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Concepts and Models of Environment of Self-Adaptive Systems: A Systematic Literature Review

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***Abstract*—The runtime environment is an important concern for self-adaptive systems (SASs). Although researchers have proposed many approaches for developing SASs that address the issues from runtime environments, the understanding of these environments varies depending on the objectives, perspectives, and assumptions of the research. Thus, the current understanding of environments in SAS development remains ambiguous and abstract. To make this knowledge more concrete, we investigated concepts and models of the environment covered in this area through a systematic literature review (SLR). We automatically and manually searched 3719 papers and selected 128 papers as primary studies. We explored and analyzed concepts of the environment covered in the primary studies and investigated cases in which the concepts were specifically expressed as environment models. In doing so, we provide trends of how SAS academia understands the environment of SAS. Specifically, this SLR provides five common characteristics of the environment, two common sources of the environmental uncertainty, and 14 reference environment models with various purpose and expressiveness. Finally, we summarized lessons learned through this SLR and directions for future SAS research on the basis of the concrete knowledge of the SAS environment.**

***Index Terms*—self-adaptive systems, environment, concept, model, systematic literature review**

I. Introduction

A self-adaptive system (SAS) adaptively changes its behavior or structure at runtime to achieve its goals and respond to unanticipated situations of the system itself or its operating environment [1]. These unanticipated situations are referred as uncertainty. Uncertainty can come from imperfect requirements, defective SAS design or implementation, or the runtime environment [2]. Among these various reasons, the environment is one of the most interesting and challenging entities to address in SAS development. It is difficult to fully anticipate at design time the environment that an SAS will encounter during its operation, and modern systems have environments that are complex and open.

To develop a system that is adaptive to an uncertain environment, numerous engineering approaches have been proposed, such as eliciting adaptive requirements from the environment [3], [4], analyzing SAS design while considering an uncertain environment [5], [6], testing an SAS implementation with environmental inputs [7], [8], and updating environmental knowledge for optimal runtime decision making of an SAS [9], [10]. In this context of active research on an SAS in an uncertain environment, one shortcoming we noticed is that the meanings of “environment” and “uncertain environment” are inconsistent across different studies. For example, different papers describe “uncertain environment” as an environment that changes itself over time, an environment that has been changed by an SAS, or an environment that has been misrecognized by sensor noise, among other definitions. This inconsistent understanding makes it difficult to compare different studies.

Although there could be many reasons for this inconsistent understanding of the environment, what we focus on is the lack of overall knowledge of how other researchers have interpreted the environment of an SAS. In the software engineering community for SASs, an implicit agreement on the concepts of the environment has been reached, but this agreement has led to ad hoc interpretations. We believe that the various interpretations of the environment of an SAS are all meaningful in establishing a concrete knowledge of it. Therefore, in this paper, we conducted a systematic literature review (SLR) to gather and analyze these interpretations. We specifically tried to find out:

- how various researchers commonly understand the concept of the environment of SAS, and
- if there are cases in which their understanding of the environment is expressed as concrete models.

For the purpose, we automatically and manually searched 3719 papers and selected 128 papers as primary studies. We examined the how the studies defined and described the SAS environment and how existing studies abstracted it as models. Specifically, in our SLR, we found and provided:

- five common characteristics of the environment of SAS and their trends in the primary studies
- two common sources of environmental uncertainty and their trends in the primary studies, and
- 14 reference environment models for SAS with different purposes and expressiveness for the characteristics.

The remainder of this paper is organized as follows. Sec-

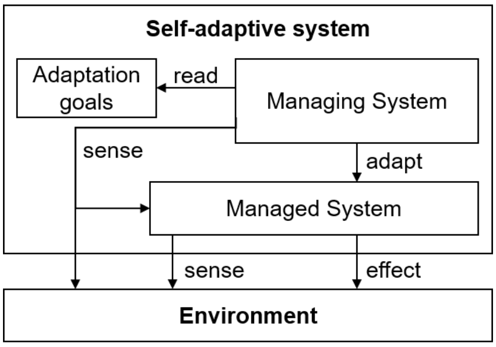

Fig. 1. Conceptual model of an SAS [1]

tion II introduces the basic concepts of an SAS and its environment. Section III presents our systematic review protocol. Section IV shows the review results for each research question (RQ). Section V discusses lessons that we have learned through this SLR, and Section VI presents future works. Section VII reveals threats and the validity of our work. Section VIII introduces other SLR papers to summarize the trends of SAS research. Section IX concludes the paper.

II. Background: SAS and Its Environment

Some papers that introduce SAS engineering provide a fundamental comprehension of SASs and the environment [1], [11], [12]. Fig. 1 illustrates a conceptual model of an SAS [1], including the relationships between the SAS and the environment. The environment is an external world comprising observable physical and virtual entities where the SAS operates. Given that the environment is regarded as uncertain, the SAS continuously senses it to reliably achieve its adaptation goals. The sensed environmental condition affects the decisions of the SAS, and these decisions, in turn, can have new effects on the environment. This high-level understanding has been agreed upon in the SAS research community, but researchers have put forward specific interpretations of the environment. In this paper, we carried out an SLR to explore how the concept of environment has been understood and modeled.

