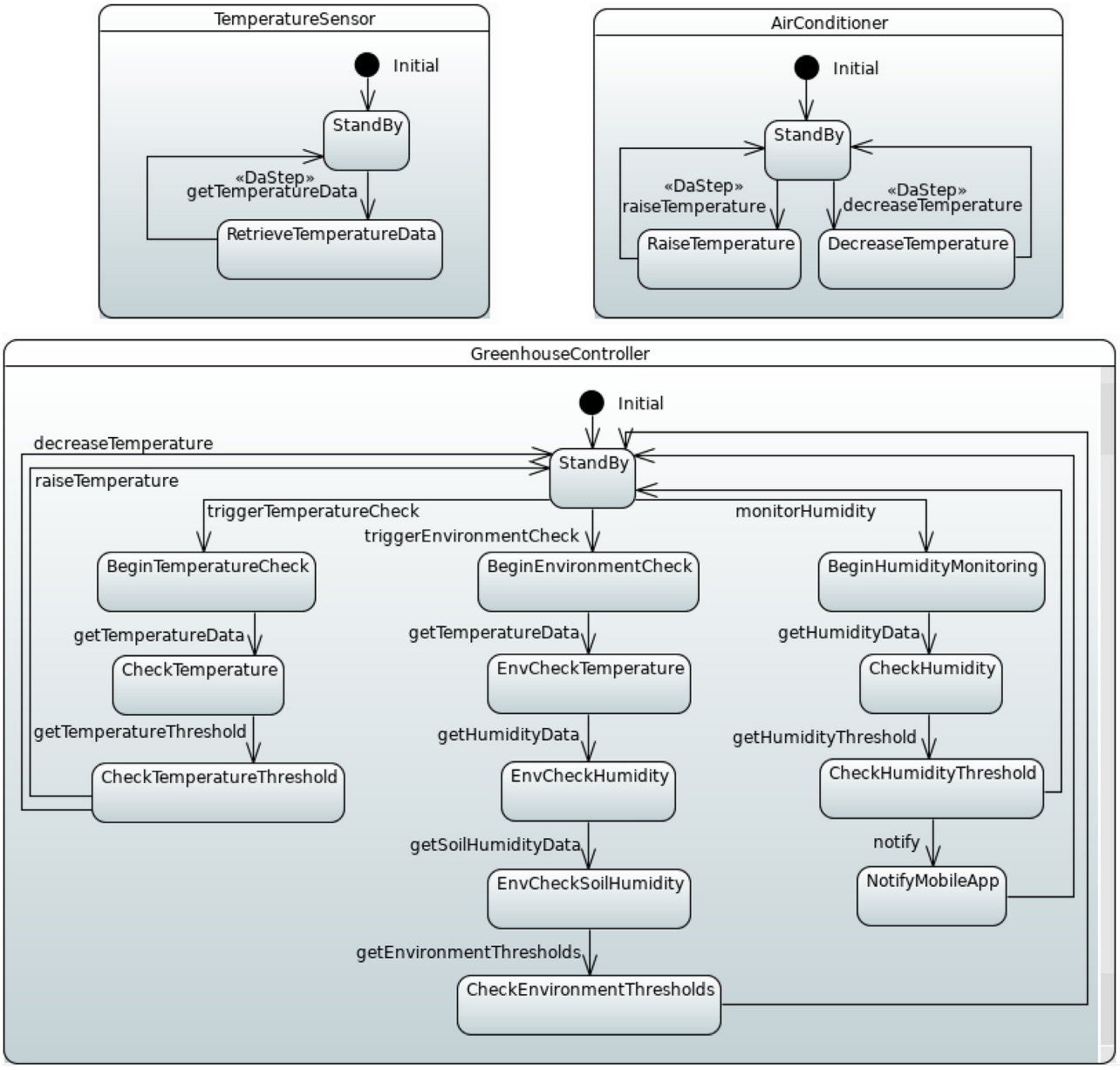


Fig. 10. UML State Machines of the *TemperatureSensor, AirConditioner* and *GreenhouseController* components.

sitions annotated by the *DaStep* stereotype fails during execution. As a consequence, in the GSPN obtained from the previous step, we define as failure states the markings reached from firing all the transitions having the *_loss* suffix, as they represent the occurrence of a failure.

The GreatSPN solver [30] is used to derive the reachability graph of markings in the net and to compute the corresponding values of σ_M. In the initial marking of the net, a token appears in the `StandBy` place of each component subnet, so that the component is ready to serve incoming requests. Immediate transitions representing failures are marked with weights derived from the failure probabilities. Since we assume that the operations belonging to the same component fail with the same probability, we report in Table 1 the initial failure probabilities of every component in ECS.

The steady state availability index can be computed by considering both the aforementioned initial marking of the GSPN and the failure probabilities. The resulting indices for the three scenarios we considered are reported in Table 2.

In order to establish the effectiveness of the fault tolerance patterns presented in Section 2.3, we apply each of them on the *TemperatureSensor* component in the *Managing Temperature* scenario. The steady state availability resulting in each case is reported in Table 3. The results show, as expected, that the application of the fault tolerance patterns increased the overall availability of the scenario, with the particular observation that *Active Replication* and *Passive Replication* induce the best improvements. Note that even a change in the second decimal digit of

Table 1
Initial failure probabilities of components in ECS.

TemperatureSensor	0.18
HumiditySensor	0.08
SoilHumiditySensor	0.07
Database	0.04
MobileApp	0.06
AirConditioner	0.23

