Architectural Solutions for Self-Adaptive Systems

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Abstract—Increasingly adopted in critical application domains, self-adaptive systems (SaS) present a particular ability to modify their behavior or configuration at runtime autonomously. The architectural activity of decision-making in an SaS requires the selection of the best software structures configuration. At the same time, requirements of quality attribute (e.g., interoperability, maintainability, reliability), adaptive capabilities (e.g., self-management, self-organization), control approaches (e.g., centralized, distributed), and human interventions must be balanced. This work presents Four4SaS, a collection of the main rationale and knowledge to architect SaS. Four4SaS’ solutions encompass well-known architectural patterns and their possible benefits and drawbacks of their use in SaS. Four4SaS’ architectural knowledge was reused for designing a river monitoring SaS. Domain-independent architectural solutions of Four4SaS can be used as an initial backbone to design future SaS and development frameworks for such systems.

Index Terms—self-adaptive system; software architecture; reference architecture; quality attribute; architectural pattern.

I. INTRODUCTION

Self-adaptive Systems (SaS) have increased their importance in the past few years, mostly because of their impact in several critical application domains, such as autonomous vehicles, smart cities, security surveillance, avionics, and health-care. SaS autonomously modify their behavior at run-time responding to operating environment changes [1].

An SaS is usually constituted by two types of systems [2]:
• Managed systems, which monitor and affect the external world with which the SaS interacts, and comprise the application logic that provides the system’s functionalities; and
• Managing systems, which encompass the adaptation logic that deals with one or more concerns, monitor both the environment and the managed systems, and adapt the latter when necessary to achieve SaS goals.

The managing system usually imposes control over the managed systems through the use of autonomic managers [3] or MAPE-K feedback loops that contain components executing activities of monitoring, analyzing, planning, and executing, and sharing domain and control knowledge [4]. During the architectural process, software architects must consider how control activities are coordinated and deployed, the most significant quality attribute requirements (e.g., performance, reliability, safety, availability, scalability), and the type of adaptive capabilities required by the SaS [5], e.g., context-awareness, situation-awareness, self-configuration, self-healing/protecting, self-optimizing, self-managing, self-organizing, and reflection.

Adaptive capabilities allow decreasing human intervention when systems’ modifications are required at run-time. Adaptive capabilities range from changes of specific data types to the reconfiguration of the complete SaS architecture in response to environmental changes, internal faults, unexpected constituents’ behaviors, integration of new constituents, new requirements, or changes in business goals. Architects must select the adequate strategies (e.g., architectural configurations, patterns, styles, and tactics, or even technologies) that enable the desired modifications without stopping the system’s operations and with the minimum human intervention. Architects’ decisions making is a challenging activity during the SaS engineering, since the success or failure of an SaS software project mostly depends upon the correctness of its architecture for considering control activities, adaptive characteristics, and quality attribute requirements. However, the rationale behind architectural decisions is frequently known only by the SaS’ software team (including architect, developers, testers), making difficult the reuse of such knowledge in other SaS projects.

In this context, one question arises: how can we support architects to design SaS architectures based on the reuse of architectural knowledge?

The main contribution of this work is Four4SaS, a collection of four domain-independent solutions that guide and facilitate the architectural design of SaS. In Section II, we identify the recurrent SaS architectural configurations (i.e., arrangements of software structures) and investigate how they have been used to address different control, quality attributes, and adaptivity requirements. Based on these findings, Four4SaS is defined in Section III. To show its feasibility, Four4SaS was applied to architect a river monitoring SaS (RMS), as detailed in Section IV. Four4SaS’ solutions were assessed by fifteen SaS architects and results of such evaluation are explained in Section V. Section VI describes threats to the validity and limitations of this work. Finally, Section VII presents the related work highlighting the contribution of Four4SaS to state of the art and details further works.

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II. MINING SaS ARCHITECTURES

This section presents the research methods conducted to identify the main software building blocks of SaS architectures and their variation depending upon adaptive capabilities and control characteristics. This knowledge is the basis of the Four4SaS’ architectural solutions. Bearing this goal in mind, we performed the following steps:

1) Recurrent architectural solutions were extracted from 13 existing reference architectures (RAs) for SaS. Shortly, a RA presents the most relevant decisions (e.g., selection and arrangement of patterns and tactics, and description of the rationale behind the proposed solutions) for designing software systems architectures in specific domains [6]. RAs for SaS were identified through the conduction of a systematic mapping study following the guidelines found in [7]. The systematic mapping protocol and extracted data used in this work are detailed in [8]. The interested reader is referred to [8] which contains IDs (RA1 to RA13) and the complete reference for each architecture.