III. Review Protocol

On the basis of some guidelines for SLR [13]–[15], we designed a review protocol that includes the review steps and specific inputs and outputs for each step (Fig. 2). Designing a review protocol in advance prevents a biased or subjective survey, and disclosing it ensures a reproducible review. According to the goal of this SLR, we specified the RQs, automated search engines, manual search venues, and the search string. The papers searched were evaluated to determine whether they were primary studies[1] under the predefined criteria. The selected primary studies were then examined thoroughly. These studies also became the sources of cross-reference searching, a step in which all the references of the primary studies were exhaustively explored to minimize the possibility of missing important papers. Any newly discovered paper was evaluated according to the selection criteria. In particular, we utilized the "snowballing" method[2]. When searching finished, we extracted predefined data items from the primary studies. The extracted data were analyzed, and the analysis results are reported in Section IV. The rest of this section describes the elements of this protocol.

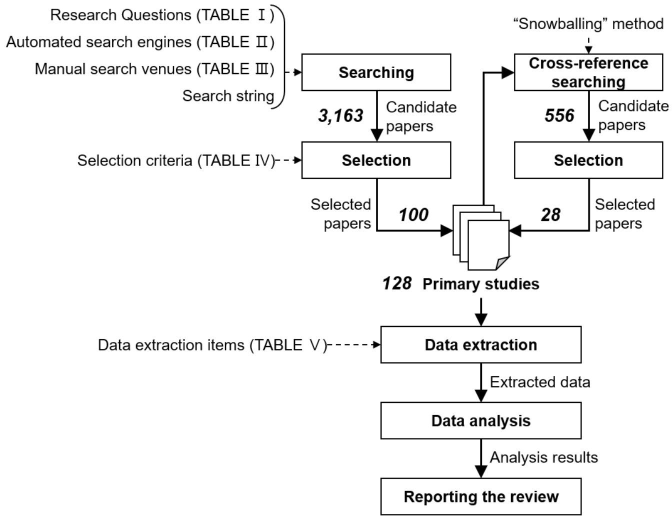

Fig. 2. Overview of the review protocol

TABLE I
Research questions

Category	ID	RQ
Concepts of the environment of SAS	RQ1	*Definitions of the environment.* How did primary studies explicitly define the "environment" of an SAS?
	RQ2	*Characteristics of the environment.* What characteristics of the environment of an SAS did primary studies mention in describing it?
	RQ3	*Sources of the environmental uncertainty.* What did primary studies consider to be the sources of environmental uncertainty?
Models of the environment of SAS	RQ4	*Modeling of the environment.* Who models, how do they model, and why do they model the environment of SAS?
	RQ5	*Application of the environment models.* When and how are the environment models used?
	RQ6	*Expressiveness of the environment models.* How are the characteristics of the environment expressed in the models?

The purpose of this SLR is to show the trends of how the concepts of the SAS environment have been understood and abstracted as environment models of SAS in software engineering. To achieve this purpose, we specified questions that will be answered, as shown in Table I. Regarding RQ1, to understand the environment of SAS, we surveyed how primary studies have explicitly defined the environment. For RQ2, both the explicit definitions and characteristics used to describe

[1]In this case, a primary study refers to a paper subject to review, and the SLR itself is a secondary study [13].

[2]The snowballing method exhaustively explores all the backward references (cited by the subject paper) and forward references (citing the subject paper) until no additional papers are discovered [16].

TABLE II
AUTOMATED SEARCH ENGINES

Discipline	Search engine
Computer science and related subjects	IEEE Xplore (http://ieeexplore.ieee.org/)
	ACM Digital Library (http://dl.acm.org/)
	DBLP Computer Science Bibliography (https://dblp.org/)
Multi-disciplinary	Web of Science (http://www.webofknowledge.com/)
	SpringerLink (http://link.springer.com/)
	Scopus (http://www.scopus.com/)
	Wiley Online Library (http://onlinelibrary.wiley.com/)
	World Scientific (https://www.worldscientific.com/)
	ScienceDirect (http://www.sciencedirect.com/)

TABLE III
MANUAL SEARCH VENUES

Type	Venue
Journal	ACM Transactions on Software Engineering and Methodology
	ACM Transactions on Autonomous and Adaptive Systems
	IEEE Transactions on Software Engineering
	Journal of Systems and Software
	Information and Software Technology
Conference	Intl. Conference on Software Engineering
	Intl. Symposium on the Foundations of Software Engineering
	Intl. Conference on Automated Software Engineering
	Intl. Symposium on Software Engineering for Adaptive and Self-Managing Systems
	Intl. Conference on Self-Adaptive and Self-Organizing Systems

the environment were clarified. RQ3 was included because environmental uncertainty is a huge area of interest in software engineering for SAS but remains an ambiguous term. In this SLR, we surveyed sources of the environmental uncertainty and their coverage in primary studies. For RQ4, we selected papers from the primary studies that proposed environment models and surveyed these modeling methods. RQ5 looked at the application of the environment models. Finally, in RQ6, we examined the expressiveness of the environment models, especially how the characteristics of the environment were represented in each model.

Different automated search engines that could help find related papers were utilized to collect appropriate primary studies for answering the RQs. The selected search engines are listed in Table II. Widely used computer science article search engines were selected, and various multi-disciplinary search engines were also used to search exhaustively for as many related works as possible. In addition, we conducted a manual search for publications in related journals and conferences (Table III) for added focus on high-end software engineering and SAS-related venues.