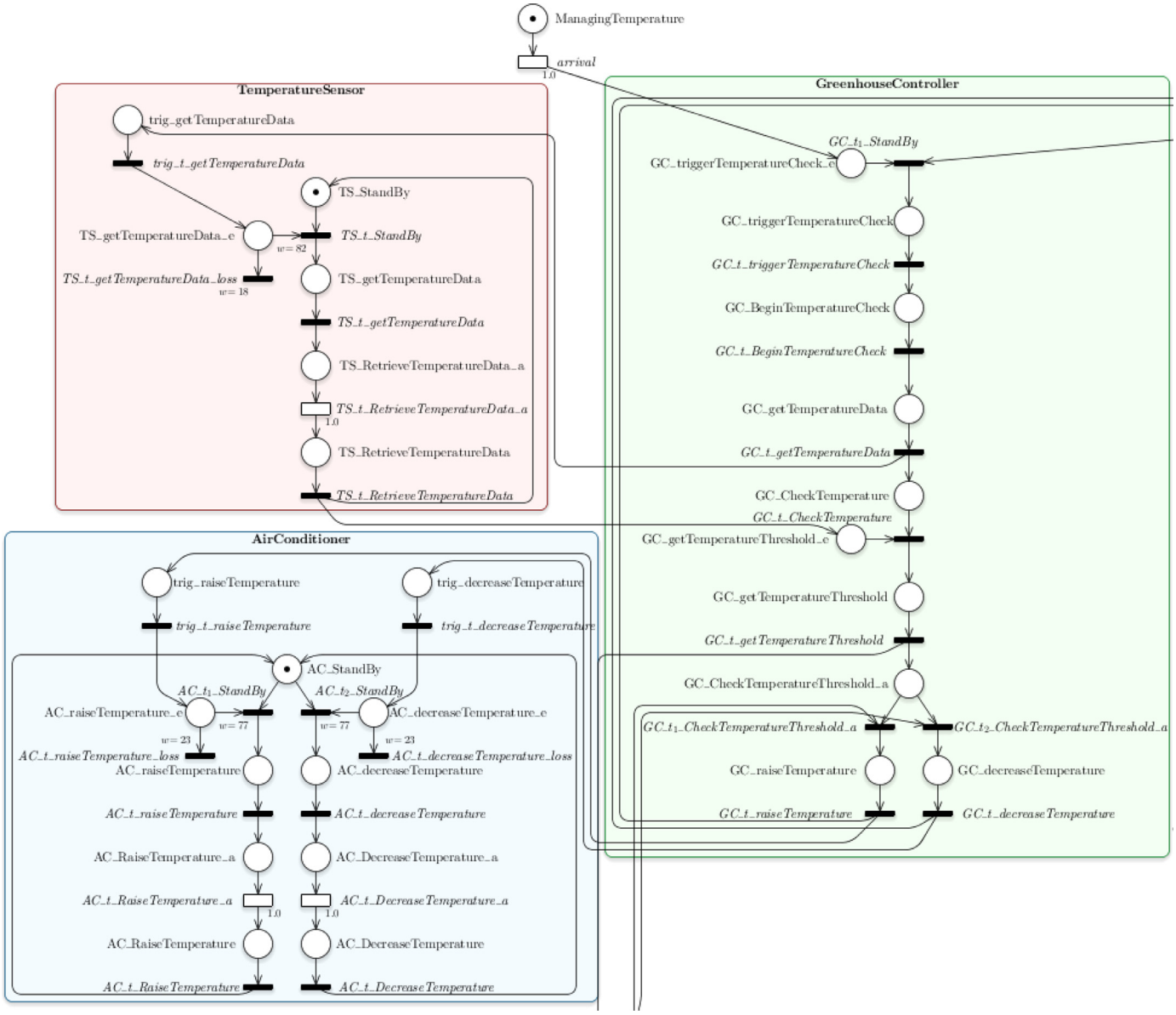


Fig. 11. Fragment of the GSPN generated for the *Managing Temperature* scenario.

availability metric is already considered relevant, since high availability systems usually require to be available up to the 99.999% of the running time (this requirement is usually referred to as *five nines*) [31].

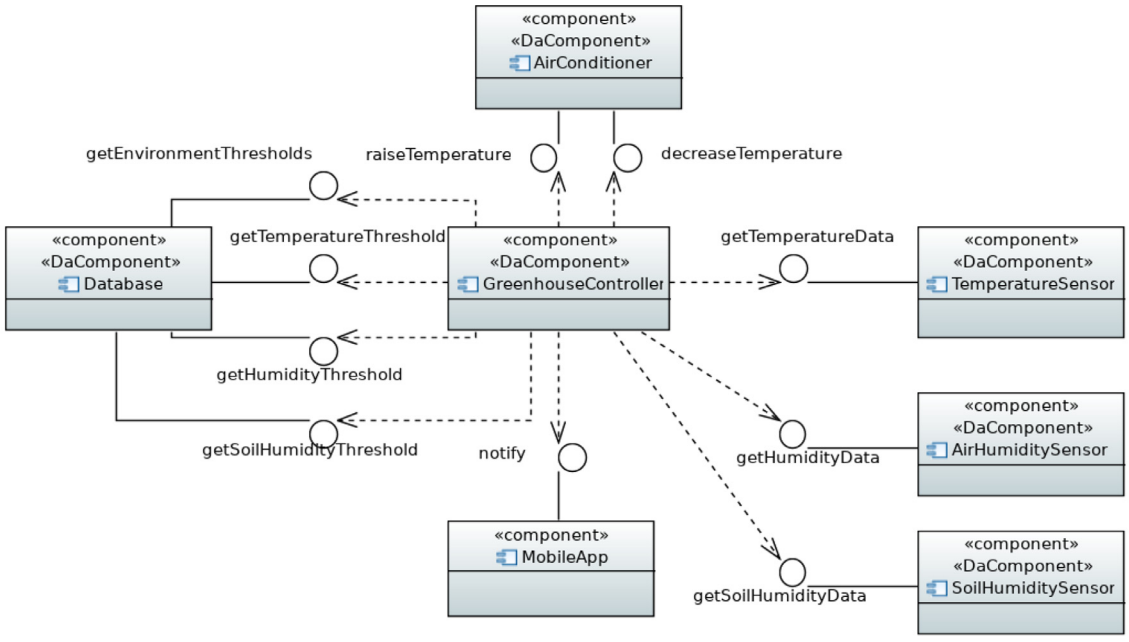
In order to further improve the system availability, we apply the *Semi-Active Replication* pattern to all the sensors components in the example application, as this pattern has proved effective in the deployment of sensors in high availability contexts [32]. Since the *Active Replication* pattern is widely used in practice to deploy high availability databases [33], we apply it to the *Database* component in each scenario. The results obtained from this refactoring are discussed in Section 5.1.3. An additional reason for the application of the *Active* and *Semi-Active Replication* patterns over their *Passive* and *Semi-Passive* counterparts resides in the stateless nature of the functionalities provided by the sensors and the database in the example application we are considering. Indeed, since the *Passive* and *Semi-Passive Replication* patterns accomplish error masking by saving the current state of a component through checkpoints, their application to stateless operations would only increase er-

Table 2
Steady state availability of execution scenarios.

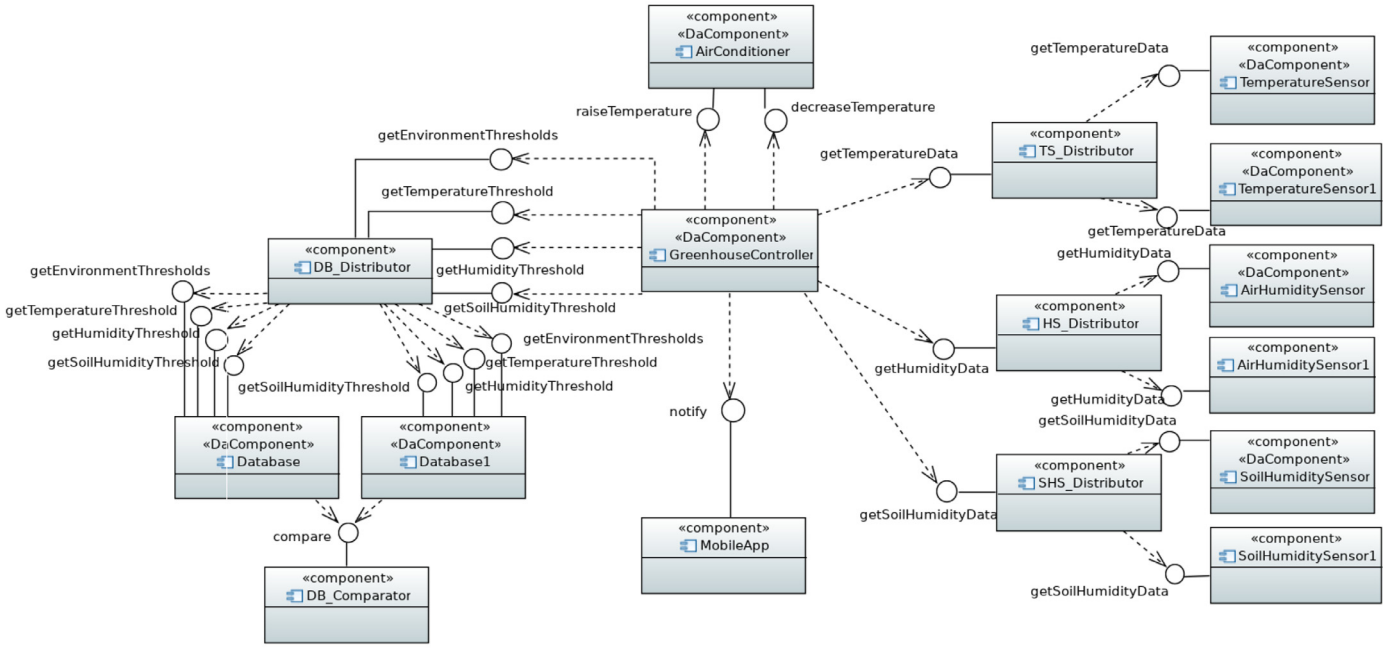
Monitoring Conditions	0.985392
Remote Monitoring	0.991672
Managing Temperature	0.977984

Table 3
Steady state availability of the *Managing Temperature* scenario after the application of fault tolerance patterns on *TemperatureSensor*.

