A Standards-based Approach for Cross-Domain Modelling of Smart City System Architectures

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***Abstract*—The inherent complexity of systems in the domain of smart cities demands a suitable modelling framework to facilitate development and interdisciplinary communication. In the domain of smart grids, the *Smart Grid Architecture Model* (SGAM) framework provided means for coping with complexity whilst supporting a cross-disciplinary understanding of modelled systems. Similar approaches exist for the automotive and industry domains. As a complex smart city system may combine various application domains, interoperability between applied modelling frameworks is imperative to simplify cross-domain collaboration. Therefore, to be suitable, a modelling framework needs to target the concerns of stakeholders from the smart city, whilst simultaneously enabling interoperability between all connected application domains. The presented approach is a standards-based systems engineering framework, implemented as *Domain Specific Language* (DSL) and based upon the *Smart City Reference Architecture Methodology* (SCRAM). Moreover, the DSL is used to model a particular system solution to evaluate its applicability.**

***Keywords*—smart city, systems architecture, systems engineering, modelling framework**

I. Introduction

The evolution of today's cities into *Smart Cities* proceeds at a fast pace. The main drivers for this are the need to handle the continuously increasing size and challenges of cities on the one hand, and the prospect, that the availability of novel Information and Communication Technologies (ICT) can contribute to solutions on the other hand. However, the complexity of applications in this context needs to be considered. As outlined in [1], the architecture of Smart Cities is expected to rest on a ubiquitous computer network, spanning from locally deployed Internet of Things (IoT) devices to various big data storage scenarios, which provide the basis for Artificial Intelligence (AI) based services. Considering aforementioned survey and other research in this field, three conclusions can be drawn:

First, the realization of Smart City use cases will affect several stakeholders with different backgrounds. Second, the technical complexity will increase dramatically and third, several use cases regarding critical infrastructure require a certain level of *dependability*.

In this context, dependability serves as an umbrella term for the characteristics: of reliability, availability, maintainability, safety, and security as declared in [2]. Because these aspects concern the architectural structure, they must be considered by design. This immediately raises the question of how to enable the engineering of dependable Smart City systems. Possible concepts for approaching this question can be found in the interdisciplinary nature of Systems Engineering (SE), as defined in [3]. The most common definition, however, is the one proposed in ISO 15288 defining SE as an "Interdisciplinary approach governing the total technical and managerial effort required to transform a set of customer needs, expectations, and constraints into a solution and to support that solution throughout its life" [4].

The interdisciplinarity of SE combines all branches of engineering. In the recent past, however, the focus has slightly shifted towards applications with a major share of work between hardware and software-related engineers. Proven concepts from software engineering like *object-oriented modelling* have been adopted and corresponding modelling standards such as Systems Modelling Language (SysML) have been introduced [5].

Furthermore, as keeping an overview of all work artefacts and ensuring their consistency over time can pose a serious challenge, the initial document-based approach to development is gradually replaced by a model-based one. In [6] it is argued that the creation of models directly supports dependability aspects of the developed system, as its increasing complexity is addressed by the application of the fundamental principles of *Abstraction* and *Separation of Concerns*. In 2007, INCOSE defined *Model Based Systems Engineering (MBSE)* as "The formalized application of modelling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." [7]. Even though MBSE covers all key SE aspects and the need for modelling is also consent within the SE community, conceptual descriptions, supporting frameworks and design rules are rather rare. Today, the application of SE and MBSE is a common approach, especially in the development of Cyber-Physical Systems (CPS). If this is also valid for Smart City systems, is the subject of the conducted research.

Therefore, the main contribution of the paper comprises two aspects. First, a standard-based modelling framework is developed and second, the framework is then used to model a use case in the Smart City domain. Both artefacts, the architecture framework and the use case model, are made publicly available.

The remainder of this paper is structured as follows. First, an overview on the background of used terms and methodology is provided. Subsequently the chosen research approach along with the selected case studies are elaborated. The results of the conducted examination are depicted in the implementation section, followed by discussion of its application and this study's findings. Ultimately drawn conclusions are introduced and an outlook on our future work is provided.