The following search string was used to find related papers:

{(**self-** OR **adapt**) AND (**software** OR **system**) AND (**environment**) AND (**uncertain**)}

Papers focusing on "software" or "system" with "self-" prefixed properties or "adapt" (as in "adaptive," "adaptiveness," etc.) were searched. The "self-" prefix identifies the most general terms of various adaptive properties [17]. We likewise searched for studies explicitly referencing the uncertain environment or environmental uncertainties of SAS, which were both caught by our specification of forms of "environment" and "uncertain." This search string was used for both the automated and manual search; the search scope included titles, abstracts, and author keywords of the papers.

TABLE IV
INCLUSION AND EXCLUSION CRITERIA

Inclusion criteria	
IC1	Papers written in English
IC2	Research papers peer-reviewed and published in conferences, journals, or books
IC3	Papers in computer science field
IC4	Papers on the topic of a domain-general software engineering approach for self-adaptive systems' adaptation to the environments
Exclusion criteria	
EC1	Duplicated papers
EC2	Papers whose contents were not fully accessible
EC3	Papers not in the form of full research papers (i.e., abstracts, tutorials, or reports)
EC4	Collections of studies (i.e., books or proceedings)
EC5	Papers summarizing existing studies or concepts (i.e., overviews, introductions, keynotes, roadmaps, or surveys)

TABLE V
DATA EXTRACTION ITEMS

RQ	Data items
RQ1	Explicit definition of the "environment" of an SAS
RQ2	Expressions explicitly mentioned to describe characteristics of the environment
RQ3	Sources of environmental uncertainty addressed in the primary studies
RQ4	Environment modeling details (modeling agent, effort, purpose, formalism, process, etc.)
RQ5	Environment model application details (application time, usage, supportive techniques, etc.)
RQ6	Characteristics of the environment expressed in the models

The searched papers were evaluated using the predefined selection criteria in Table IV. There were both inclusion and exclusion criteria. If a paper satisfied all the inclusion criteria and none of the exclusion criteria, then it was selected as a primary study. Inclusion criteria IC4 evaluated whether a paper was appropriate to answer our RQs. Our purpose was to gain a general knowledge of the environment of an SAS from papers on developing systems to be adaptive to the environment, so only domain-general SAS engineering papers were included. All the authors of this work read the abstracts of the papers (and the introductions if needed) and together judged if the papers were appropriate to answer our RQs. Other criteria helped control the discipline focus, quality, and form of the primary studies.

Extracted data items were identified for each RQ (Table V). Data extraction was conducted manually, and the collected data were analyzed to answer the RQs.

IV. REVIEW REPORT

Following our predefined review protocol, we searched 3163 papers (2987 automatically, 176 manually) and selected 100 primary studies. Using the "snowballing" method, we searched an additional 556 references and selected 28 more primary studies. Thus, a total 128 primary studies were surveyed

TABLE VI
DEFINITIONS OF ENVIRONMENT

Explicit definition of the "environment" of SAS	Ref.
"anything observable by the software system, such as end user input, external hardware devices and sensors, or program instrumentation"	P6
"the physical world or computing elements that are not under control of the system"	P24
"circumstances that interact with or affect the system"	P77

(Fig. 2). The details of searching and selection, such as the number of papers for each engine and venue or the criteria evaluation results, are accessible on our website but not fully described here[3]. From the primary studies, we extracted data and analyzed these to answer the six RQs. Throughout all the review steps, to create a reproducible and objective survey, we recorded all the outputs for each step and made all the review data, including extracted raw data, accessible[3]. In this section, we report the analysis results for each RQ.

A. Concept of the Environment of SAS

RQ1) Definitions of the environment of SAS: We first collected explicit definitions to understand the environment of an SAS. We searched sentences explicitly defining "environment," such as "environment is defined as..." or "environment means...." Owing to the strict format of sentences, only three explicit definitions were found, as listed in Table VI[4]. [P6] defined environment as external and observable objects. [P24] highlighted the fact that it is not under the direct control of an SAS. By contrast, [P77] defined environment as circumstances interacting with the SAS. In paraphrasing the existing definitions, we can say that *the environment of an SAS is a set of external and observable objects that are not under the control of the SAS but interact with it.*

The definitions are acceptable and indicate some key characteristics of the environment, such as *diverse factors*, *externality*, *observability*, and *interaction*. However, only a few of the selected studies explicitly defined environment, and they varied considerably in terms of the authors' perspectives. Such differences made it difficult to get considerable knowledge about the concept of environment from the existing definitions only. This outcome confirmed the assumptions that drove our motivation to conduct this SLR. Fortunately, the studies without explicit definitions implicitly shared a common understanding about the environment. consequently, we attempted to gather this understanding in answering RQ2 on the basis of these definitions.

RQ2) Characteristics of the environment of SAS: To establish the concept of the environment of an SAS, we collected characteristics of this environment. Despite the limited explicit definitions in RQ1, almost all the primary studies described the environment of an SAS of their interest. We searched for all the sentences that included "environment" in the primary studies and collected and categorized the numerous adjectives and nouns from the sentences that described the environment, as shown in Table VII. The expressions in the primary studies are organized in the first column and then listed in the second column. We discussed how to classify various expressions into some common characteristics and, finally, organized the five common characteristics of an SAS environment. Descriptions for each characteristic and the related expressions are also given in Table VII.