Initial (no refactoring)	0.977984
Semi-Active Replication	0.985605
Active Replication	0.988511
Semi-Passive Replication	0.98026
Passive Replication	0.989855



(a) Initial Component Diagram of ECS



(b) Refactored Component Diagram of ECS

Fig. 12. Component Diagrams before and after the change propagation.

ror masking complexity and cost without providing additional benefits over the *Active* and *Semi-Active Replication* patterns.

4.4. Change propagation

After the analysis and refactoring step, the UML^{JASA}-GSPN bidirectional transformation is applied in backward direction on the refactored GSPN model. In particular, the refactored UML Sequence and State Machine Diagrams are generated for each scenario. These new diagrams contain the changes applied to the GSPN during the refactoring step and propagated back by the execution of the transformation.

Moreover, the back propagation of changes generates additional software components. The updated Component Diagram is reported in Fig. 12b. In particular:

- *Monitoring Conditions*: the components *TS_Distributor, TemperatureSensor1, HS_Distributor, AirHumiditySensor1, SHS_Distributor*, and *SoilHumiditySensor1* have been introduced by the application of the *Semi-Active Replication* pattern on *TemperatureSensor, AirHumidity-*

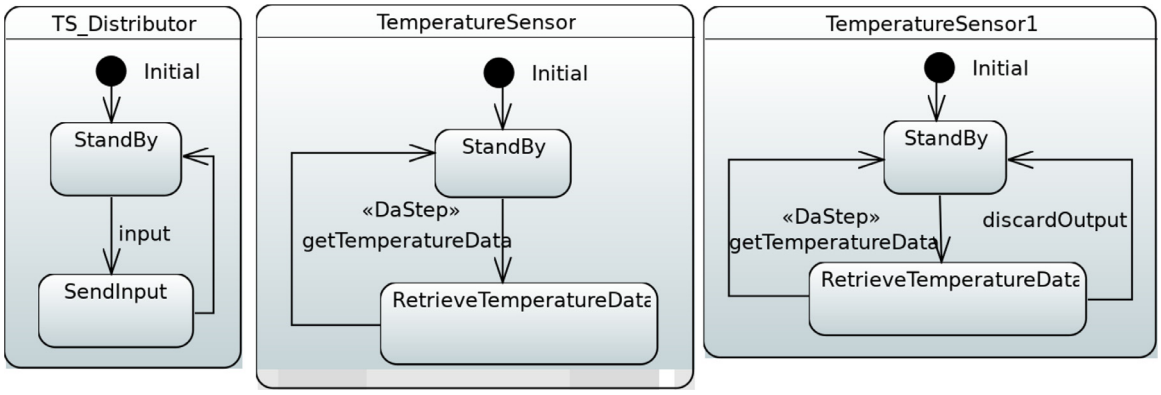


Fig. 13. UML State Machines generated from the back propagation of the *Semi-Active Replication* pattern on *TemperatureSensor*.

Sensor, and *SoilHumiditySensor*, while the components *DB_Distributor, DB_Comparator*, and *Database1* have been introduced by the application of the *Active Replication* pattern on *Database*;

- *Remote Monitoring*: the components *HS_Distributor, AirHumiditySensor1*, have been introduced by the application of the *Semi-Active Replication* pattern on *AirHumiditySensor*, while the components *DB_Distributor, DB_Comparator*, and *Database1* have been introduced by the application of the *Active Replication* pattern on *Database*;
- *Managing Temperature*: the components *TS_Distributor, TemperatureSensor1*, have been introduced by the application of the *Semi-Active Replication* pattern on *TemperatureSensor*, while the components *DB_Distributor, DB_Comparator*, and *Database1* have been introduced by the application of the *Active Replication* pattern on *Database*;

As a consequence of the back propagation, nine new state machines have been generated by enforcing the `StateMachine2PetriNet` relation and its triggered relations. The state machines corresponding to the original components are instead restored without any modification. In addition, each state machine corresponding to replicas in the *Semi-Active Replication* pattern (i.e., all sensors' replicas) includes a new `discardOutput` transition that represents the case in which no failure occurs in the original component and, as a consequence, the data computed by the replica must be discarded. As an example, the UML State Machines generated (*TS_Distributor* and *TemperatureSensor1*) and restored (*TemperatureSensor*) from the *Semi-Active Replication* pattern on the *TemperatureSensor* component are included in Fig. 13.

The refactored UML Sequence Diagrams for the scenarios *Monitoring Conditions, Remote Monitoring*, and *Managing Temperature* are shown in Figs. 14–16, respectively. In such diagrams, the application of the *Semi-Active Replication* pattern can be noticed by the presence of the `discardOutput` message that is sent from each sensor component (e.g., *TemperatureSensor, AirHumiditySensor, SoilHumiditySensor*) to its corresponding replica. Moreover, alternative fragments are created to model the two cases in which a failure may or may not occur. Lifelines for the newly created distributor and comparator components are included as well.

Finally, the obtained model is consistent with respect to the consistency relation defined in the transformation, and it is compliant with the source metamodel.

5. Results evaluation

In this section we discuss the evaluation we have performed with the aim of answering the following research questions:

RQ1: Does the approach generate an analyzable availability model from a software architecture model?

RQ2: Does the approach generate a valid software architecture model back from an availability model?

RQ3: Does the approach help to identify the fault tolerance patterns that better improve the system availability?

The evaluation has been conducted by applying the approach to the Environmental Control System (ECS) example application, described in Section 4. The software design has been modeled by means of UML diagrams; then, for each scenario the following process has been applied:

- the UML^{JASA}-GSPN bidirectional transformation has been executed in forward direction: thus, a Sequence diagram and a set of State Machine diagrams have been given as input and the corresponding GPSN has been obtained as output;
- the resulting GPSN has been analyzed to obtain the steady state availability index, and it has been then refactored on the basis of the fault tolerance patterns defined in Section 2.3;
- the UML^{JASA}-GSPN bidirectional transformation has been executed in backward direction: thus, the changes performed on the GPSN have been propagated to the UML model.

5.1. Insights on research questions

In order to assess the approach according to the research questions, several measurements and properties have been considered for each step of our evaluation. The results of the performed experiments are discussed in the context of each research question on the basis of the selected evaluation criteria.

5.1.1. RQ1: Analizability of the generated analysis models

In order to answer this research question, we have observed the results obtained by transforming the UML models in the corresponding GPSN models, as well as by applying the refactoring actions. For evaluating if the considered GSPN models can support our analysis, we refer to a set of basic behavioral properties (as introduced in Murata [34]) discussed as following.

Reachability: In order to decide if the considered GSPN is reachable, we have to establish if any state of the modeled system is reachable from the initial state through a finite sequence of transitions. Formally, it is the problem of finding if any given marking M is contained in the set of markings reachable from the initial marking M^0. This property is required since the availability metrics we considered are defined as reward functions on the reachability graph associated to the GSPN, as described in Section 4.3.