II. Related Work

A. Smart City Reference Architecture Methodology

Pursuing the aforementioned aspects in the investigated Smart City domain requires the establishment of a holistic picture of buildings, infrastructure, processes, applications, or, smart cities in general - which represents the heart of the MBSE paradigm. As argued in [8], there are only limited research results on the application of SE and more specifically MBSE in the context of Smart Cities. Therefore, an effort is being made by standardization bodies to establish a common methodology to support a holistic understanding of Smart Cities and serve as a basis for future standardization activities. The *International Electrotechnical Commission's* work on the IEC 63188 [9] standard is promising in respect of defining necessary engineering artifacts to meet concerns of common stakeholders in the Smart City context, whilst providing alignment to central systems engineering and architecture description standards ([4], [10]).

The proposed Smart City Reference Architecture Methodology (SCRAM) consists of eleven Viewpoints (VPs) and numerous corresponding model kinds, which are framing major concerns of key stakeholders in the Smart City domain. Nevertheless, only a concise overview of all proposed VPs and model-kinds is provided by this paper, for a detailed description refer to [9]. The *Value VP* describes the problem space, together with a mission- (what needs to be done) and a vision statement (the expected solution). Therefore, the stakeholders including their concerns are investigated and the resulting high-level requirements, user stories, and use cases are defined. The *Big Picture VP* examines the solution space from a high abstraction level, providing details on solution characteristics, architectural principles, and necessary business processes. The first aspects of the intended solution are discussed in the *System-solution engineering VP*, where low-level use cases are provided followed by a decomposition of necessary system capabilities into resulting functions, accompanying processes, and provided services. Also, essential decisions, events, and reports alongside information flows, data schemas, and key performance indicators are defined here. If solution platforms are to be used, the *Platform engineering* and *Platform component engineering VPs* define all important aspects (like terminology, specifications, capabilities, infrastructure, services, and others). Possible automation approaches in engineering are discussed in the *Software factory VP*, outlining intended prototyping, engineering, assembling, testing, deployment, and monitoring practices. The *Solution engineering VP* outlines detailed implementation aspects, providing a further decomposition of capabilities, functions, and processes. The intended integration of platform components, as well as external systems from the same or various other application domains, are also discussed. Here an extension of this VP and integration of Generic Smart City Architecture Model (GSCAM) is proposed, which is outlined in the following section. The *Crosscutting aspects engineering VP* examines interoperability, security, privacy, safety, and reliability concerns, which typically influence the system at multiple or all levels of abstraction. Finally, administrative and management aspects are further investigated in the *Corporate*, *Risk Management* and *Standards VPs*, providing information on the organizational and governance structure, project, and risk management aspects and currently applicable or future standards.

B. Cross-Domain modelling

Previously discussed research shed some light on the specifics of engineering approaches for single application domains. As solutions for complex problems in the context of Smart Cities might span over several application domains (each with its challenges, stakeholders, and solution providers), the need for specification and modeling of interrelations between involved domains continuously gains importance. In [11] a framework-based approach for modeling Smart City solutions spanning over multiple application domains is proposed, which is depicted in fig. 1. While the presented framework expresses a rather generic first step, it is based on the extensive and now broadly accepted research on smart grid domain [12] with associated Smart Grid Architecture Model (SGAM) framework and proposes the concept for Application Domain Cubes (ADCs) and their corresponding Interrelations (ADI). Thus, outlining promising means for structured modeling and interconnection of various application domains (e.g. automotive, health, or transportation), when a distributed cross-domain system or rather a System-of-Systems (SoS) needs to be developed. An ADC can be defined and modeled utilizing well-defined frameworks (e.g., SGAM) or be customized to reflect a particular domain's needs. However, as the proposed concepts were not investigated any further, their actual applicability remained unclear.

Recently, in [13] the problem was approached by aligning state-of-the-art frameworks from Smart Grids, Automotive, and Industry 4.0 domains to ISO 42010 and ISO 15288 and mapping them to the Software Platform Embedded Systems (SPES) framework, which itself is a model-based engineering framework for embedded systems [14]. While the conducted studies identify a potential interoperability interface for the investigated domains, they also reveal significant differences in the granularity of models in each framework and therefore only support interconnection via a common requirements view-