Diversity: Environment comprises diverse environmental factors. The term environment does not only mean a specific object, but a set of environmental factors of interest. Specification of the environment requires a set of specifications of each environmental factor of interest. An environmental factor could be cyber, physical, human, external service or systems, or even time. As there can be various environmental factors, they may each have their own constraints or rules, such as law of physics. Therefore, the environment of an SAS should be finally defined according to the domain knowledge.

Externality: Environment is outside the SAS boundary. Therefore, only objects that are outside the system boundary can be regarded as environmental factors. Given its externality, environment is not under the direct control of the SAS. It is not directly modifiable by an SAS like a system variable, but an SAS can give a stimulus to the environment through actuators and so on.

Observability: Every external object of interest can be regarded as an environmental factor of an SAS, but a constraint is that the object must be observable by the SAS. Therefore, defining an environment of an SAS is related to the monitoring capability of the SAS. In SAS academia, we do not regard all external things as an environment but as external and observable things. Environment is observable by monitoring components of an SAS, so the SAS can respond to the environment.

Interactivity: Environment and SAS interact and thus affect each other which is why the adaptation of a system to the environment is needed. Environment specification should specify the mutual influence of the environment and the SAS. Environmental influence on the SAS can be adverse or supportive of SAS goals. An external and observable object not related to and interacting with the SAS does not need to be regarded as an environmental factor.

Uncertainty: Environment is not certainly anticipated at design time. It is uncertain because it is an external element. If SAS engineers have considerable domain knowledge, then a better expectation of the runtime environment can be made, but a complete knowledge of the external factor is almost impossible. Continuous environment monitoring of the SAS reduces the uncertainty. Numerous expressions implying limited and incomplete knowledge about the environment, such as unknown, change, dynamic, probabilistic, and so on, are used.

Fig. 3 shows how many papers mentioned each characteristic of the environment. This information indicates what

[3]Access the SLR website for all the review data: https://sites.google.com/se.kaist.ac.kr/sas-environment-slr/

[4]Citation numbers for primary studies begin with "*P*". A list of the primary studies is provided on our SLR website due to lack of space.

TABLE VII
CHARACTERISTICS OF THE ENVIRONMENT OF SAS AND THEIR EXPRESSIONS

Organized characteristics	Explicit expressions	Description
Diversity	(Diverse factors) computing/physical (environment element), user (human), system, service, time, factor	The environment consists of diverse (environmental) factors/elements, for example, computing or physical elements, users (humans), or external systems (services).
	(Constrained) constraints	An environmental element has its own constraints.
Externality	(External) external, surrounding	The environment is outside of the SAS boundary.
	(Operational) operation, execution, deployment, runtime	The environment is where a system is deployed, operates, and executes at runtime.
	(Out of control) no control, indirect	An SAS cannot (directly) control its environment.
Observability	(Observable) observable, sense, monitor, measure	The environment is observable by an SAS.
	(Interpretable) parameter, attribute, variable, value, data, input, condition, event, phenomena	An SAS perceives and interprets its environment based on data or values of the environmental variables or parameters. Perception is the SAS's environmental input condition or event.
Interactivity	(Interaction) interaction, influence, affect, impact, interface, trigger	The environment interacts with an SAS, so it affects and is affected by the SAS.
	(Media) sensor, effector/actuator	An SAS interacts with the environment through its sensors and effectors (actuators).
	(Incompleteness) error, noise, variation in sensing, signal interference, failure	Interactions between environment and SAS can be incomplete or may be failures.
	(Adverse influence) disturbing, unsafe, adverse, disruptive, unfavorable, threat	The environment may adversely affect SAS goal satisfaction.
	(Supportive influence) resource	The environment may be supportively used for SAS goal satisfaction.
Uncertainty	(Unpredictable) uncertain, unforeseen, unexpected, unpredictable	The environment is not fully anticipated at the design time of an SAS.
	(Misunderstanding) unknown, lack of knowledge, missing	Knowledge of the environment may be incomplete. SAS can meet an unknown environment. Missing environmental parameters could exist.
	(Dynamic) change, fluctuation, dynamic	The environment dynamically changes its states or behavior over time.
	(Probabilistic) non-deterministic, probabilistic, stochastic	The environmental knowledge is non-deterministic.

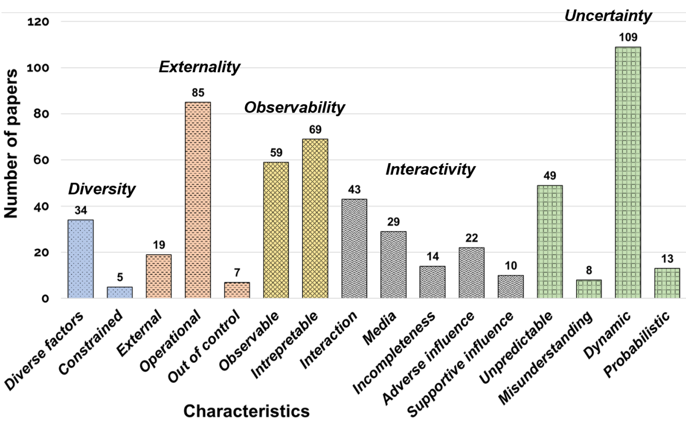

Fig. 3. Number of mentions of characteristics of an SAS environment

environmental characteristics were relatively familiar to the researchers as expressed in their writing. For example, "dynamic operating environment" was one of the most widely used expressions to describe the environment. The figure shows trends in the characteristics mentioned. More important than the trends, however, is that in addressing RQ2, the various characteristics and expressions were organized to help understand the environment more comprehensively. Although there were few clear definitions, the SAS research community has established a significant and implicit agreement on the characteristics of an SAS environment. Lastly, we were able to make these agreed upon characteristics explicit and visual.