2) The recurrent SaS’ architectural solutions were extracted from the 13 RAs for SaS listed in [8]. Solutions were classified and summarized according to the main elements of an SaS architecture, namely, information about SaS’ constituent systems, control characteristics, adaptive capabilities, and architectural patterns, detailed, respectively, in Sections II-A to II-D, and summarized in Table I and mentioned in the remainder of this section.

A. Constituents Systems of SaS

An SaS is formed of two types of constituent systems: the managed and the managing systems. Each constituent system can present diverse adaptive capabilities; hence it can also be considered as an SaS. This characteristic requires architectures with multiple adaptation levels, i.e., SaS’ composition is based on managing systems hierarchies [2], as those proposed by RA2, RA6, RA8, RA10, and RA12.

B. Control Characteristics

Control in SaS is related to the distribution level of the managed and managing systems and the decentralization level of the control activities (i.e., monitoring, analysis, planning, and execution) [2]. Hence, the following control strategies can be adopted to address adaptive capabilities in SaS:

- **Category 1: (The managed and managing systems, and the control activities are centralized).** This strategy is common in SaS with capabilities as situation-awareness (RA1 and RA5) and self-configuration (RA3, RA6, RA8, and RA10);
- **Category 2: (The managed systems are distributed, while the managing systems are centralized and the control activities are decentralized.)** This category supports capabilities as self-configuration (RA12) and self-management (RA9 and RA11) in SaS;
- **Category 3: (Both managed, and managing systems are distributed, and the control activities are decentralized).** This strategy has been used in SaS with capabilities of self-management (RA2) and self-optimization (RA7); and
- **Category 4: (Both managed, and managing systems are distributed, and the control activities are full-decentralized).** SaS with capabilities of self-organization can be addressed using this control category (RA4, RA13).

The implementation of these control strategies is mostly based on the MAPE-K loop and its variations, as detailed in Table I. To represent domain and control knowledge, repositories, ontologies, and conceptual models are commonly used by the RAs to represent such knowledge.

C. Requirements of Adaptive Capabilities

Architectural solutions proposed in RAs have a focus on adaptive capabilities as situation-awareness, self-configuration, self-management, and self-organization. Reflection is considered in SaS’ architectures with self-management and self-configuration characteristics. Most RAs (i.e., 8/13) consider the occurrence of changes, simultaneously, in both managed and managing systems. Different SaS’ structures can change, ranging from managed systems’ entities (e.g., components, services, or interfaces) to managing systems’ plans, policies, and goals. No human involvement allows to execute close adaptations (as in RA1 and RA10), i.e., the SaS themselves manage a number of predefined adaptive actions, and no new behaviors and alternatives can be introduced at run-time [5]. Moreover, most architectures define open adaptations, i.e., new goals, requirements, and policies can be added, and even new adaptable entities can be introduced by humans [5].

D. Architectural Patterns and Quality Attribute Requirements

The most employed architectural patterns to design SaS and address diverse adaptivity and quality attribute requirements are described as follows.

**Layers** have been widely used regardless of the desired adaptive capabilities. Layers allow complex behaviors through hierarchies (RA1, RA3, RA4, RA5, and RA11). Lower layers implement fast adaptations (i.e., reconfigurations of the managed system), and higher layers are responsible for time demanding adaptations (i.e., selection of the best policy or plan to achieve missions based on current system status). Lower layers in RAs achieve performance requirements (RA1), and higher layers address reliability properties (RA10). Interoperability can also be supported by establishing generic connections between managed systems and managers (RA2 and RA5). Layers’ separation of concerns enhances maintainability and modifiability requirements [9].

**Shared-data Repository** is commonly presented in SaS architectures with self-configuration, self-management, or self-organization capabilities. It allows access to persistent data, ensuring the availability of context, control, configuration, and domain information. Also, it avoids undesired changes on data
due to modifications in managed and managed systems, contributing to modifiability [9] of SaS (RA2, RA4, RA9, RA11, and RA12). Finally, repositories reduce data exchange between managed and managing systems, and between hierarchies of these systems.

