System of Systems Models Enabling Interoperability for Value Creation

An Industry IoT Consortium and Digital Twin Consortium Whitepaper

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ABSTRACT

The world's economies operate through an intricate web of interconnected systems, spanning business and operational systems. Improving efficiency and reducing waste in these systems is crucial. However, traditional methods of optimizing individual systems are no longer adequate.

Digital twins have been introduced into the operational environment as a new approach to better use digital technologies to operate real-world assets. These systems are increasingly interconnected forming large and complex systems and thus face similar challenges.

This paper presents systematic and comprehensive approaches based on the System of Systems (SoS) concept and models, which enhance the interconnectedness of systems, make existing capabilities[1] more accessible, foster emergent new capabilities, and create more value for business and society. This value is driven by SoS's ability to dynamically form larger systems and enable emergent[2] capabilities, towards the goal of making the world's economy of interconnected systems vastly more capable, efficient and less wasteful.

The principles and practices of SoS are applicable to digital twin systems that are increasingly interconnected with each other and other systems. The paper emphasizes the importance of SoS interoperability, supported by common conceptual models and standardization, and calls for community efforts to develop appropriate open SoS standards. In addition, the paper provides several use cases describing how the SoS model can be implemented in various industries.

1 INTRODUCTION

1.1 CONTEXT AND BACKGROUND

The world economies function as vast webs of interconnected systems. These systems, complex and multifaceted, interact in myriad ways, influencing the ebbs and flows of global economic activity. These systems are increasingly digitized (operated by software) and instrumentalized (embedded with sensors from which data can be gathered and analyzed). With the rise of digital twins, real-world entities are represented in and connected to the digital world, further expanding the existing vast web of interconnected systems, deeply into the real-world.

An IBM report [1] identifies 11 core systems that make up our world's economy (see Figure 1-1). Each system, vast by itself, has evolved to meet a specific societal need, together forming a global

[1] *The term "capability" used here generally refers to the ability (potential) and capacity (performance) of a system in delivering certain outcomes and values. It is concerned with what and how well a system can deliver in achieving certain business goals.*

[2] *The term "emergent" used here follows its meaning in the context of complex systems, where it refers to new properties or capabilities that arise from the interactions among system components, which do not exist in and may not be predictable from the properties of the individual components.*

system of systems representing the global Gross Domestic Product (GDP). These systems are an amalgamation of systems by public and private sector organizations, spanning multiple industries. They depend on each other and have cause-and-effect relationships.