RQ3) Sources of the environmental uncertainty of an SAS: Among the characteristics of an environment, uncertainty is one reason that a system should monitor and adapt continuously to the environment. However, the use of the term "uncertainty" is typically conceptual and ambiguous and can thus cause inconsistent understanding among engineers. To tackle ambiguous understanding[5], we examined concrete sources that cause environmental uncertainty. In the selected primary studies, we found three papers [P22, P94, P102] that proposed taxonomies of environmental uncertainty sources. We leveraged their taxonomies to analyze which sources were widely addressed in the primary studies. We summarized these taxonomies of sources[3] and reorganized them as presented in Table VIII.

As the descriptions of existing sources had overlapping meanings, so we reorganized the sources into two common sources. The first common source of environmental uncertainty is ***limited environmental knowledge***. An SAS engineer may have limited knowledge about the environment because the environment changes or the environment was not fully identified. Sometimes, SAS engineers can miss some environmental factor in consideration. The primary studies have divided this source into different types of environmental factors (cyber, physical, and human). However, the common reason for the uncertainty is the limited environmental knowledge no matter the type of factor.

[5]We also surveyed definitions of "uncertainty" and "environmental uncertainty," but these were not included in this paper due to lack of space. Please refer to our website[3].

TABLE VIII
SOURCES OF ENVIRONMENTAL UNCERTAINTY

(Reorganized) Source	(Existing) Source	Existing description (P22, P94, P102)	Existing terms (P22, P94, P102)
1. Uncertainty from limited environmental knowledge	Overall (Cyber factor)	"current operating conditions, which are continuously invalidated due to changes" [P22] "the context of execution changes" [P22] "the environment conditions are close to a change" [P102] "Events and conditions in the environment that cannot be anticipated" [P94]	"Uncertainty in the context" [P22,P102], "Uncertainty of parameters in future operation" [P22,P102], "Unpredictable environment" [P94]
	- Physical factor	"the effect of physical world on the software is a subset of context, which was described in the previous source (uncertainty in the context)" [P22]	"Uncertainty in cyber-physical systems" [P22,P102]
	- Human factor	"the behavior of the crew (human) may be very unpredictable" [P22]	"Uncertainty due to human in the loop" [P22,P102]
2. Uncertainty from incomplete environmental interaction	Inaccurate sensor	"A sensor ... may return a slightly different number every time ..., even if the actual value ... is fixed." [P22] "Random and persistent disturbances that reduce the clarity of a signal" [P94]	"Uncertainty due to noise" [P22,P102], "Sensor noise" [P94]
	Sensor failure	"When a sensor cannot measure or report the value of a property" [P94]	"Sensor failure" [P94]
	Inaccurate effector	"system's ability ... is not only a function of the accuracy of its software, but the precision in the physical steering components (actuator)" [P22] "An adaptation that alters the execution environment in unanticipated ways" [P94]	"Uncertainty in cyber-physical systems" [P22,P102], "effector" [P94]
	Effector failure	"an actuator ... can either fail during an adaptation or ... introduce adverse effects upon the execution environment" [P94]	"effector" [P94]

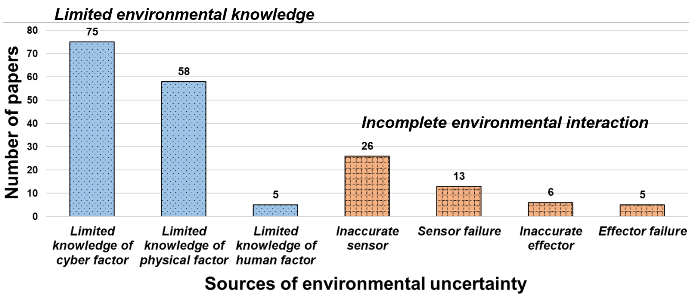

Fig. 4. Frequency of addressing each source of environmental uncertainty

A second orthogonal source of environmental uncertainty is ***incomplete interaction with the environment***. Even if the environment is well specified, environmental uncertainty arises if the interaction with the environment is not as expected. SAS interacts with the environment through sensing and effecting. If sensing or effecting fails or returns inaccurate or noisy results, then the environmental uncertainty would increase.

We reorganized the common sources of environmental uncertainty, but the existing source terms and descriptions are cited in Table VIII for reference.

In fig. 4, we also analyzed how many primary studies addressed each source of environmental uncertainty. In these sources, environmental uncertainty caused by limited environmental knowledge was addressed more than uncertainty from incomplete interaction. However, limited knowledge about the human environmental factor was rarely addressed compared to the others. With regard to the sources of incomplete interaction, the sources related to sensors were relatively familiar to researchers, as evidenced in the writing, more so those related to effectors. In noting the trends, we must also acknowledge that even if various studies are addressing "environmental uncertainty," their use of this term does not necessarily rely on the same source. Therefore, researchers need to specifically explain their concerns regarding a particular source of environmental uncertainty to prevent misinterpretation.