We verified the reachability of our GSPN models by using the GreatSPN tool, that is able to compute reachability graphs where every marking in the net is reachable from M_0. In our experiment, we can observe that all the reachability graphs have been successfully created. In Table 4, we report the cardinality of the reachability set $RS(M_0)$ for each scenario. In particular, the *Initial* values refer to the GPSN models obtained by applying the UML^{JASA}-GSPN bidirectional transformation, whereas the *Refactored* values refer to the GSPN models after the

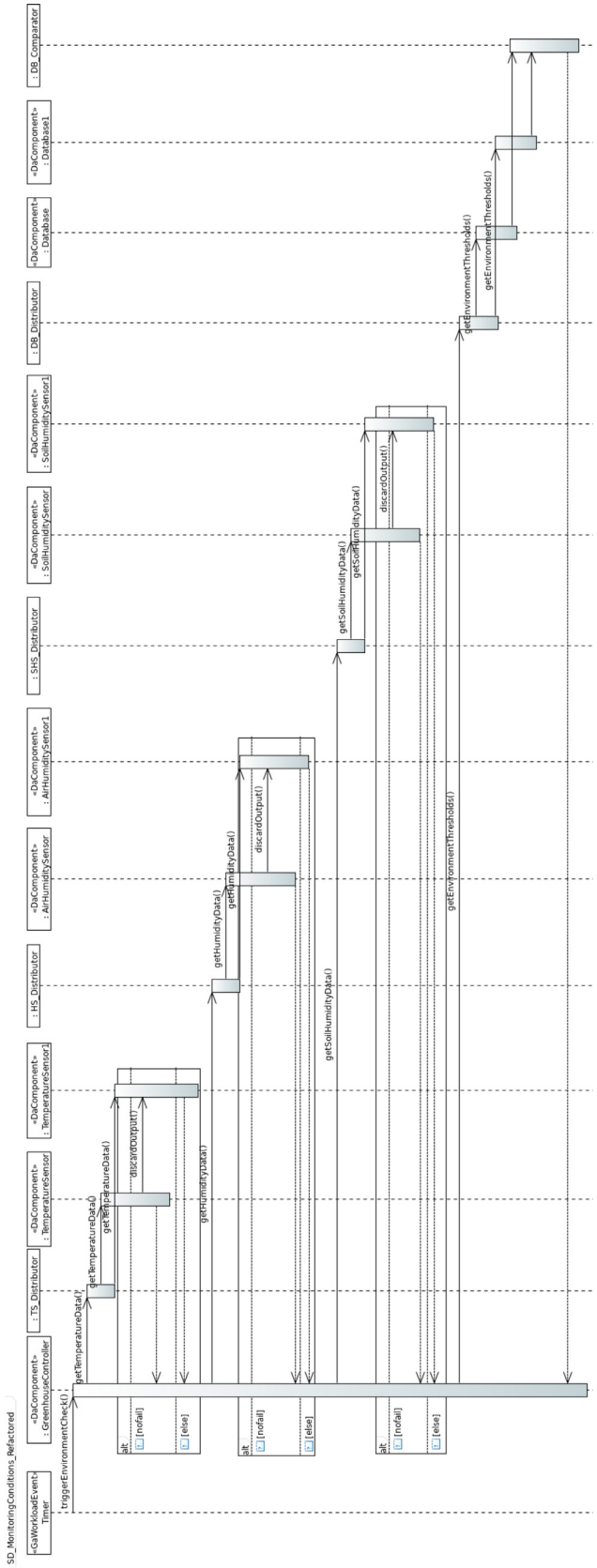


Fig. 14. UML Sequence Diagram of the *Monitoring Conditions* scenario.

Table 4
The cardinality of the reachability set of the GSPNs.

	Initial	Refactored
Monitoring Conditions	73	152
Remote Monitoring	66	105
Managing Temperature	77	116

refactoring described in Section 4.3. The new elements introduced by the refactoring of the GSPN caused an increase in the cardinality of the reachability sets because they originated new markings. Since we were able to compute finite reachability sets, we can assert that the application of the transformation in forward direction and of the refactoring patterns have generated reachable GSPN models.

Boundedness: A GSPN model is said to be bounded or safe if the number of tokens in each place does not exceed a fixed number for any marking reachable from the initial marking M_0. This property is required for the steady state availability analysis as bounded GSPNs are isomorphic to finite Markov Chains [35].

By considering that (i) a GSPN is bounded if and only if its reachability graph is finite [36], and (ii) we showed in Table 4 that finite reachability sets can be computed before and after the refactoring, we can assert that all the GSPNs (i.e., initial and refactored ones) are bounded.

More generally, our transformation is designed so that the generated GSPNs cannot contain transitions without input places. This property is a necessary condition for boundedness. Moreover, none of the proposed refactorings introduces this type of transitions.

Liveness: This property is closely related to the complete absence of deadlocks. A GSPN is said to be live if, for any reachable marking, it is possible to ultimately fire any transition of the net through some further firing sequence.

In our experiment, we can observe that all the GSPNs (both initial and refactored) are live, because from any reachable state it is possible to enable any transition by a firing sequence. In particular, the transitions modeling failures are *L1-live*, as they can be fired at least once in some firing sequence starting from the initial marking M_0. As an example, the transition *TS_t_getTemperatureData_loss* in Fig. 17 is a *L1-live* one, as it can potentially fire only once, when at least one token is in the place *TS_getTemperatureData_e*. All the other transitions in the GSPN are *L3-live*, since they can fire infinitely, as well as all transitions in Fig. 17 except *TS_t_getTemperatureData_loss*. In general, liveness of obtained GSPNs can be checked by the GreatSPN solver that we have adopted.

5.1.2. RQ2: Validity of the refactored architecture

In order to answer this research question, we have observed the results obtained by transforming the refactored GSPN back to the UML software architecture. To evaluate if the refactored architectural model is a still valid software architecture, we considered a set of properties that are commonly used in the analysis of software architectures [37].

Correctness:

It is an external property of an architectural model and ensures that it fully realizes the system specification. In order to evaluate the correctness of a refactored UML model resulting from the application of the approach, we need to consider the following aspects:

- We assume that the initial software architectural model is correct (i.e., it realizes the system specification).
- The refactoring applied on the GSPN model obtained from the forward application of the implemented UML^{JASA}-GSPN bidirectional transformation does not break the conformance to the system requirements. In fact, the adopted fault tolerance patterns make use of replicas and checkpoints techniques to provide error masking, thus without altering the original functionalities of the refactored component (as detailed in Section 3.3).

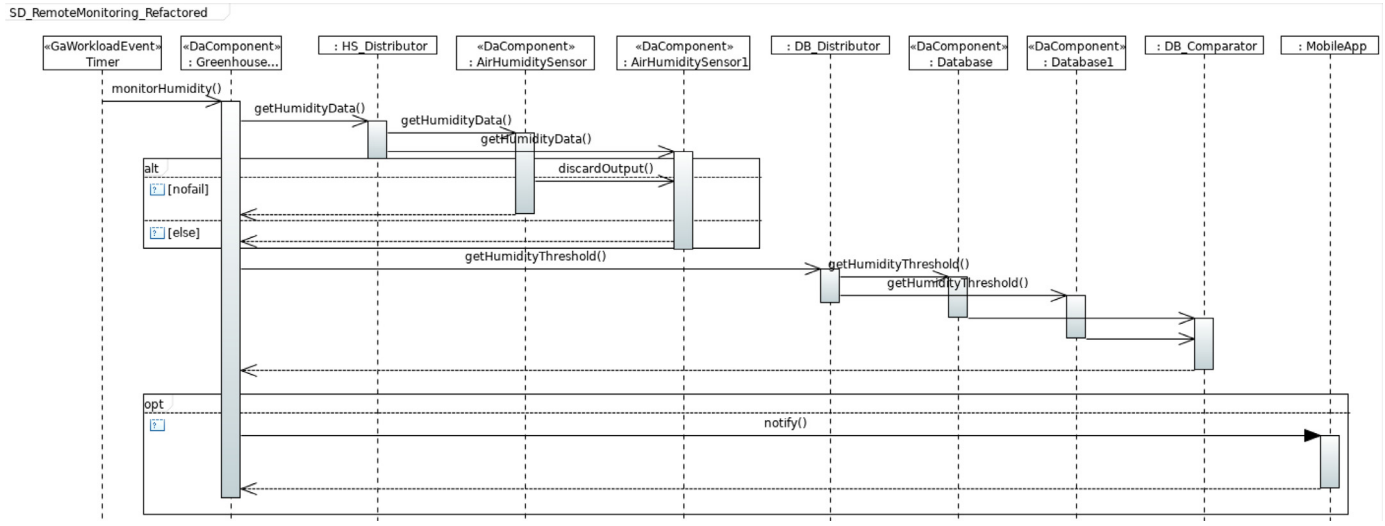


Fig. 15. UML Sequence Diagram of the *Remote Monitoring* scenario.