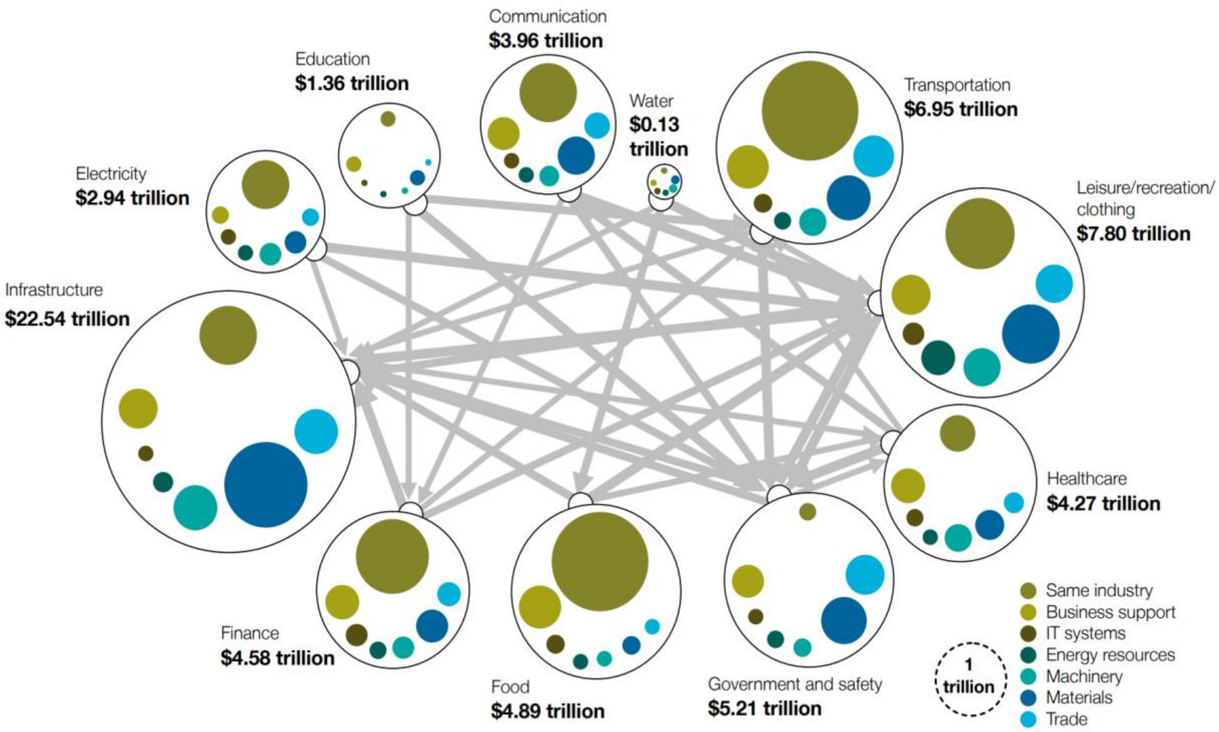

Figure 1-1: Core systems in the world economy.

Up to this point, progress in an individual system is often the result of independent processes of designing, deploying, operating, and evolving them with isolated goals by its operator. It is often done without holistically considering how it affects the other systems in its global environment[3]. When the goals and objectives are only defined within a system, it may cause increased inefficiencies in other related systems to the point where there is a net overall increase in waste. To provide a sense of scale, the IBM [1] report estimated that our planet's system of systems carries inefficiencies totaling nearly US$15 trillion, or 28 percent of worldwide GDP, from which approximately US$4 trillion could be eliminated.

Today's global challenges, such as food security, clean water access, energy shortages, climate change, and sustainability, are too complex and impacting too many systems and industries to be solved by independent advancement of individual systems. Optimizing at a granular level, be it at the scale of individual enterprises, value chains, cities, nations, or even international coalitions, is not sufficiently effective. Instead, a comprehensive, coordinated, and continuous

[3] *This is not necessarily because of the lack of foresight and desire but largely due to the overwhelming complexity that is usually involved. Instead of monolithic system design, the SoS approach discussed in this paper allows independent design and operations of individual systems but offers more effective ways to manage the global impacts when these systems are connected together.*

effort across all systems is necessary. This requires a new mindset and a holistic "System-of-Systems" (SoS) approach to address global inefficiencies.

The traditional way of optimizing individual systems and allowing them to be interconnected as an afterthought presents paramount challenges in interoperability alone and has become insufficient for further progress, as aptly described by the IBM paper[1]. We need more systematic and comprehensive approaches supported by common SoS conceptual models and interoperability standards for enabling and enhancing dynamic interconnectedness of systems, enhancing composability of SoS, making existing capabilities more broadly available, facilitating emerging capabilities, fostering environments in which these capabilities can be leveraged to deliver new values to the society.

The idea of SoS is not purely conceptual and technical. Rather, it presents a strong value driver and paradigm to make the society operate more efficiently overall by reducing the vast waste that is pervasively present. The impact of successful and broad adoption of SoS would have profound and long-lasting impact. Indeed, the societal and industrial value of an SoS approach, driven by the imperative to address global challenges, is the key motivator for producing this paper.

1.2 Purpose and Audience

This paper is the result of collaborative efforts by the Digital Twin Interoperability Joint Working Group, which was formed by the Digital Twin Consortium (DTC) and the Industry IoT Consortium (IIC) to investigate and address interoperability challenges in implementing digital twin systems.

The paper proposes System of Systems (SoS) conceptual models for composing interconnected and interoperable systems to overcome current challenges limiting their value potential. Based on such models, it further explores the two key features of digital twins, namely composition and federation, to better enable emergent capabilities and value creation from interconnected systems.

Several cross-industry use cases that benefit from building larger and increasingly interconnected systems including digital twin systems are presented. These examples serve as a launching point for reference implementations that incorporate the proposed models and demonstrate substantial outcomes, such as reducing integration costs, minimizing data preparation and normalization effort, and enabling a federated marketplace to deliver interoperable edge-to-cloud services at scale.