B. Models of the Environment of an SAS

RQ4) Modeling of the environment of an SAS: A model is an abstraction of a subject that represents its important features, and so examining existing environment models allows us to find important features of the environment. In RQ4-RQ6, we provided an analysis of reference environment models. We found 14 unique models that represent the environment of an SAS from the 128 primary studies, and these are listed in Table IX. If a paper named the model, then the name is presented in the table; otherwise, a descriptive name we created for the model is listed. All the models provide an abstraction of the environment of an SAS, but their representations varied depending on the purpose of the modeling and the authors' perspectives. In addition, the formalism of the model was decided based on the authors' purpose. Some models followed standardized formalisms, while others were created using the authors' modeling languages or rules. These details are summarized in the table. While the models are not explained individually in detail (the reader is directed to the original reference for this information) due to a lack of space, the insights obtained from their analysis (modeling process and modeling effort) are shown.

We summarized the modeling processes for each model[3] and noticed common milestones for the modeling of the environment of an SAS. The milestones were as follows:

- Modeling the system boundary and environmental factors
- Modeling the environmental impact on the system goal
- Modeling interfaces of the system-environment interactions
- Modeling the variability of the environment

TABLE IX
MODELS OF THE ENVIRONMENT OF SAS

ID	Model name	Representation	Modeling purpose / usage	Formalism	Ref.
M1	Interactive app model	Program, program interface, environment, environment interface, uncertainty, configuration	SAS testing environment	-	P17
M2	RELAX-marked conceptual environment model	Environment, environmental factors, sensors, etc.	Uncertainty-aware requirements elicitation	UML class diagram	P25
M3	PRISM stochastic environment game player model	System, environment, sensor model	Uncertainty-aware formal analysis	MDP	P28
M4	Environment model of Tropos4AS	Environmental artifacts, relationships to system agents	Testing environment code generation	UML class diagram	P36
M5	DTMC environment model	Stochastic environmental change	Optimal adaptation decision making	DTMC	P44
M6	Environmental constraint graph	Environmental states and their correlations	Improving model checking validity	Graph	P52
M7	Learning Petri net environment model	Environmental states	Formal analysis of SAS behavior and environment	Petri net	P63
M8	Environment domain model	Environmental state changes responding to system actions	Runtime behavior model revision	-	P66
M9	Interactive state machine and uncertainty specification	Environmental change, sensor and actuator noise, and environmental constraints	Uncertainty-aware and realistic verification	State machine	P72
M10	Ragnarok uncertainty genome	Numeric information of uncertainty sources	Exploring adverse environmental conditions	-	P82
M11	Game of testing environment model	Environmental state change responding to system actions	Environment model learning for runtime testing	MDP	P97
M12	Contextual variable dependency tree	Contextual variable states and their dependencies	Environment-aware requirements elicitation	Tree	P124
M13	System-environment interaction state model	Interactions between a software system and environment	Optimal adaptation decision making	State machine	P127
M14	Environment configuration variability and reconfiguration model	Environment situation variabilities and reconfiguration process	Environmental condition test case generation	-	P128

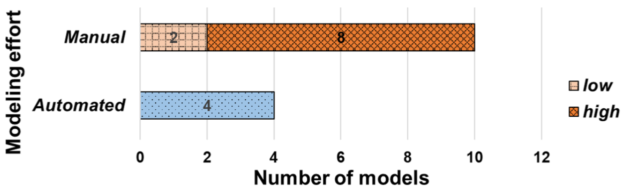

Fig. 5. Modeling efforts of the environment models

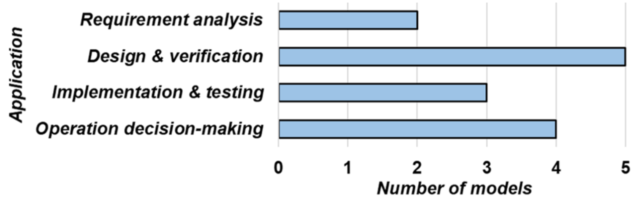

Fig. 6. Application of the environment models

All 14 modeling processes included at least one milestone. The first milestone was identifying the system boundary and enumerating the environmental factors that are outside of the system boundary. The second milestone focused on the goal of the SAS and modeled how the environment affects the goal. The third milestone highlighted the boundary between the SAS and the environment. It represented how the SAS and the environment utilize their interfaces, such as sensors and actuators. The fourth milestone modeled the variability of the environment. It expressed how the environment is able to change itself over time or is changed by the SAS. It is not necessary to achieve all the milestones, and they do not need to be achieved in a sequential order. The choice of milestones depends on the modeling purpose.

We also examined the modeling efforts for each model, and these are summarized in Fig. 5. We divided the modeling efforts into automated and manual modeling. Automated modeling generated environment models automatically through the use of data by their methods (M5, M6, M8, and M11). Manual modeling was divided into two cases. The first case (high) is when significant expert-level environment knowledge, such as how environment behaves or which environmental conditions are expected, is required (M2, M3, M4, M7, M9, M10, M13, and M14). The second case (low) is when modeling can be completed with assistance, such as data, without significant knowledge (M1, and M12). Among the 14 models, only four were modeled automatically. The others were manually modeled. It is natural for engineers to build models manually for their purposes. However, the fact that most manual models require significant environmental knowledge suggests that the results of many engineering techniques using environment models can vary, depending on the quality of the engineer's knowledge.