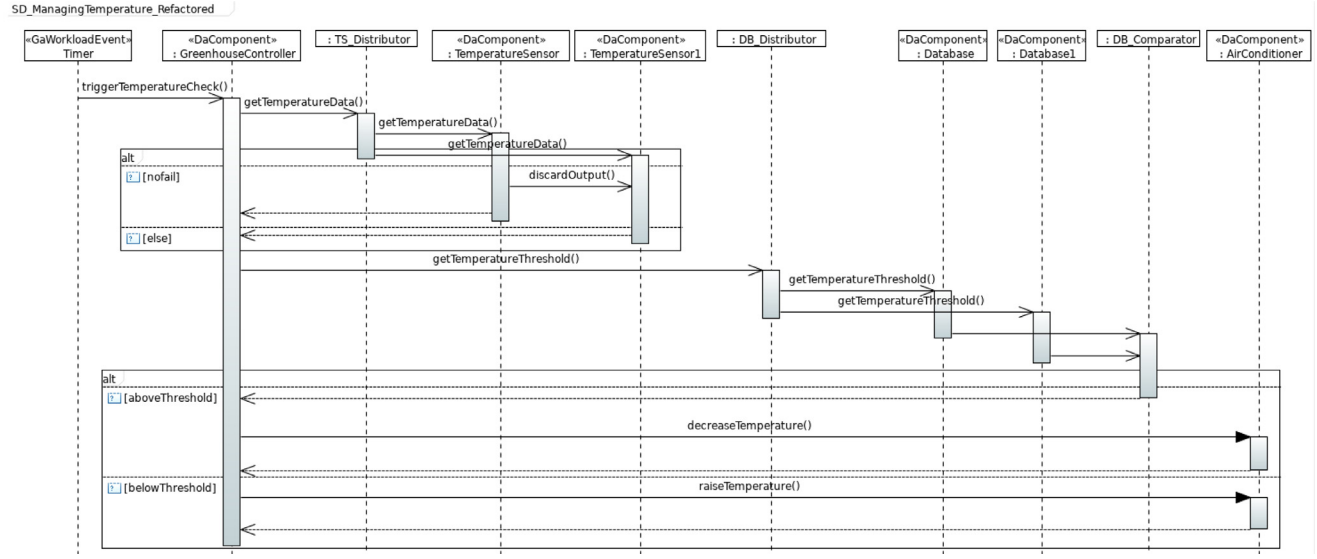


Fig. 16. UML Sequence Diagram of the *Managing Temperature* scenario.

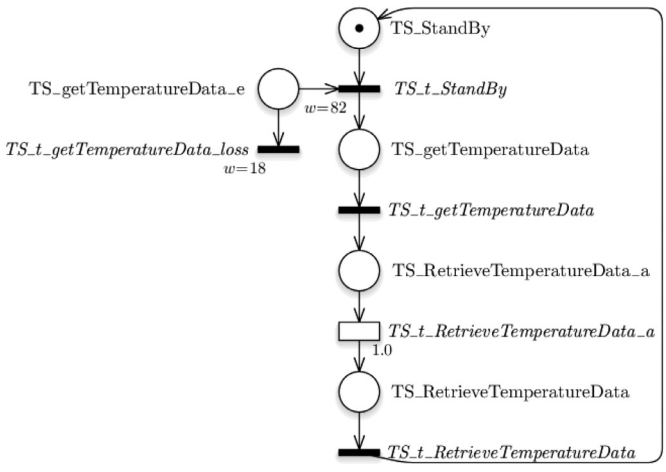


Fig. 17. GSPN subnet of the *Temperature Sensor*.

- The UML^{JASA}-GSPN bidirectional transformation is able to generate consistent solutions with respect to the relations specified in the transformation itself. In other words, the backward application of the transformation propagates changes by correctly mapping the refactoring patterns on GPSN in refactoring patterns in UML (i.e., without altering the original functionalities of the system). For instance, when a replica is introduced in the GSPN (e.g., Semi-Active and Active Replication pattern in Section 4), an additional state machine that contains the same states and transitions of the original component is introduced in the UML model, as well as additional messages from/to the replicated component.
- Finally, this aspect is strictly related to the correctness of bidirectional transformations. Formally, a bidirectional transformation T between two classes of models, M and N, is characterized by two unidirectional transformations: $\overrightarrow{T} : M \times N \rightarrow N$ and $\overleftarrow{T} : M \times N \rightarrow M$. T is said to be *correct* if for any pair of models $m \in M$ and $n \in N$, $T(m, \overrightarrow{T}(m,n))$ and $T(\overleftarrow{T}(m,n), n)$ [38]. The capability of the JTL framework to correctly execute the transformation is discussed in Cicchetti et al. [12], Eramo et al. [23]. As a proof of concept, by running

our transformation on forward and backward directions without any change on the example application, the transformation generated the same pair of models.

Completeness: This property is verified whether all necessary architectural elements are defined and whether all design decisions are made. In order to evaluate the completeness of the refactored UML model, let us to consider the following aspects:

- We assume that the initial software architectural model is complete.
- The refactoring applied on the obtained GSPN model operates only on components with probability of failure, without eliminating or modifying other architectural elements, where changes performed on those components are limited to the error handling. For example, in the Semi-Active Replication pattern described in Section 3.3, the primary component is enriched exclusively with elements that allow sending messages to the backup component in order to signal that no errors occurred and the output can be discarded.
- The UML^{JASA}-GSPN bidirectional transformation is able to preserve the completeness of the solution with respect to the relations specified in the transformation itself. The changes defined in the refactoring patterns are mapped in changes involving only the corresponding components without eliminating or modifying other architectural elements. For instance, the modification described above is translated in UML by means of adding a message in the corresponding Sequence Diagram and a transition in the corresponding State Machine.
- Finally, this property is related to another property of bidirectional transformations, namely the *hippocraticness* [38]. A transformation T is said to be *hippocratic* if for any model $m \in M$ and $n \in N$, $T(m, n)$ implies $\overleftarrow{T}(m, n)$ and $T(m, n)$ implies $\overleftarrow{T}(m, n)$. In our context, it means that the backward execution of the UML^{JASA}-GSPN transformation does not modify any part of the UML initial model that still complies, along the specified relation, with the refactored GSPN. In other words, the transformation only modifies the portions of the UML model where refactoring patterns have been applied in the related GSPN model portions. The capability of the JTL framework to guarantee hippocraticness is discussed in Cicchetti et al. [12], Eramo et al. [23].

Consistency: It is an internal property of an architectural model ensuring that the defined architecture does not contain contradicting information. In order to evaluate the consistency of the refactored UML model, let us consider the following aspects:

- We assumed that the initial software architectural model is consistent.
- Examples of inconsistencies are inconsistent names, interfaces, and refinements of architectural elements. The UML^{JASA}-GSPN bidirectional transformation specifies the mapping between UML and GSPN elements by preserving the consistency of names and structure (e.g., in the GPSN models the same names are used for the corresponding elements). On our example application, indeed, we observed that the generated architecture does not contain information that contradicts the initial one.
- Finally, the JTL framework helps in guaranteeing this property. In fact, the invertibility of a transformation can be severely affected in case of partial transformations that do not cover all the concepts. The consequent information loss may give place to unwanted behavior when the transformation is reversed. The traceability engine of JTL is able to preserve the missing information and restore it, thus avoiding loss of information [39].

5.1.3. RQ3: Pattern selection for availability improvements

It is obvious that the application of any fault-tolerance pattern should improve the system availability, as it will be shown and discussed in Table 5. It is, instead, less obvious to identify the patterns that more effectively improve the system availability when applied to specific components within defined scenarios.

Table 5
Steady state availability computed on the initial ($\mathfrak{A}_0$) and refactored ($\mathfrak{A}'$) architecture.

	$\mathfrak{A}_0$	$\mathfrak{A}'$
Monitoring Conditions	0.985392	0.990771
Remote Monitoring	0.991672	0.994207
Managing Temperature	0.977984	0.993316

This research question aims at addressing such issue, by showing the effects on the system availability of the application of fault tolerance patterns to different components in different scenarios.