This paper expands on concepts described in three related publications on digital twin architecture:

- "Digital Twin System Interoperability Framework" (Digital Twin Consortium) [2]

- "Platform Stack Architectural Framework: An Introductory Guide" (Digital Twin Consortium) [3]
- "Digital Twin Core Conceptual Models and Services" (Industry IoT Consortium) [4]

These documents, including this one, provide complimentary ideas by examining digital twins from different perspectives and will benefit readers who are building digital twin systems in their diverse applications across industries. However, these insights are also valuable for a broader range of systems beyond those specifically involving digital twins.

2 System of Systems Fundamentals and Conceptual Models

The System of System (SoS) concept has emerged from many system designs. It comprises a unique combination of characteristics and common design patterns that make it valuable for composing complex and dynamic systems.

Maier published his seminal work on SoS in 1998 [5] that advanced its concept with an emphasis on the need for collaborative, communication-based architectures in SoS design. The so-called 'Maier Criteria' proposed in this work identifies challenges in SoS, helping to address their unique complexities. Since then, the field of SoS research has been rapidly evolving, with significant contributions from diverse disciplines like engineering, computer science, management, and social sciences.

Current research in SoS encompasses a multidisciplinary approach focusing on visualization, communication methodologies, interoperability, distributed resource management, architecture design, data policies, and formal modeling languages [6][7][8]. SoS research extends beyond its traditional stronghold in the defense sector, finding applications in national air and auto transportation, space exploration, healthcare, Internet design, software integration, energy management, and power systems [9][10][11].

In this section, we will outline SoS features and propose conceptual models, taking into account current consensus understandings, however, with unique perspectives and emphases, to serve as a pragmatic foundation for exploring the widespread and diverse applications of SoS.

2.1 Basic Concepts and the 6C Dimensions

To serve as a basis for discussion and deliberation of System of Systems (SoS)[4], including its conceptual models and how interoperability can be addressed with the models, let's first establish working definitions of SoS and other concepts associated with it, in alignment with the

[4] *Our discussion of Systems and System of Systems will assume they have significant digital (software) capabilities, or at the least managed by some digital components, though the concept of Systems and System of Systems encompass a broader range that may include pure physical systems.*

established standards definitions from ISO/IEC/IEEE, which are also adopted by INCOSE, IIC, and OMG [27][28][29].

According to ISO/IEC/IEEE 21839[29], an SoS is a “set of systems or system elements that interact to provide a unique capability that none of the constituent systems can accomplish on its own”.

As a working definition aligned with this concept, a **System of Systems (SoS)** is an arrangement of independently operated systems that collaborate to achieve common objectives, with emerging capabilities and values.

On the other hand, according to ISO/IEC/IEEE 15288[28], a system is an “arrangement of parts or elements that together exhibit a stated behavior or meaning that the individual constituents do not”.

In the same spirit, as a working definition, a **System** is a cohesive organization of things and mechanisms built and operated to provide certain capabilities to achieve specific purposes.

It is often difficult to distinguish between SoS and systems, as the distinction lies in multiple dimensions and requires a comprehensive analysis to arrive at a more definitive and holistic characterization. To make it easier, we have outlined six dimensions of comparing SoS with systems: Composition, Connection, Completeness, Construction, Continuance, and Capability, which we call the 6C Dimensions. The 6C dimensions may also help understand how the distinctive features of an SoS may solve some of the challenges faced by the conventional approaches, as described in the early sections. These dimensions are listed in Table 2-1.

Dimensions	**System**	**SoS**
Composition	Predefined	Organic
Connection	Integrated	Interoperable
Completeness	Deterministic	Nondeterministic
Construction	By a single stakeholder	By one or more independent stakeholders
Continuance	Controlled	Collaborative
Capability	Predetermined	Emergent

Table 2-1: 6C Dimensions for distinguishing SoS and systems.

- **Composition**: the composition dimension indicates how the whole is made up by the parts. The composition of a system tends to be predefined, or put together by design, following the conventional engineering process of design, build, deploy and use. In contrast, an SoS tends to form and grow organically, that is not by design, at least not by the strict sense of conventional engineering processes.