RQ5) Application of the environment models: In answering this RQ, we examined how the environment models were used. We summarized the applications of the models in Fig. 6. We categorized the four usages of the models. The first was requirement analysis. Some environment models were used to explicitly identify environmental factors and elicit requirements they affected (M2 and M12). Another application was

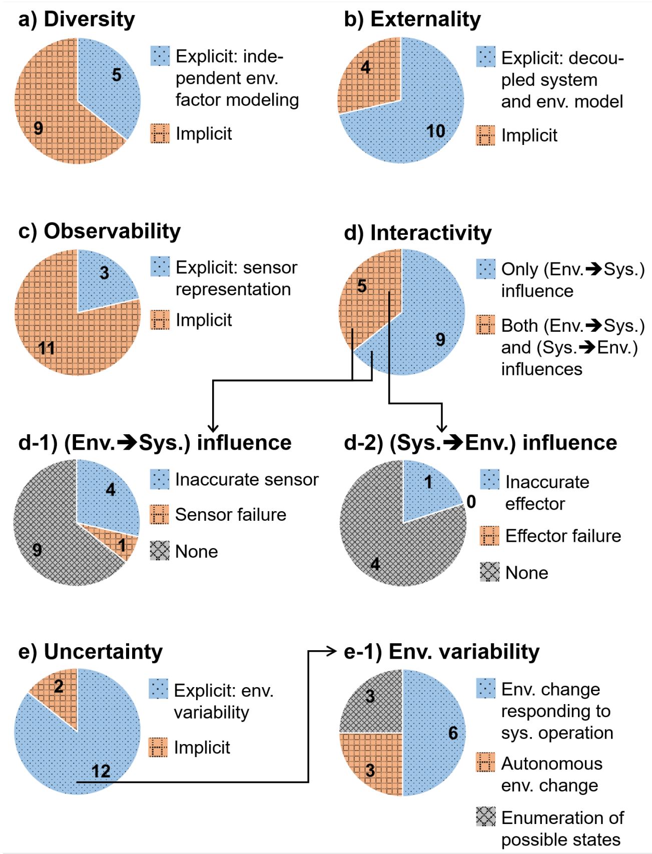

Fig. 7. Representations of the SAS environment characteristics in the models

using the environment models as verification environments to mimic the actual environments of SASs (M3, M6, M7, M9, and M10). This was the most common usage. Another way to use the environment model was in generating testing inputs for an SAS (M1, M4, and M14). The environment models of verification and testing were used to explore failures of an SAS that were triggered by the environment. The last application of the models was for the decision making of an SAS during operation (M5, M8, M11, and M13). The environment models were generated or updated during runtime, and they helped an SAS make optimal decisions in the runtime environment. The usage of each model is presented in Table IX.

We also summarized techniques that support leveraging the models but did not present them here due to a lack of space (they are available on our website[3]). However, one point that we would like to share here is that a common supportive technique of 11 models was simulation, which is regarded as the most fundamental use of environment models.

RQ6) Expressiveness of the environment models: Finally, we examined how the environment characteristics (revealed in answering RQ2) were represented in the models. Fig. 7 shows the analyzed results for each characteristic (the details of each model can be found on our website[3]). For diversity (Fig. 7a), five models (M2, M4, M6, M10, and M12) required explicit modeling of each environmental factor. They highlighted the independence of the factors and could also represent the interaction among the factors. The other models implicitly showed that an environmental condition comprising diverse variables. For externality (Fig. 7b), 10 environment models (M1-M6, M10-M12, and M14) were decoupled from the system model. However, the other models were coupled with the system model, and externality was implicitly a part of their modeling process. For observability (Fig. 7c), only three models (M1-M3) explicitly described how the environment is monitored by an SAS representing sensor interfaces for environment observation. The others did not show an observation mechanism in the model but just assumed it.

For interactivity (Fig. 7d), all the models illustrated interactions between the environment and the SAS, but the direction of interaction influence can be in either direction. First, environmental conditions can affect the SAS; second, SAS behaviors can affect the environment. Nine models (M2-M7, M10, M12, and M14) represented only how the environment affects the system. They showed how the SAS goal is affected by or how the SAS reacts to the numerous environmental conditions. Only five models (M1, M8, M9, M11, and M13) represented two-way interactions. They modeled how the environment is changed by the SAS's behaviors, in addition to the SAS's reaction to the environment. When modeling the interactions, the incompleteness of the environment was also represented in some models. Among the models that expressed environmental influence on the SAS (Fig. 7d-1), only four representations of inaccurate sensors (M1, M3, M8, and M9), such as sensor noise, and one representation of sensor failure (M10) were found. Among the models expressing the SAS behavior's influence on the environment (Fig. 7d-2), only one representation of an effector or actuator possibly being inaccurate was found (M9). This result demonstrates that, so far, most models assume ideal interactions.

With regard to uncertainty (Fig. 7e), although there may be various ways to represent this in the environment, we included how models represented the variability of the environment because most models did this. Twelve models (M1, M3, and M5-M14) explicitly represented the variability of the environment, but two models (M2, and M4) just assumed the environmental condition can vary over time and did not represent it. Among the 12 models (Fig. 7e1), six models (M1, M7-M9, M11, and M13) represented how the environment responds to the SAS operation, and three others (M3, M5, and M14) modeled autonomous changes in the environment over time. These nine models usually specified environmental states and reactive or autonomous state transitions. The remaining three models (M6, M10, and M12) represented variability as an enumeration of possible environmental states. In answering RQ6, we found that every model had a unique expression for the characteristics of the environment depending on the perspective, and we showed the trends of those expressions in this work.