We define the following notation for the remaining of this section. We denote by: $\mathfrak{A}_0$ an initial architectural model; $r_{ftp}(C)$ a single refactoring action, which consists in applying a single fault tolerance pattern *ftp* to a specific component *C; R* a refactoring strategy, that is the joint application of multiple r_{ftp} actions to specific components ($R = \{r_{ftp}(C)\}$). A refactoring application obviously leads to a refactored architecture $\mathfrak{A}'$, namely: $R(\mathfrak{A}_0) \rightarrow \mathfrak{A}'$.

The system availability will be denoted by *Avail*, and it is intended to be computed on a specific architecture $\mathfrak{A}$, in the context of a specific execution scenario denoted by ES^x (where x is the scenario name, e.g., *MT* stands for *Managing Temperature* in our example application), while varying the failure probability (FP_I^y) of the architectural component y within the range I.

We start by investigating how changes in failure probabilities affect the improvements introduced by the application of the fault tolerance patterns in a specific execution scenario. Fig. 18 shows how the steady state availability of the *Managing Temperature* scenario (ES^{MT}) is altered when varying the failure probability of the *TemperatureSensor* component (FP^{TS}) in the interval [0.01, 0.5].

The figure shows the availability $Avail(\mathfrak{A}_i, ES^{MT}, FP^{TS}_{[0.01,0.5]})$ computed for five alternative architectures:

(i) the initial architecture $\mathfrak{A}_0$ in red, on which no refactoring action is applied;
(ii) the architecture $\mathfrak{A}_1$ in heavy green, on which the refactoring action r_{SAR} (i.e., *Semi-Active Replication* pattern) is applied on the *TemperatureSensor* component (i.e., $R(\mathfrak{A}_0) \rightarrow \mathfrak{A}_1$ where $R = \{r_{SAR}(TS)\}$);
(iii) the architecture $\mathfrak{A}_2$ in light green, on which the refactoring action r_{AR} (i.e., *Active Replication* pattern) is applied on the *TemperatureSensor* component (i.e., $R(\mathfrak{A}_0) \rightarrow \mathfrak{A}_2$ where $R = \{r_{AR}(TS)\}$);
(iv) the architecture $\mathfrak{A}_3$ in heavy blue, on which the refactoring action r_{SPR} (i.e., *Semi-Passive Replication* pattern) is applied on the *TemperatureSensor* component (i.e., $R(\mathfrak{A}_0) \rightarrow \mathfrak{A}_3$ where $R = \{r_{SPR}(TS)\}$);
(v) the architecture $\mathfrak{A}_4$ in light blue, on which the refactoring action r_{PR} (i.e., *Passive Replication* pattern) is applied on the *TemperatureSensor* component (i.e., $R(\mathfrak{A}_0) \rightarrow \mathfrak{A}_4$ where $R = \{r_{PR}(TS)\}$).

The results show that, while the *Active Replication* and *Semi-Active Replication* patterns perform better with small failure probabilities values, the *Passive Replication* and *Semi-Passive Replication* patterns are more robust to an increase in the failure probability of the components they are applied on. This figure shows how our approach can support the designer decisions to identify the best refactoring actions with respect to the variation of system parameters. More specifically, in this case the *Semi-Active Replication* pattern appears to be the best choice when the failure probability value of *TemperatureSensor* is within the range [0.01, 0.115], whereas, for higher values, *Passive Replication* pattern should be preferred.

In order to move from single refactoring actions to combined ones, for each considered scenario, we have first measured the availability on the GPSN model before and after applying the refactoring changes

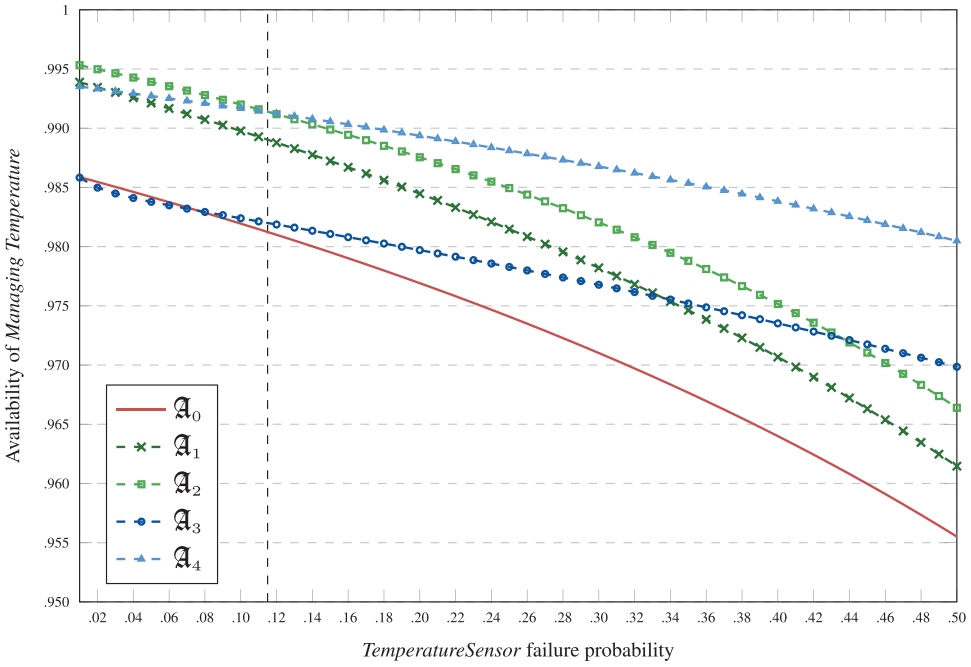


Fig. 18. Availability of *Managing Temperature* scenario vs. *TemperatureSensor* failure probability under single refactoring actions.

mentioned at the end of Section 4.3, namely $R(\mathfrak{A}_0) \rightarrow \mathfrak{A}'$, where $R = \{r_{SAR}(TS), r_{SAR}(HS), r_{SAR}(SHS), r_{AR}(DB)\}$. The observed steady state availability indexes resulting from the analysis are reported in Table 5. The availability is computed on the *Monitoring Conditions* (ES^{MC}), *Remote Monitoring* (ES^{RM}), and *Managing Temperature* (ES^{MT}) scenarios by considering the specific failure probabilities reported in Table 1. The measures highlight that the application of the fault tolerance patterns has improved, as expected, the availability in each considered scenario.

The *Managing Temperature* scenario had an improvement of 15.332×10^{-3} after the application of the *Semi-Active Replication* pattern on *TemperatureSensor*, and the *Active Replication* pattern on the *Database* component. The *Monitoring Conditions* scenario had an improvement of 5.379×10^{-3} after the application of the *Semi-Active Replication* pattern on *TemperatureSensor, HumiditySensor* and *SoilHumiditySensor*, and the *Active Replication* pattern on the *Database* component. Finally, the *Remote Monitoring* scenario had an improvement of 2.535×10^{-3} after the application of the *Semi-Active Replication* pattern on *HumiditySensor*, and the *Active Replication* pattern on the *Database* component.

Then, we performed a sensitivity analysis of availability, for each considered scenario, by varying in the interval [0.01, 0.5] the failure probability of each refactored component involved in the scenarios.

In what follows, we show how some changes in the failure probabilities of components affect both the initial architecture $\mathfrak{A}_0$ and the refactored architecture $\mathfrak{A}'$ obtained by applying R defined above to $\mathfrak{A}_0$. In particular, Figs. 19–21 report the results for the *Monitoring Conditions, Remote Monitoring*, and *Managing Temperature* scenarios, respectively.