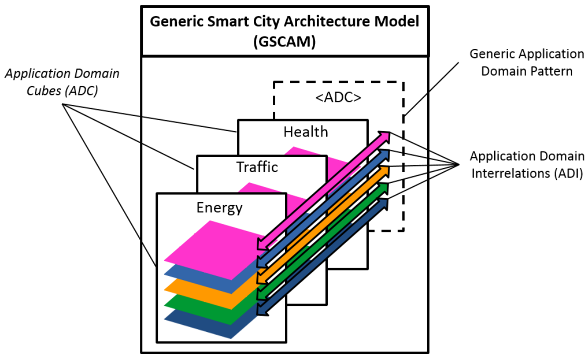

Fig. 1. Generic Smart City Architecture Model (GSCAM) [11]

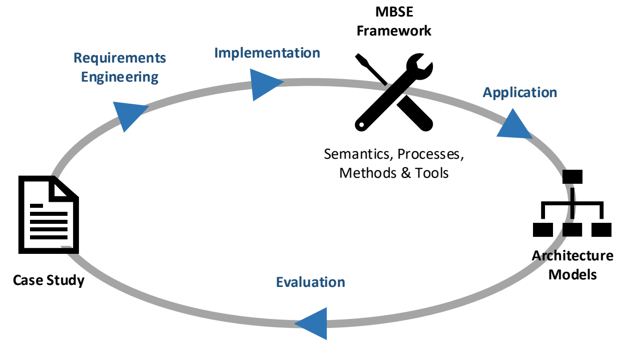

Fig. 2. ADSRM Research Approach

point. Furthermore, the lack of a modeling stack is identified, which further impedes the creation of holistic solution models (including aspects of both domain architecture and technical realization). However, this issue was addressed in [15] with their proposal of a Domain Specific Systems Engineering (DSSE) modeling framework including a unified modeling stack, providing an opportunity for use in a cross-domain modeling context, as investigated by this paper. Therefore, the original ADI concept is extended to provide interoperability between affected ADCs as well towards the surrounding Smart City SoS.

III. Approach

As outlined in Section I, a standard-based engineering approach is crucial for the interdisciplinary and cross-domain development of Smart City systems. Besides the plain engineering process, a broadly accepted architecture framework is needed as context for development, which is the aim of the presented research.

An agile mode of procedure is beneficiary for obtaining first results, which are incrementally enhanced in small steps while addressing the problem domain and making use of established methodologies. Concluding, the theoretical concepts of *Agile Design Science Research Methodology (ADSRM)*, as proposed in [16], appear to be a suitable method for developing applicable results and are chosen as the main research paradigm for this paper.

For this purpose, a case study is initially defined together with a starting set of particular questions. Next, research requirements are specified, and research is conducted. The developed framework then is applied to the initial case study and the resulting application models are evaluated. Based on the evaluation, the set of research questions is refined and extended. If necessary, the case study is expanded before the next iteration takes place. Fig. 2 depicts the discussed process.

In the application of ADSRM, the selection of appropriate case studies is imperative, as the results are highly dependent on them and otherwise have a risk of possible bias. Hence, in addition to the inherent validation by application of the developed framework on the selected case study, the artifacts are continuously aligned to current standardization efforts [9], [17]. In the following, the case study is described in more detail.

A. Infrastructure service for Electric Vehicles

While considering the architecture of an Electric Vehicle (EV), including its production, would exceed the scope of this paper, the focus is set on its interactions with the Smart City, thereby extending previously conducted research [13]. How the development of EVs affects SE is outlined in [12], also mentioning the engineering needs across multiple domains. Therefore, only the architecture of a system providing valet parking and charging services as part of a Smart City infrastructure service and its interconnection to the affected application domains are considered in this specific work.

Therefore, a smart parking garage is introduced, which extends the Smart City's infrastructure and adds new communication aspects towards the EV. First, the EV should be able to communicate its battery status and other charging parameters to the infrastructure, obtaining suitable parking options. Second, the garage needs to communicate with the EV and provide (automated) guidance to currently vacant charging stations. The garage should also communicate its vacancies to the infrastructure, enabling proper routing of incoming vehicles. Hence, the architecture of the infrastructure service is extended by outlined aspects, thereby validating and, if necessary, adapting previously obtained artifacts. The resulting Domain Specific Language (DSL) needs to satisfy following requirements:

- Developed models should provide interoperability between all affected domains
- A semantic for enabling cross-domain architecture modeling should be considered
- An alignment of models to existing SCRAM viewpoints and model-kinds should be achieved

Based on the outlined case study, the developed artifacts are validated towards their feasibility and the general applicability of the proposed modeling stack.