V. Lessons Learned

The analyzed results of this SLR were described in the previous section. In this section, we summarized the lessons learned through this SLR. First, through this SLR, we propose the following analysis results:

- *Five common characteristics of environment*: diversity, externality, observability, interactivity, and uncertainty (described in RQ1 and RQ2)
- *Two common sources of environmental uncertainty*: limited environmental knowledge, and incomplete environmental interaction (described in RQ3)
- *14 reference environment models*: modeling process, application, and expressiveness of each model (described in RQ4-RQ6)

Second, not restricted to specific RQs, we also learned the following four common perspectives of primary studies for specifying or modeling the environment of an SAS:

- *SAS boundary and external factors*: Identifying a system boundary is essential in defining the environment; identifying the external environmental factors then follows. This perspective guides engineers to clarify a boundary of an environment of SAS under consideration.
- *Environmental impact on the SAS goal*: Understanding how the environment affects the SAS goal is important to clarify the purpose of adaptation. This perspective guides engineers to elicit purposes and appropriate methods of adaptation.
- *Interface of the SAS-environment interaction*: Interfaces between the environment and the SAS, such as monitored environmental variables, actuating variables of the SAS, or specification of incomplete interaction (e.g., noise or failure), should be identified. This perspective helps to define an environment in the view of an SAS. It also specifies the limited amount of information about the environment and control capability over the environment that the SAS can have.
- *Variability of the environment*: Change of an environment over time or by the SAS should be identified for analysis by the SAS in the environment. This perspective helps to enumerate possible environmental states that an SAS will encounter during runtime. It also reveals the insufficiency of domain knowledge of SAS engineers and guides to define the degree of adaptiveness required for the SAS.

Although these four perspectives of environment specification or modeling were not always fully covered in each primary study, these must be sufficiently understood to have concrete knowledge about a specific environment of an SAS. These four common perspectives will help researchers sufficiently consider various aspects of the environment throughout the whole development process of the SAS and in the modeling.

VI. Future Works

We collected and analyzed environment models and found some limitations of existing environment modeling for SAS. In this section, we identify some research challenges and limitations of the existing environment modeling for SAS as follows:

- *Limited consideration of various environmental characteristics*: Few papers systematically identified the characteristics of the SAS environment prior to this work, so the various characteristics of the environments were often not explicitly expressed. Future modeling should reflect the diverse characteristics and perspectives of the SAS environment.
- *Limited consideration of various sources of environmental uncertainty*: Although there are various sources of environmental uncertainty, existing models did not represent them comprehensively. Future research should also address complex environmental uncertainty in which various sources are combined.
- *Considerable manual effort and domain knowledge required for modeling*: Adaptations based on environment models are increasing, but they still rely on manual models and domain knowledge. For the effective use of the environment model, additional research on automated or data-driven model generation is needed.

To overcome these limitations, this SLR provided background knowledge about the environment of SASs.

VII. Threats to Validity

Every survey paper must deal with the threat of poor representativeness in the primary studies that have been chosen. To reduce this threat, we designed a systematic review protocol (shown in Section III), so that we could exhaustively search for related papers as much as possible and select primary studies objectively. In addition, having and presenting a review protocol makes our method reproducible by readers. Another threat is the possibility of biased analysis of the collected data. To reduce this threat, we attempted to utilize the existing expressions or terms and reorganized them for the analysis, as shown in Tables VII and VIII. Nevertheless, because the authors' viewpoints can inevitably be reflected in the interpretation of data, all raw data extracted from the primary studies were disclosed[3] so that anyone can re-examine them and our conclusions.

VIII. Related Surveys on SAS

Several SLRs have provided the trends of research on SAS engineering. Weyns et al. identified tradeoffs of architectural self-adaptation and proposed research directions [18]. Yang et al. [19] and Sucipto et al. [20] investigated requirement engineering approaches for SASs. Muccini et al. analyzed the state of the art of architectural adaptation approaches for cyber-physical systems [21]. Da Silva et al. investigated UML-based modeling languages for SASs [22]. Recently, applications of machine learning in SASs were surveyed by Saputri et al. [23]. Thus far, no systematic survey have been conducted to explore the concepts and models of the environment of an SAS; and as far as we know, this is the first SLR to address them.

IX. Conclusion

To provide an overall landscape of current knowledge of the environment in SAS engineering academia, in this paper, we conducted an SLR and investigated how primary studies described the concepts of the environment. In addition, we investigated how the studies represented the environment as models. Following a systematic review protocol, we selected and analyzed 128 primary studies. Through answering six RQs about the concepts and models of the SAS environment, we provided five common characteristics of the environment (diversity, externality, observability, interactivity, and uncertainty), two common sources of environmental uncertainty (limited environmental knowledge and incomplete environmental interaction), and 14 reference environment models. We also identified four common perspectives of the environment specification (specifications of SAS boundary and external factors, environmental impact on the SAS goal, interface of the SAS-environment interaction, and variability of the environment) and suggested limitations and future works of environment modeling for SAS. This review report will guide future research by providing concrete knowledge of the environment to be considered in SAS development and environment modeling. Additionally, all review data are open so that they can be reused.

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