  When a system is being designed, careful and detailed considerations are given to account for what parts it has, what functions they perform, and how the parts are put together to provide the overall capability of the system. However, when systems are joined together to form an SoS, additional functions may be needed to enable them to connect or interact with each other. These functions may not be part of the original design of the systems. However, these SoS-enabling functions may become part of the original system design as SoS becomes more widespread and these SoS-enabling functions more standardized.

  A car is a system, with its parts, e.g., wheels, chassis, engine, designed to be assembled to build the whole – the car. In contrast, a group of proximal vehicles, loosely termed as a convoy, on a highway is an SoS with its constituent systems, individual vehicles, joined together to form the whole – the convoy, typically by circumstances, often dynamically, and even transiently.

- **Connection** characterizes how the parts of the whole are interconnected. The parts in a system are typically tightly integrated by design while the parts in an SoS, i.e., systems, are loosely coupled and may be dynamic, which requires stronger interoperability.

  The engine of a car needs to be perfectly fitted into the chassis and with other parts of the drivetrain to meet the design specifications. A vehicle joins a convoy by moving along in proximity with other vehicles at similar speed in the same direction by following a set of simple rules.

- **Completeness** signifies the state of the whole having all the necessary or appropriate parts. A system has by design a certainty and finality of what and how many parts it should possess. An SoS generally does not have the certainty of what and how many parts, systems, it may have. In other words, individual systems may join or leave the SoS.

  A car, when leaving the factory to be delivered to its customer, can be checked against a list if all its parts have been put together, in their right place, to ascertain its completeness. On the other hand, a convoy of vehicles on the highway can change any time, the notion of completeness generally does not apply.

- **Construction** describes how the whole is built, by a single or a multitude of responsible or authoritative entities[5]. A system, at least at its final stage of construction, is usually built by a single entity. An SoS does not, however, have a single entity that is responsible for its construction. An SoS is formed by systems joining together and these systems may be built by various responsible entities.

  A car is built by a car manufacturer in its final assembly stage. The vehicles in a convoy on a highway are usually built by various car manufacturers. When a convoy is formed, each vehicle in it is driven by an independent driver.

- **Continuance** conveys how the whole, a system or an SoS, is operated and maintained to deliver its capabilities and values throughout its lifecycle. During this lifecycle, a system operator typically has full control and responsibility, acting as the central authority, whereas in an SoS, independent system operators collaborate to ensure the SoS's overall operations.

  A driver of a car has full control over the car running on the highway. Each driver of the group of proximal vehicles (the convoy) on a highway collaborates with each other to ensure safe and efficient passage.

- **Capability** underscores the potential and performance of the whole in terms of its functionality. A system has a set and predetermined capability based on its design

[5] *Entity is used to loosely refer to a legal person or some form of organization.*

specifications. It delivers functions as intended and expected. Conversely, an SoS exhibits capabilities that may not be predetermined due to the dynamic nature of its constituent systems, and the collaborative operations among them. While individual systems within an SoS have defined capabilities, the collective outcome often results in emergent capabilities and/or behaviors that were not explicitly designed or intended.

A car is designed to provide transportation with specific features like speed, fuel efficiency, and safety based on its model and specifications. However, a convoy of vehicles on a highway, when operating as an SoS, may exhibit capabilities such as collective traffic flow management, reduced air resistance through drafting, or enhanced safety through coordinated movements, which were not capabilities of any individual car but emerge due to their collective operation.

There are some additional characteristic differences between a system and an SoS, as derived from the 6C dimensions. For example, there is notable distinction in adaptability between a system and an SoS. Unlike a system, an SoS tends to be organic in its composition and nondeterministic in its completeness, and additionally, its parts tend to be loosely coupled - requiring connections that are interoperable, not integrated (or more tightly coupled in connection). An SoS allows a level of fluidity in how it can change in the parts it consists of and in the ways the parts are inter-connected not usually seen in a system. In other words, an SoS tends to be dynamic. As a result, an SoS may demonstrate stronger adaptiveness and resilience against changes, especially against those that are adversary.