Blackboard and Pipes and Filters have been applied in SaS’ architectures with situation-awareness capability (RA1, RA5). Together, both patterns benefit performance since the blackboard allows efficient delivering of data between system’s layers [9], and the pipe and filters pattern grants concurrent execution of adaptations by high-level layers [9].

**Publish-Subscribe** is used in SaS’ architectures for self-optimization (RA7) with the following benefits: (i) performance to communicate data among SaS entities; (ii) modifiability due to low coupling between entities; and (iii) dynamic scalability, since managed systems can enter or exit without affecting other parts of the SaS.

**Service-Oriented Architecture (SOA)** has been applied in SaS with capabilities of self-organization and self-configuration (RA4, RA12). SOA benefits are: - interoperability of managed systems; - evolution and dynamic scalability of SaS according to new demands of resources; - availability of managing systems through their replication for processing monitored data of managed systems. The combination of SOA and Enterprise Service Bus (ESB) facilitates the integration of multiple managed systems, mediating and transferring monitored data to all the managing systems interested in such data.

**Master-Slave** has been adopted in SaS’ architectures with self-management properties (RA11). It benefits performance providing low response times to control changes in the managed system.

**Broker** facilitates mediation, communication, interoperability and integration of heterogeneous managed systems. Brokers have been considered for SaS with self-configuration requirements (RA12).

**Decorator** pattern allows behavior adaptations at fine granularity level, e.g., adaptations of components objects or parameters values. Decorator can improve the reliability of adaptations in SaS with self-configuration properties (RA12).

**HIIC** (Hierarchical Inter-Intra Collaborative) proposes hierarchies of MAPE-K loops and their coordination to make possible a decentralized control in SaS [10]. HIIC has been used in SaS with high-level adaptive capabilities as self-configuring or self-management (RA13).

### III. Four4SaS: Architectural Solutions for SaS

Adaptive capabilities and distributed levels of control and constituent systems have a strong influence at determining SaS’ architectures. *Four4SaS* defines four generic and reusable solutions based on the architectural knowledge mined from RAs for SaS. Table II summarizes each *Four4SaS* solution, detailing information about:

- Control strategies adopted by the solutions (C1 to C4) and mentioned in Sections III.A to III.D;
- Monitored elements in the SaS (i.e., managed systems layer or manager systems layer);
- Reasons ([R]) why adaptations are required;
- SaS’ elements ([E]) that need to be adapted;
- Adaptive requirements that are possible to address with the *Four4SaS* solutions;
- Adaptation type, depending on whether the architecture allows open or close adaptations;
- Benefits ([B]) regarding quality attribute requirements and capacities achieved with the solutions; and
- Possible drawbacks ([D]) that the solutions could bring to an SaS.

In this table, in the cases where the reasons for adaptations ([R]), elements to be adapted ([E]), benefits ([B]), and
Fig. 1: Architectural solution for SaS with control strategies C1, C2, C3, and C4
TABLE II: Description of Four4SaS’ Architectural Solutions

<table>
<thead>
<tr>
<th>Four4SaS Solution</th>
<th>Monitored Elements</th>
<th>Reason for Adaptation</th>
<th>Elements to be Adapted</th>
<th>Adaptivity Requirements</th>
<th>Adaptation Type</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy C2</td>
<td>Managed and managers systems layers</td>
<td>[R1], [R3]; [R4] Faults discovery or diagnosis.</td>
<td>[E1], [E2]; [E3] Behavior, states, or configuration of systems in the managers layer.</td>
<td>Self-configuration and self-management of the SaS</td>
<td>Close and open adaptations</td>
<td>[B3]; [B4] Systems at the managed systems layer can scale; [B5] Redundancy of monitored or managed systems; [B6] Hierarchies of manager systems allow complex SaS’ reconfigurations or adaptations.</td>
<td>[D3], [D4]; [D5] The mediation layer can be a single point of failure; [D6] High-level managers are no scalable;</td>
</tr>
<tr>
<td>Control Strategy C3</td>
<td>Managed and managers systems layers</td>
<td>[R1], [R4]; [R5] Management of performance and resource allocation.</td>
<td>[E1], [E2], [E3]; [E4] Mediation layer.</td>
<td>Self-optimization and self-management of the SaS</td>
<td>Close and open adaptations</td>
<td>[B3], [B4], [B5], [B6]; [B7] It enables the identification, prevention, and recovery from faults, at all layers, due to problems in physical nodes.</td>
<td>[D4], [D5], [D6]; [D7] Possible bottleneck in the mediation layer due the increment of data to be transferred.</td>
</tr>
<tr>
<td>Control Strategy C4</td>
<td>Managed and managers systems layers</td>
<td>[R1]; [R6] Instantiation, activate, deactivate, remove, update elements located in the managers systems layer; [R7] Scale elements in the manager systems layer.</td>
<td>[E1], [E2], [E3], [E4].</td>
<td>Self-organization and scalability of the SaS.</td>
<td>Close and open adaptations</td>
<td>[B3], [B5], [B6], [B7]; [B8] Various high-level managers can address multiple adaptive capabilities at the same time; [B9] Monitored data can be distributed to multiple managers for different purposes; [B10] Systems at the managed and manager layers can scale;</td>
<td>[D5], [D7]; [D8] Possible conflict between adaptive properties; [D9] Additional strategies for coordinating highly distributed autonomic managers located in the manager systems layer.</td>
</tr>
</tbody>
</table>