IV. Implementation

As in contrast to Smart Grids with SGAM and Industry 4.0 with Reference Architecture Model Industry 4.0 (RAMI 4.0) in Smart Cities there is no standard model yet available, this presented a severe challenge regarding the definition of use cases, involved actors, participating systems, and implementation platforms. However, as the previously outlined IEC 63188 standard is making an ISO 42010 aligned approach of creating a baseline for common stakeholders, viewpoints, and model kinds for Smart City systems, it provides an opportunity to start with a foundation for architectural descriptions and consolidate our recent efforts for DSL creation.

To create an initial framework structure, in a top-down approach, the rather abstract GSCAM concept was first extended to include recent research on domain specific systems engineering [15] and cross-domain architectures [18]. The resulting DSL was subsequently augmented with previously outlined viewpoints and model kinds defined by SCRAM. In the next step, following a bottom-up approach, the resulting intermediate language definition was applied to the chosen case study and aligned to its specific requirements thereby evaluating and further refining resulting DSL artifacts.

Providing a better alignment to the previously outlined DSSE framework, the extended structure is grouped by hierarchy levels of Model-Driven Architecture (MDA), as defined in [19]. Therefore the SCRAM VPs *Value* and *Big Picture* were placed in the Computational Independent Model (CIM). They describe the problem space using vocabulary familiar to its experts and present what the system is expected to do while hiding all technology-related specifications to remain implementation agnostic. The semantic model (SeM), abstract, and concrete syntax model (ASM & CSM) for the Big Picture VP are exemplarily depicted in Fig. 3.

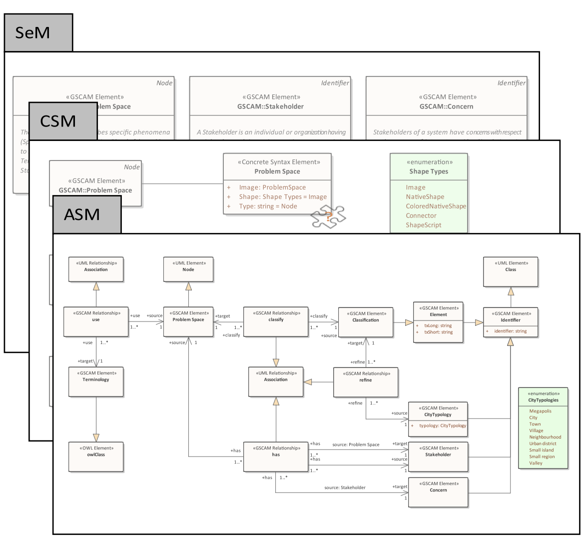

Fig. 3. DSL for Smart City architecture description

The *System-Solution engineering VP* provides details and properties of necessary functions, services, and processes, while not specifying the technology in detail. Therefore, it is placed in the Platform Independent Model (PIM). Describing detailed solution and technology aspects, including the development and usage of platforms and external systems, the *Solution engineering*, *Platform engineering*, *Platform component engineering* and *Software factory VPs* are placed in the Platform Specific Model (PSM), alongside with connected ADCs. Ultimately the *Crosscutting concerns*, *Risk management*, *Standards* and *Corporate VPs* are considered in a model spanning across all MDA layers, as they may affect various or even all parts of the developed system. Fig. 4 depicts the resulting architecture model, which serves as a redesign and extension of previously discussed GSCAM.