A car missing a wheel or having an additional wheel on the road would not function or would not provide the capability as expected or required. In contrast, a convoy of vehicles, adding or subtracting a few vehicles, would still behave qualitatively the same way. In fact, the formation of a convoy of vehicles changes all the time, with its size and shape altering constantly.

Furthermore, the Construction and Continuance dimensions together highlight another important elemental distinction between a system and an SoS in “ownership” and “controls”. In this aspect, a system is akin to a ‘sovereign state’ while an SoS, in contrast, is often similar to a weak form of ‘federation of sovereign states”, or a treaty-bound alliance of states.

A system tends to be built and operated by a single responsible entity. For an SoS, on the other hand, each of its constituent systems is built and operated in principle by an independent responsible entity who collaborates with the others at the SoS level. Therefore, there tends to be no single responsible entity for the SoS level, at least not all the time. However, it does not preclude an overall coordinating and orchestrating entity for the operation of an SoS. Generally, one can speak of an SoS as a ‘federation’ of cooperating systems.

In this sense, each responsible entity for a system joining an SoS shares a common vision of the SoS and agrees to and abides by certain rules when becoming a member of the SoS. In doing so, the systems can connect and interact with each other in a way that can achieve their shared goals.

Since it lacks a top-down design and control scheme enabling tight integration of the parts as in the case of a system, an SoS emphasizes its reliance on interoperability between its constituent systems in enabling the connection and interaction among them.

Systems form parts of a System of Systems (SoS), and an SoS can be part of a larger SoS. Conversely, an SoS cannot be part of a single system. Similarly, a system cannot be part of another system, as its parts lack the fullness of capability and independence to be systems themselves. (see Table 2-2).

There is some confusion regarding the idea that a system cannot be part of another system, which arises from contextual differences. A system is defined by its capability and purpose. For example, a car is considered a transportation system that moves on solid surfaces while carrying loads. In this context, the car's engine is not a separate system but a part of the car system. However, the engine can be viewed as a system in itself when considered for its purpose of providing drive to move objects.

Parts → / Whole ↓	**System**	**SoS**
System	No	No
SoS	Yes	Yes

Table 2-2: Composition characteristic of system and SoS.

Neither a system nor an SoS exists in vacuum but in some ***Environment***, the context that determines the setting and circumstances of all interactions and influences with a system or SoS of interest.

The concept of capability provided by a system and an SoS are central to their usefulness. A ***Capability*** is a description of ability and capacity to deliver certain outcomes and values.

For example, the capability of a water pump includes its ability (potential) to pump water (e.g., versus that to pump air) and the capacity (performance) at which it pumps water (e.g., some measure of volume per unit time). A capability can be viewed as an implementation-independent specification of a function to achieve an effect in the physical or virtual world. A capability is characterized by properties and can be restricted by constraints (e.g., a particular pump is a borehole submersible pump that can operate at depths up to 50m with a capacity of 1000 m^3/s).

The capabilities of an SoS should ideally be more than the union of capabilities of the constituent systems, i.e., new capabilities may emerge as a result of the composition of the constituent capabilities. Each constituent system plays an essential role in the SoS in contributing their capabilities to form the overall capability of the SoS.

Constituent systems in an SoS generate information in their operation and then share part of this information with the other constituent systems. New information may be generated in an SoS from the synthesizing or processing of the aggregated information that would not have been possible from any individual system alone. In particular, this applies to systems using artificial intelligence (AI) /machine learning (ML) algorithms where the results depend fundamentally on input data and may be self-learning. This emerging capability arising from analytics, especially those with self-learning on the aggregated information, can make an SoS more adaptable to the changes of itself and its environment.

As an example, the capabilities of an SoS in the energy sector with renewable generation should ideally be more than the sum of the power generation from all plants. Consider an SoS that encompasses solar and wind energy generators, conventional power plants, energy storage facilities like batteries, and electricity consumption units such as residential homes, industries, and commercial spaces. The solar generators have the capability to produce electricity during sunlight hours, which varies by weather conditions and seasons.

Wind generators produce electricity contingent on wind speeds, which can also be variable. The conventional power plants provide a consistent, stable energy output, and the energy storage facilities have the capability to store excess energy during low consumption times and discharge it during peak demand. Meanwhile, electricity consumption units have fluctuating demands based on time of day, weather conditions, and other factors.