A drawback ([D1]) are presented in more than one solution, they are described in their first occurrence, and only their codes are used in the text. Architects can use this table as a guide to select the adequate solution for architecting an SaS. Each solution is depicted in Figure 1 and explained as follows.

A. Architectural Solution for SaS with control strategy of Category 1 (C1)

To design SaS with adaptive requirements of situation-aware and self-configuration, architects can structure their systems, as shown at the upper-left of Figure 1. This architecture is adequate for SaS that, based on measures obtained from the managed system, require to make changes in the adaptation plans or policies, or even in the behavior, state, or configuration of such systems. SaS modifications occur when the final user (SaS administrator) updates the adaptation plans and policies, faults are detected, or managed systems change their state and configuration. This architecture allows close adaptations, i.e., the manager system (e.g., autonomic manager) decides which type of reconfiguration should be executed based on policies or plans previously stored in a shared repository.

One benefit, shared by all Four4SaS’ solutions, is to enhance modifications and maintenance of SaS’ elements thanks to the low-coupling that Layers provide. This first solution also makes it possible to execute fast reconfiguration of the managed system when the control activities (i.e., monitor, analyze, plan, and execute) are organized as a centralized MAPE-K feedback loop that follows the Pipes and Filters pattern. Fast communications are as well possible when the Blackboard pattern (allocated in the Repositories layer) is used to store and communicate all measures obtained from the managed systems.

A drawback of this solution is that the SaS will have a monolithic and no scalable architecture. Besides, the existence of a unique autonomic manager can result in a single point of failure that could completely stop the SaS’ operations. Additionally, the centralized control made by the autonomic manager only allows addressing an individual adaptive property at the time, limiting the type of adaptations that an SaS can perform.

B. Architectural Solution for SaS with control strategy of Category 2 (C2)

The second solution of Four4SaS (presented at the bottom-left side of Figure 1) allows adaptive capabilities of self-configuration and self-management. Comparing with the previous alternative, this solution requires monitoring both managed and managers systems. The information obtained from monitored systems is used by high-level managers to define which elements to change, i.e., behavior, state, and configuration of managed systems and low-level managers, due to faults presented by the monitored systems. It is possible to execute close adaptations in an SaS. Open adaptations are also possible since final users (SaS administrators) can send new policies directly to high-level managers. The distributed property of managed systems requires a Mediation layer to support data transfer between managed systems and managers.

One benefit of this architecture is the possibility to scale and replicate managed systems and low-level managers, increasing the reliability of monitored data. This is possible by the allocation of managed systems in distributed physical nodes. Additionally, the distribution of managers, following
a hierarchy of MAPE-K components, allows to plan and execute more complex adaptations by high-level autonomic managers. This characteristic also favors the SaS’ reliability. In this architecture, fast changes are possible when the Master-Slave or Decorator patterns are used as a basis to organize MAPE-K hierarchies. The combination of Broker and Publish-Subscribe patterns can be used to structure the Mediation layer, improving interoperability between managed systems and managers and the performance when data is transferred.

One drawback is that Mediation layer can be a single point of failure, disconnecting the managed systems and stopping the SaS operation. Moreover, managers at the high level are not scalable, hindering the achievement of multiple adaptive properties.