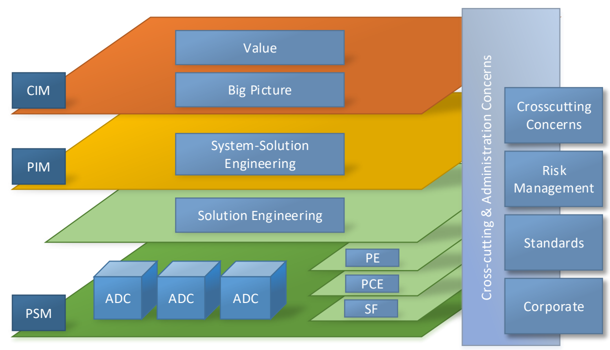

Fig. 4. Extended Generic Smart City Architecture Model

To provide a holistic MBSE framework for cross-domain systems or SoS in Smart Cities and to increase acceptance and collaboration across all engineering disciplines, the concerns of all affected application domains need to be considered. Therefore, SCRAM is extended by providing necessary information in a specific structure and desired level of detail for every application domain. As previously discussed research in contexts of Smart Grid, Industry 4.0, and Automotive domains suggests, the structuring of modeling artifacts is designated in well-defined ADCs. While every ADC is modeled using their designated DSL and corresponding framework functionality, the necessary interoperability aspects are modeled using ADIs.

An ADI describes the required connection and necessary interrelations between application domains, hence supporting the desired overall functionality. As every interrelation may affect multiple components of an application domain, necessary interfaces, resulting in physical connections, used protocols and exchanged information need to be provided. Therefore an ADI is modeled as an interoperability aspect and belongs to cross-cutting concerns of the model. Furthermore, also dependability aspects need to be considered carefully, as the newly introduced connection to other application domains may have unexpected effects on the originally independently designed system.

V. Application

Following ISO 42010 guidelines, after defining an architecture description language that covers all necessary viewpoints, and model kinds, the corresponding views and models can be used to describe the actual System of Interest (SoI). Additionally, as the case study is considering an infrastructure service for charging and routing of EVs, the modeled architecture also provides deeper insights into the cross-domain engineering of systems in the Smart City.

According to the previously discussed DSL structure, key parts of CIM, PIM, and PSM are presented in more detail, specifically focusing on the infrastructure service and interoperability aspects towards the connected application domains.

A. Computational Independent Model

Required views for the description of the problem and solution space, as well as a stakeholder map along with required high-level use cases, were modeled using the provided DSL. The problem space was described using the proposed *Problem Space Overview Diagram* and contains textual descriptions of the problem space, the resulting mission statement, and a vision statement, which frame the expected results.

Architectural models serve as systematic contemplation of final requirements in the context of the SoI, therefore necessary aspects, like an assessment of stakeholders, their concerns, and high-level requirements, were addressed by the proposed *Problem Space Analysis Diagram*. The identified concerns are then refined by high-level requirements, user stories and use cases. The intended solution, as part of the *Big Picture VP*, is then addressed by the *Solution Space Overview* and *Solution Space Analysis Diagrams*, where the system context is defined and further detailed by documentation of solution constraints, emergent characteristics, and architecture principles. Additionally, a reference capability map provides a top-level overview of necessary solution properties.

B. Platform Independent Model

After investigating concerns of the problem space and defining the system context, the *System-solution engineering VP* aspects were modeled. Necessary decisions regarding used platforms and supporting solution partners are documented using *System-Solution Overview Diagram*. This diagram also allows the identification and modeling of essential key performance indicators for the developed infrastructure system. Previously specified reference capabilities are linked to more detailed system capabilities and then further decomposed into, processes, functions, services, and information flows, provided by the *System-Solution Analysis Diagram*. The system-level logical architecture, however, is modeled using native SysML and Unified Modelling Language (UML) diagrams.

C. Platform Specific Model

As the provided framework divides the PSM into various sections, represented as packages in the model, the solution aspects concerning implemented infrastructure services are modeled in the *Solution Engineering Package* using *Solution Overview*, *Solution Analysis* and *Solution Structure Diagrams*.

According to IEC 63188, applications in the Smart City domain can greatly benefit from the utilization of existing services and platforms. Hence, the investigated case study makes use of the Open Urban Platform (OUP), as defined in [20]. Essential aspects of the used platform and its components are modeled in their corresponding *Platform Engineering* and *Platform Component Engineering Packages*. Fig. 5 exemplary depicts one platform component and its provided services.