The emergent capability of this SoS is to provide a consistent and reliable electricity supply to the consumption units regardless of the inherent variability in renewable energy production and demand fluctuations, by synthesizing and analyzing relevant information across all the systems and the environment.

Each constituent system plays a crucial role in the SoS by contributing their individual capabilities to form the overall capability of the SoS, ensuring that energy is available when needed and stored when in excess, while minimizing overall carbon emission. Clearly these emergent capabilities cannot be achieved by the “simple sum” of the individual systems (not connected and not interacting).

As another example, a sensor SoS may comprise a network of sensors of the same type (e.g., temperature) at varying locations. The sensor data is synthesized using algorithms, taking into account the sensor location and by identifying and eliminating outliers in the sensor measurements (‘sensor data fusion’).

The resulting fused sensor values can cover a larger area (e.g., as a heat map) demonstrating the overall pattern of temperature and the dynamic of its change over the area . They also offer a higher level of trustworthiness than the individual sensors. The sensor network is in this sense an

SoS with a more advanced capability (measurement and understanding) than that provided by any constituent system (individual sensor).

2.2 System of Systems Conceptual Models

Conceptual models play a crucial role in comprehending systems, encompassing their structures and behaviors, as well as their interactions with other systems. By using common models, interoperability can be simplified. Due to their complexity, an SoS can be examined from multiple perspectives. In this section, we present several models, each from a different perspective, that describe the essential characteristics necessary for designing and implementing effective SoS.

2.2.1 SoS Composition Model

The SoS Composition Model describes how an SoS is made up (Figure 2-1).

An SoS is composed of two or more systems and/or SoS as its constituent systems.

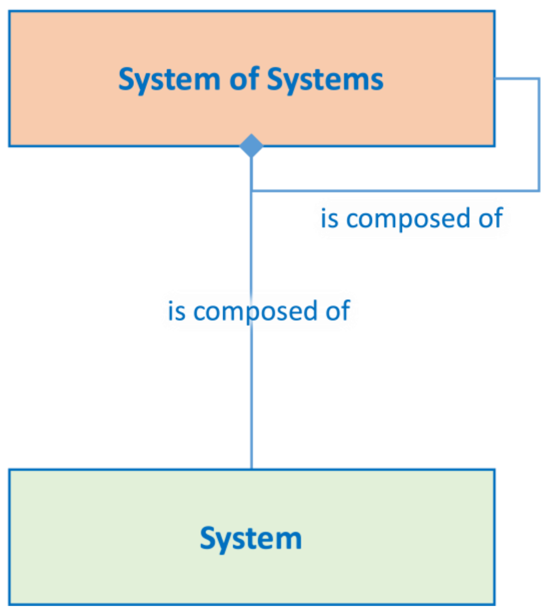

Figure 2-1: System of Systems composition model.

2.2.2 System of Systems Contextual Model

An SoS exists and functions in a given Environment, in which other SoS may co-exist, independently of the SoS under consideration. A given environment contains one or more independent SoS; more precisely, one or more independent SoS may emerge in a given Environment. An SoS is composed of two or more constituent systems, each can be a system or an SoS, organically (as opposed to by-design). The SoS Contextual Model (Figure 2-2) describes how an SoS is related to its environment and its constituent systems.

An SoS manifests overall capabilities, including emerging capabilities arising from interactions between its constituents, the utilization of which causes effects to its environment as its utility and adverse effect.

A constituent **system** consists of components, by system design.

- A system manifests its capabilities to the environment, independent of those from the SoS it participates in.
- A system may participate as a party and play one or more roles in an SoS, fulfilling certain contracts. In doing so, it is involved in value streams in the SoS, contributing to value creation by the SoS for the environment.
- A system may advertise and offer its capabilities to other systems in the SoS. It may also use capabilities offered by other systems within the SoS.