C. Architectural Solution for SaS with control strategy of Category 3 (C3)

This solution aims both self-optimization and self-management capabilities. As shown in the upper-right side of Figure 1, the managed and managing systems are distributed. They can be modified at run-time and, together with the Mediation layer, are the elements being monitored. Hierarchies of MAPE-K components are allocated in different nodes; hence, control activities are decentralized. This characteristic benefits the execution of complex reconfiguration and the management of SaS performance and resource allocation capabilities. This architecture presents similar benefits to the previous solutions. An additional benefit is the identification, prevention of faults and recovering from the failures caused by the physical decoupling of MAPE-K hierarchies. This property increases the SaS’ reliability. An important drawback is the possible bottleneck in the Mediation layer due to the increase of the transferred data [9].

D. Architectural Solution for SaS with control strategy of Category 4 (C4)

The last strategy distributes and monitors both managed systems and managers. Hence, SaS with requirements of high scalability, flexibility to add/activate/deactivate/update elements, and self-organization can use this solution as a blueprint for their architecture.

This solution benefits diverse types of adaptations with distinct complexity performed by fully-decentralized managers deployed in multiple nodes, following the Hierarchical MAPE-K or HIIC [15] patterns. As a complement, the use of SOA, Broker, or ESB favors the scalability [9] of managed systems and managers in an SaS. These characteristics differentiate this solution from the previous three, as depicted at the bottom-right side of Figure 1.

This solution is the most complete among the Four4SaS’ solutions, enhancing quality attributes of maintainability, reliability, and interoperability, as listed in Table II. Possible drawbacks are related to the simultaneous execution of multiple adaptive requirements that can generate conflicts [5], [11]. This drawback can be overcome through the coordination of highly distributed and hierarchical managers [11]. Additionally, the use of a Mediation layer to communicate data, events, and control can generate problems in the performance and reliability of the SaS.

IV. APPLYING Four4SaS: THE RMS CASE

A River Monitoring System (RMS) is responsible for monitoring river levels in a given region. It consists of systems/devices, such as motes, gateways, river monitors, sensor observation services, web map services, and emergency services. Motes and gateways are distributed over the river banks. Each mote measures and communicates its observations (e.g., water level, temperature, pressure, or pollutants) or its configuration information (e.g., description, identification, classification of the mote) to the closest gateway. Gateways establish, at run-time, specific river areas situation, detecting unexpected events (e.g., floods in a region), defining plans to overcome problematic situations (e.g., to restart unavailable motes), and executing such plans. Gateways share a central repository containing control information, such as adaptation plans, emergency situations, motes network configuration, and policies. Gateways communicate information of the river areas and systems situations to River Monitor components, which aggregate the information received from all gateways to establish an overall panorama of the river and send this information to the user applications. The River Monitor receives reconfiguration requests from user applications (e.g., requesting water and temperature levels of the entire or parts of the river) and communicates new behavior or configuration policies to gateways and motes. More information about RMS can be found in [12].

Selecting a Four4SaS’ Architectural Solution

Before selecting a Four4SaS’ solution, the RMS must be characterized according to SaS properties defined in Section III and Table II:

- **Monitored elements**: motes and gateways, both distributed over the environment (i.e., river);
- **Managers**: gateways (physically distributed) and river monitors (both possibilities: centralized or distributed);
- **Reasons for adaptations in the RMS**:
  - *Interoperability and Flexibility*: It is required to add, remove, instantiate, deactivate, and activate motes and gateways without requiring manual adaptations;
  - *Scalability*: It is required to continuously add more motes and gateways to cover new river(s) areas independently of the city;
  - *Reliability*: It is important to identify when motes and gateways are unavailable (e.g., hardware problems). Additionally, it is required to detect, prevent faults and recover from faults occurred in motes and gateways; and
  - *Maintainability*: Modifications in policies, requirements, adaptation plans, or even in individual motes and gateways must not affect the RMS operation.
- **Elements to be adapted**:
  - Adaptation plans, policies, and requirements;
  - Motes’ behaviors, states, and configuration (e.g., measurement rates of water level);
- Gateways’ behaviors, states, and configuration; and
- Capacity of supporting multiple connections and large amount of data transferred among systems.

- **Type of adaptation:** The RMS requires to adopt close adaptations in motes and gateways, and open adaptations (involving final users) to make possible new policies of reconfiguration (e.g., increase in the water levels measurement rates of motes in a region).