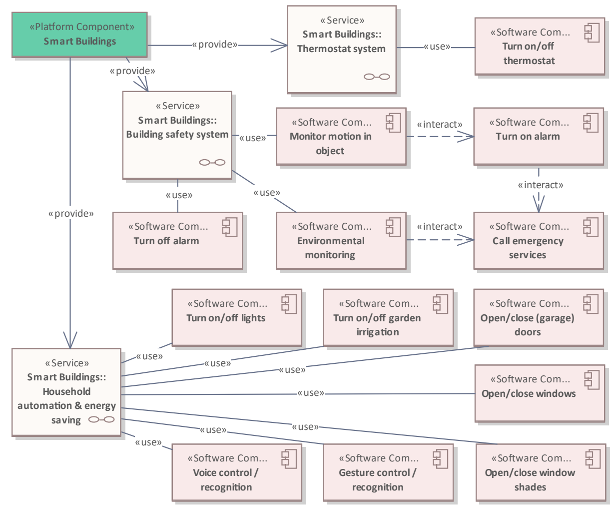

Fig. 5. Structure and provided services of a component

When the modeled solution interacts with external application domains, they are modeled as external black-box systems or more specifically as ADCs. ADCs can represent well-defined frameworks (such as SGAM, Automotive Reference Architecture Model (ARAM), and RAMI 4.0) or can be customized to express the needs of a particular application domain. The interrelations of SGAM and ARAM ADCs to the Smart City domain are examined in detail. Therefore, all required ADIs are first defined as black boxes in the *Solution Engineering Package* and then further detailed as interoperability aspects, as described in the next section.

D. Cross-cutting & Administration Concerns

Aspects that affect the developed system on various hierarchy levels are modeled as crosscutting concerns. Therefore, the *Interoperability Diagram* is used to examine necessary connections between parts of the system or between connected systems. Hence, describing necessary logical interfaces, types of connections between components (physical or virtual), used protocols, and transferred information. These details can be defined manually as needed or in a structured way, by using ADIs to connect ADCs in the *Solution engineering* section. In the logical architecture model, an ADI behaves as a uni- or a bi-directional interface, which, however, links and groups all mentioned aspects into an *Interoperability Package*. When an ADC model is part of the same model repository as the Smart City model, the newly created dependencies between ADCs are automatically reflected for all affected components. If for any reason, an ADC is modeled in a separate repository, the created ADI *Interoperability Package* can be transferred to the related model to maintain the consistency of the solution's documentation.

The modeled case study and resulting artifacts extended in the following ADSRM iterations, detailed documentation of the created model, including a depiction of the particular ADCs, is provided online [21] for further reference.

VI. Findings

After successfully applying the resulting framework structure and defined DSL elements to the selected case study, it could be observed that a complex cross-domain system can be modelled and structured with the provided framework. Also, interoperability aspects between connected application domains could be elaborated on in detail. The desired traceability of connections and dependencies across application domains could be provided as well, both for combined and separate solution model repositories.

As a major outcome of the study, the introduced Application Domain Cube and Application Domain Interrelation elements provide a semantic for modelling of cross-domain aspects and are seamlessly integrated into the SCRAM and MDA aligned framework structure. Technically, the currently available framework implementation already provides capabilities for the modelling of a complex Smart City system. The focus that was set on structural aspects of the framework allowed a thorough investigation of various viable approaches for the integration of existing and new concepts. Thus, at the current state, a high degree of re-use of existing frameworks and standards is ensured, despite the significantly increased level of complexity for architectures in the Smart City domain.

However, the currently provided framework lacks guidance and supporting functionality, as known from SGAM and RAMI 4.0 frameworks. Furthermore, as the standard for the creation of a Smart City Reference Architecture (SCRA) [17] is still under development, there is currently no blueprint available for system solutions. These could together pose as limiting factors for initial acceptance of the currently provided MBSE framework.

VII. Conclusion and Future Work

Being part of a System-of-Systems (SoS) in a Smart City context introduces new interoperability and dependability challenges to previously mostly independently developed and operated systems from various application domains. Hence, the concepts presented in this paper provide a standards-based approach to addressing those challenges. An SCRAM based architecture framework has been proposed that fosters cross-domain modelling and interdisciplinary work. The implemented DSL has currently been made available [21] as an add-in for the modelling tool *Enterprise Architect* by Sparx Systems.

The findings made during the application of the framework drive the future work of the authors. First, guidance and supporting functionality will be added. In addition, the framework will be used for modelling a standard-based reference architecture, which can serve as a blueprint for new solutions.

Besides these considerations, investigations will take place on how to integrate further supporting functionality towards model transformations and exploit Smart City models for evaluating particular solutions in Co-Simulation scenarios.

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