The curve notation is the same as for Fig. 18. For example, in Fig. 19 we depict $Avail(\mathfrak{A}_0, ES^{MT}, FP^{TS}_{[0.01,0.5]})$ and $Avail(\mathfrak{A}_0, ES^{MT}, FP^{DB}_{[0.01,0.5]})$ as solid curves, whereas $Avail(\mathfrak{A}', ES^{MT}, FP^{TS}_{[0.01,0.5]})$ and $Avail(\mathfrak{A}', ES^{MT}, FP^{DB}_{[0.01,0.5]})$ as dashed curves, respectively. For the other two figures, of course, the scenario and the related involved components are different. For the sake of clarity, in the legend of each figure we indicate, beside the architecture name, the involved component whose failure probability varies to obtain that specific curve.

The graphs clearly show improvements of the availability in all scenarios. Moreover, by comparing the effects of refactored components with those of original ones, we can see that, while the failure probability increases, the availability decreases more slowly after the refactoring. In other words, we can observe that the architecture $\mathfrak{A}'$ can better withstand an increase in failure probabilities than $\mathfrak{A}_0$ does.

Finally, we remark that this analysis provides further support to designers, by distinguishing the robustness of a refactoring strategy vs. failure probability variations of different components. For example, Fig. 19 shows that R is more effective on the architecture $\mathfrak{A}'$ when the *TemperatureSensor* failure probability increases with respect to when the *Database* one increases. Indeed, this effect is emphasized by the increasing distance between solid and dashed red curves, whereas the distance between orange curves remains more or less the same all across the *Database* probability failure range.

5.2. Threats to validity

In this section, potential threats to validity associated with the experimental evaluation are discussed, by distinguishing internal, external, construct and conclusion validity.

Internal validity: concerns any extraneous factor that could influence our results. In general, the implementation of the approach could be defective, as well as the results of the analysis could be inaccurate. We mitigated these threats: i) by specifying our transformation on the base of already existing mapping from Sequence Diagrams and Statecharts to GSPNs [28]; ii) by considering already existing fault tolerance patterns [15]; iii) by considering well-established methods for stochastic availability assessment [29]; iv) by delegating the availability analysis to an external solver [30]. Obviously, all the above actions mitigate the possibility of introducing faults in the model transformation, because it is based on solid specifications. We recall here that, by construction, the transformation only produces, as output, models conforming to both metamodels, although we have not performed any formal proof on the semantic correctness of the results.

External validity refers to the generalizability of the obtained results. With reference to the model transformation, we have adopted standard metamodels, thus the approach can be applied to any other conforming model. The analysis can be generalized to other models, even

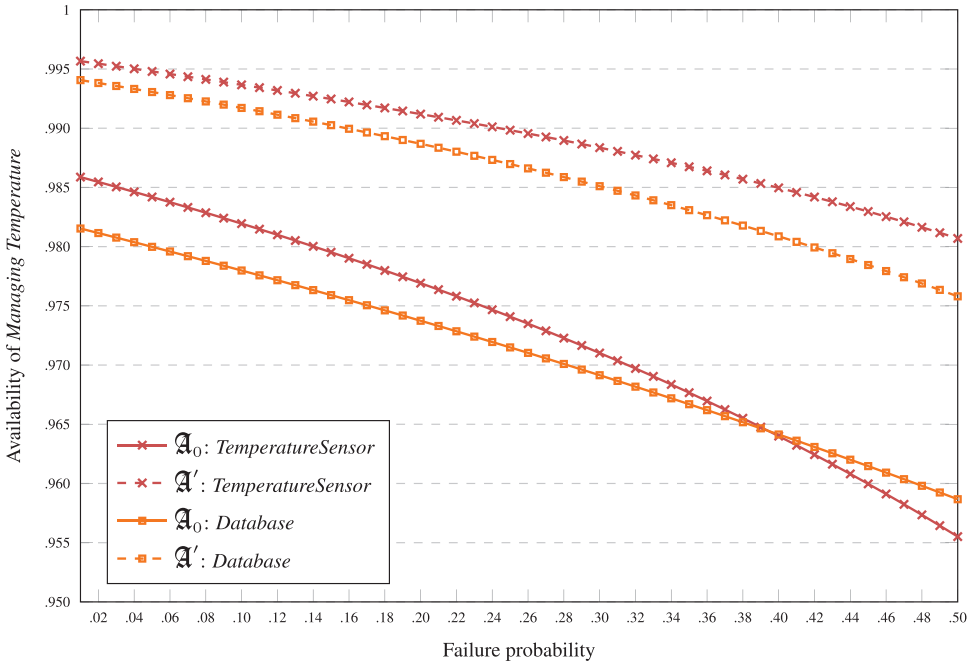


Fig. 19. Availability of *Managing Temperature* scenario on the initial ($\mathfrak{A}_0$) and refactored ($\mathfrak{A}'$) architecture vs. failure probabilities under combined refactoring actions.

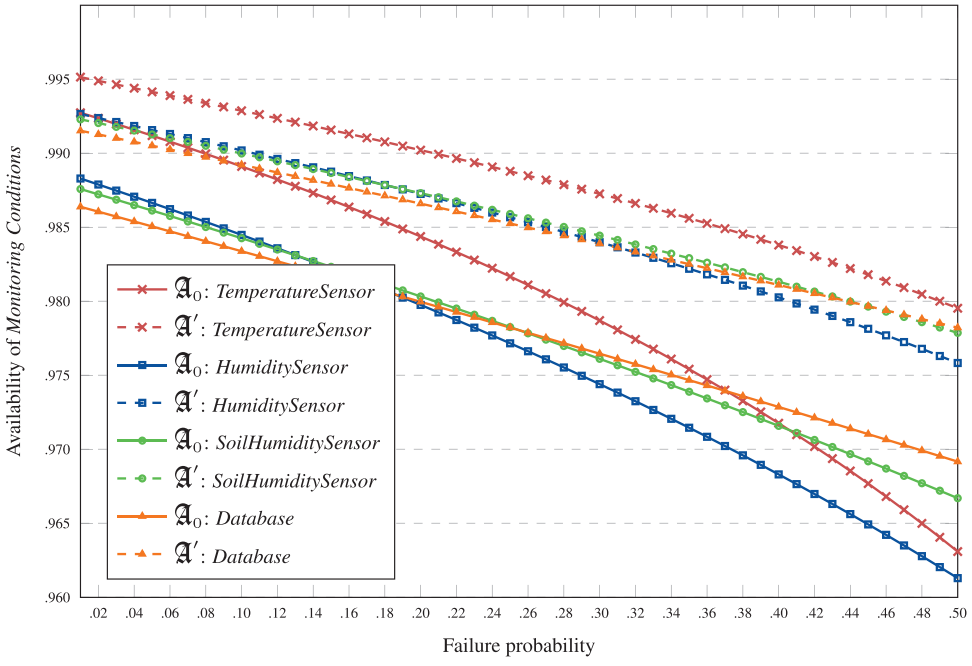


Fig. 20. Availability of *Monitoring Conditions* scenario on the initial ($\mathfrak{A}_0$) and refactored ($\mathfrak{A}'$) architecture vs. failure probabilities under combined refactoring actions.

though the considered fault tolerance patterns obviously change their effectiveness depending on the specific software system. However, our approach can be extended to apply additional patterns at the cost of specifying them in GSPN. Finally, the size of the example application considered here is not very large, but complex enough to demonstrate the effectiveness of the approach. Nothing can be asserted about the scalability of the approach on large size architectures, which remains one of our future objectives. However, we remark that our approach is intended to be used within a decisional process that usually is not constrained by hard real-time requirements, like it could have been the assessment of availability at runtime. Hence, even several hours of processing time could represent a reasonable cost to be afforded in practice for exploring a solution space difficult to inspect without automation.

Construct validity concerns the validity of our results with respect to the evaluation criteria. As said, we considered well-know methodologies and methods existing in literature both for the transformation specification and the availability analysis. This mitigates the presence of factors that can compromise the validity of the experiment and of the results.

Conclusion validity concerns the reliability of the measures that, in this case, refers to the reproducibility of the results. In order to ensure that our results are reproducible, we repeated each measurement three times and made sure that there were no differences between the measured values with an approximation of 10^{-5}. The artifacts considered in this experiment are supplied via a GitHub repository,[9] and the experiment can be reproduced locally within the JTL framework.