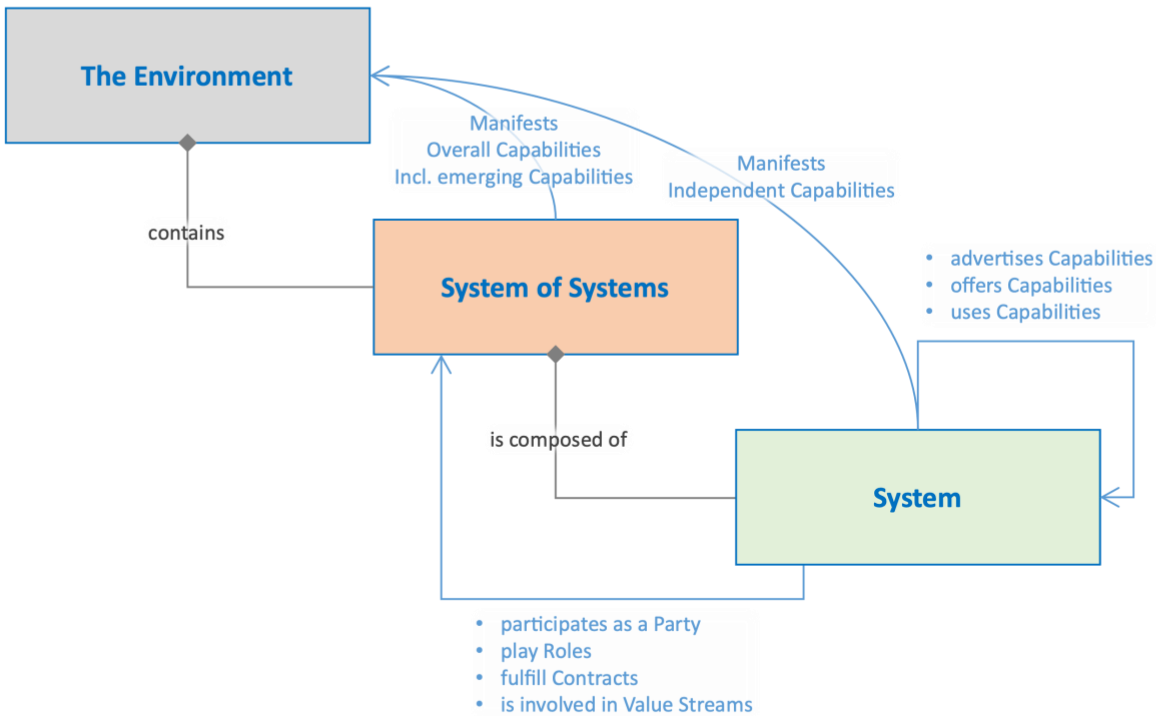

Figure 2-2: System of Systems contextual model.

The above description, though terse, attempts to represent some important concepts about SoS. Below are definitions of terms that are used.

Party: A Party is an autonomous and identifiable agent that has interest, ability, and responsibility in participating in the activities or engaging interactions in an SoS.

Role: A role is a set of functions assumed by a party to initiate and participate in the realization or the use of capabilities in an SoS.

A party may assume more than one role, and a role may be fulfilled by more than one party.

Contract: The binding agreements by which the interest, responsibility, and the ways of interactions among systems within an SoS are governed.

Value Stream[6]: A value stream is a sequence or chain of activities and capabilities where each step or stage adds value. [34]

This chain of value creation in an SoS is formed by the interaction between the systems allowing their capabilities (e.g. offered as services) to build upon each other. At each stage, value is added by the use of the capability, which in turn can be passed to other downstream systems and finally the end users in the environment. Moreover, feedback mechanisms within this chain can further enhance the value proposition, leading to continuous improvement and innovation.

A value stream can be understood as the flow and enhancement of value through the use of capabilities of an SoS, ensuring alignment, collaboration, and optimization of capabilities for the benefit of all involved parties in value creation.

Systems are built and operated by design to provide certain capabilities to serve certain purposes in a given environment. Generally, they may not be originally designed to participate in a larger SoS.

When multiple systems, originally designed, built, and operated independently, come together in a shared environment, they form a larger entity known as an SoS. Each participating system in this SoS acts as a party and assumes specific roles in their interactions. As these systems connect and engage with one another, they can exhibit new capabilities that do not present when they operate in isolation. Such emergent capabilities arise from the collective interactions. Consequently, the aggregate capabilities of an SoS, inclusive of these emergent capabilities, surpass the mere combination of the individual systems' capabilities. This leads to a value greater than the cumulative values offered by each individual System.