Therefore, the RMS’ architecture needs to address adaptive capabilities of self-configuration and self-organization. Considering that multiple adaptive properties are necessary, managed systems and managers are distributed, and scalability is an important requirement of this SaS, it is required full-decentralization of autonomic managers’ control activities. Analyzing Four4SaS’ solutions in Table II, the best option for the RMS’ architecture is to follow the solution with control strategy C4. Figure 2 presents the final RMS architecture as an instance of this solution.

**V. Four4SaS Assessment**

To assess Four4SaS’ quality characteristics (e.g., usefulness) to design software architectures of SaS, we ran an evaluation with architects that could use Four4SaS in their projects. They were trained in Four4SaS and they answered an online questionnaire (available at [8]) designed based on the TAM evaluation questionnaire [13]. The questionnaire included validated constructs from TAM to evaluate five criteria: usefulness, ease of use, demonstrability, feasibility, and the quality of architectures created with Four4SaS. An example of using an SaS architecture with Four4SaS was discussed during the training, specifically the RMS presented in Section IV.

Fifteen (15) architects participated in this study. They had 2 to 8 years (N=15, Min=2, Max=8, Mean = 4) of experience working with SaS for different application domains, including IoT, embedded, healthcare, crisis and emergency, robotics, banking, and spacial systems.

Answers to each question were scored from 1 (strongly disagree) to 7 (strongly agree). Table III summarizes the results of Four4SaS’ assessment. For each question, the amount of answers scored in a specific value (from 1 to 7) are given. Score tendencies are highlighted in gray-color scale. For each criterion, aggregated results are presented, detailing the mean, standard deviation, median, mode, and minimum and maximum scores given by respondents.

The majority of responses positively scored all evaluation criteria. We only obtained a negative result for the feasibility criterion, regarding “All information that is necessary to

1A cell in white color represents that no architect scored a question with such a value.
understand Four4SaS are available". The 53% (i.e., 8/15) of architects answered this question with score less or equal to 3 and median of 3 (somewhat disagree).

We also provided the possibility to respondents include free text. The main architects’ feedbacks were: (i) systematization of the selection of Four4SaS solutions and support to the architectural decision-making using automated tools; (ii) offering of metrics on possible trade-offs of using Four4SaS solutions in specific projects; (iii) improvement of the Four4SaS description using different architectural views, implementation details, and a website to link additional information; (iv) automatic code generation based on Four4SaS architectures to support productivity; and (v) use of Four4SaS as a basis to product-line architectures in specific SaS domains, e.g., IoT.

VI. LIMITATIONS

Threats to search, data, and research validity of our work were mitigated by following the guidelines to conduct systematic mapping study [7] and to execute an online questionnaire with SaS architects following the TAM approach [13]. In [8] are presented the protocol, execution, and extracted data of our systematic mapping study, as well as the form and results of conducting the TAM questionnaire.

The main limitation of Four4SaS is that its architectural solutions are described in a higher abstraction level. Hence, architects need to refine the Four4SaS structures for achieving more detailed architectures of their concrete SaS projects. To overcome this limitation, Four4SaS must be also disseminated to the SaS practitioners and researchers to be used in different projects, making possible the identification of Four4SaS variations and possibly complementary solutions.

VII. FINAL REMARKS

Several strategies for designing SaS architectures have been proposed during the last decade. Most of them are focused on investigating feedback loops (as MAPE-K) as core elements of SaS architectures [14], [15], [16], [17]. Researchers also have proposed some patterns for self-adaptation [18], [19] and runtime software evolution [20], some of them oriented to SOA-based SaS [19].

Four4SaS solutions advance the state of the art by bringing to the light reusable architectural knowledge about how to design SaS considering variations of adaptive capabilities, quality attribute requirements, necessity of human involvement to perform open or closed adaptations, and the distribution level of SaS constituents (i.e., managed and managing systems) and control operations. Four4SaS solutions are based on evidence obtained from 13 published SaS reference architectures, listed in [8].

As future work, Four4SaS solutions could be formalized in an SaS architectural framework to guide decision-making and allow automatic code generation of SaS. More efforts must be also invested to better understand the trade-offs arising from addressing simultaneously multiple adaptive characteristics in SaS architectures (e.g., following the C4 strategy of Four4SaS).

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