[9] https://github.com/SEALABQualityGroup/JASA.

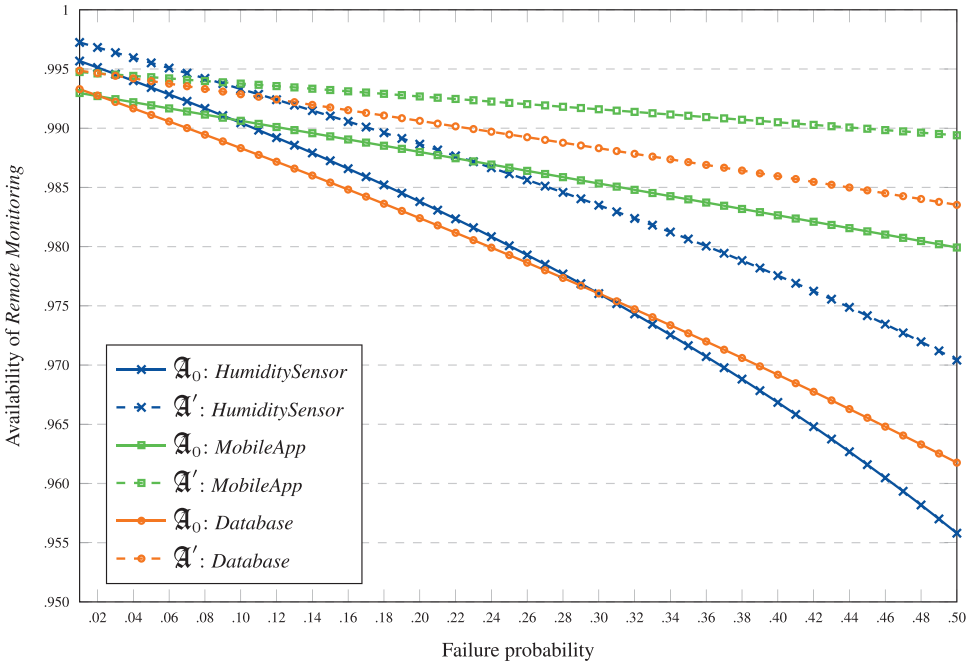


Fig. 21. Availability of *Remote Monitoring* scenario on the initial ($\mathfrak{A}_0$) and refactored ($\mathfrak{A}'$) architecture vs. failure probabilities under combined refactoring actions.

6. Related work

Several approaches have been introduced in the last few years to derive analysis models from annotated software models. Bondavalli et al. [40] represents one of the first attempts at enriching a UML design to specify dependability aspects. The authors define UML extensions to generate Stochastic Petri Net models for dependability analysis automatically. High-level SPN models are derived from UML structural diagrams and later refined using UML behavioral specifications. The transformation relies upon an intermediate model, and no standard UML profiles are employed since none were available at the time of publication. In [41], Huszer et al. propose a transformation of UML statechart diagrams into Stochastic Reward Nets (SRN) to conduct a performance and dependability analysis. The transformation is defined as a set of SRN patterns, and the dependability analysis is performed under erroneous state and faulty behavior assumptions. Mustafiz et al. [42] also present a mapping between a probabilistic extension of statecharts and a Markov chain model for quantitative assessment of safety and reliability. Bernardi et al. [26] propose a transformation of UML sequence, statechart and deployment diagrams into a GSPN model for performability analysis. Software models are annotated using the former standard UML SPT profile. Our bidirectional transformation is based on the mechanisms related to statechart transformation as formally specified in Bernardi and Merseguer [26], which we have implemented in JTL. By taking advantage of bidirectional transformations, the designer can automatically propagate the refactoring performed on the analysis model back to the UML model.

On top of automated derivation of analysis models from software models, several approaches have been built for multi-objective software architecture optimization driven by non-functional attributes. None of these approaches explicitly consider availability as a target, even though some of them consider failure probabilities of components and/or platform devices.

In particular, in Martens et al. [43] an evolutionary algorithm is introduced for optimizing performance, reliability and cost. Failure probabilities are associated to hardware connectors only, and a discrete-time Markov chain is generated to calculate the probability for the whole system to be in a failure state. Hence, this approach considers different model elements to be subject to failures, as well as a different non-functional target property with respect to our work. Moreover, the architecture refactoring actions in Martens et al. [43] are not specifically targeted to fault tolerance as in our case, but rather generic refactoring actions, such as component replication. These differences about target properties and non-specific fault tolerant actions remain in other similar works that have appeared in the context of architecture optimization, such as [44].

In the context of bidirectional model transformations, a round-trip engineering process between models representing different views of the same system is formally defined in Hettel et al. [45]. In the performance analysis domain, in a previous paper [9], we have introduced a similar approach to the one presented in this paper. In particular, we have defined a bidirectional model transformation between UML software models and Queueing Network (QN) performance models. The forward transformation path generates the performance model from the initial software model, whereas the backward one is used to generate, after the analysis, a new software model from the modified version of the performance model. In [46] two methods to tackle the problem of deriving architectural changes from model-based performance analysis results have been compared: (i) to perform refactoring on the software side by detecting and solving performance antipatterns, or (ii) to modify the analysis model using bidirectional model transformations to induce architectural changes. This represents an interesting study for reasoning on the pros and cons of modifying a non-functional model as opposite to applying modifications to a software architectural model.

In [47], the authors propose principles to use fUML (Foundational Semantics for Executable UML Models) and Alf (Action Language for fUML) as a simulation environment. However, this approach provides only the structural modeling constructs of UML, whereas the ability to model behavior is limited to UML activities. Hence, in order to exploit the simulation environment, availability parameters (such as the failure probabilities) should be defined within the modeling language and the simulation engine could require to be extended to process them. As opposite, the use of languages as DAM that natively supports the definition of dependability parameters, coupled with transformations towards analysis models like GSPNs, does not require to extend the modeling language and the solution/simulation engine. Finally, this process would be subject to scalability problems, as pointed in Berardinelli et al. [48,49].

To the best of our knowledge, this is the first paper proposing an automated propagation of changes performed on an availability model back to an architectural model. Even though the scope of this paper

is limited to the modeling notation context considered here (i.e., UML-DAM and GSPNs), our approach represents a first step towards the usage of bidirectional transformations for closing a round-trip process for software availability modeling and analysis.

7. Conclusion

In this paper, we proposed JASA, a model-driven framework that supports a round-trip availability analysis process based on software architectural refactoring. We used bidirectional model transformations to map software architectures represented by UML models to GSPN analysis models and vice versa. In fact, after the analysis, the obtained GSPN is modified according to a proposed catalog of refactoring based on well-known fault tolerance patterns. Finally, the changes are back propagated to the software architecture with the aim of improving the software availability. The effectiveness of our approach has been demonstrated on an Environmental Control System, in terms of ability to generate analyzable availability models from software architectures and valid software architectures from availability models. Also, we showed how to select more effective fault-tolerance patterns in different execution scenarios.

Although we considered a set of well-known fault tolerance refactoring techniques, the approach can be extended to support further user-defined refactoring actions and to automate the application of such actions on GSPN models completely. In this respect, the bidirectional model transformation needs to be modified in order to cope with a larger set of relationships. As a possible consequence of this modification, the change propagation from analysis to architectural models may result in the generation of multiple architectural alternatives, because a single refactoring action in a GSPN can be mapped in more than one refactored architectural model. This is our main future work direction, where we can still exploit the JTL transformation engine that is able to support non-bijective mappings by generating all the alternative solutions according to the specification. In the same direction, a further challenge for the future is to introduce a human-assisted process for choosing among multiple suggested alternatives.

Finally, another line of future investigation encompasses the extension of the proposed methodology to further non-functional requirements such as reliability and safety.

Credit author statement

The contribution of each author is equivalent for all the CRediT (Contributor Roles Taxonomy) roles.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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