2.2.3 System Capability and Relation Model

When a system becomes part of an SoS, it forms relations with other systems in the SoS and offers specific capabilities as services to them. At the same time, it may consume services offered by them as well. The delivery and receipt of these services are governed by relations, ensuring trust is maintained (Figure 2-3).

Service here is defined as a self-contained, coherent, and discrete means of realizing capabilities for delivering values.

[6] *Although sometimes referred to as value chain, TOGAF refers to value streams as "an end-to-end collection of value-adding activities that create an overall result for a customer, stakeholder, or end-user." The main difference is that value chains focus only on economic value, while value streams focus on how business value (of any kind) is accumulated in each activity sequence [34].*

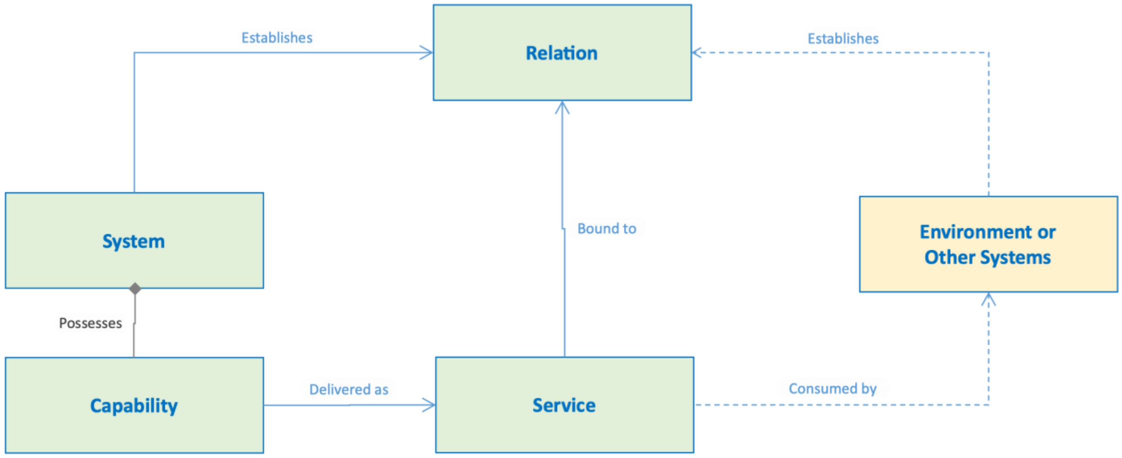

Figure 2-3: System capability and relation model.

The concept of capability can be approached from two perspectives: a business perspective and a technical perspective. The business capability of a system refers to its ability and capacity to perform certain functions that address specific business problems. In contrast, technical capability refers to the system's ability and capacity to implement those functions to realize the business capabilities.

For example, information exchange has been a business capability for centuries, but the technical capabilities for achieving it have changed dramatically in recent times. From the use of letters and post systems supported by horse carriages to telegrams (both wired and wireless), telephones, email, instant messaging, video conferencing, and more, the means of information exchange have become faster, more efficient, and more cost-effective, enabling almost ubiquitous usage.

This evolution demonstrates how technical capabilities can greatly enhance a system's business capabilities, as well as how technology can transform the way in which we achieve those capabilities. The combination of business and technical capabilities is key to solving business problems and achieving business goals.

In the world of software engineering, the term "service" refers to a specific concept that plays a crucial role in the development of SoS. Most technical capabilities, including those that are implemented in hardware, are typically managed, extended, encapsulated, and exposed through software. Nowadays, these capabilities are often implemented as services (e.g. exposed as Application Programing Interface – API), which provide a way to encapsulate implementation details and expose functionality in a standardized manner. This approach is known as Service-Oriented Architecture (SOA).

SOA enables software functionalities, such as retrieving specific information or executing a set of operations, to be implemented in a way that allows different clients, or service consumers, to reuse them in different application contexts. The Organization for the Advancement of

Structured Information Standards (OASIS), a standards organization, defines a service as "a mechanism to enable access to one or more capabilities, where the access is provided using a prescribed interface and is exercised consistent with constraints and policies as specified by the service description." [13]

The SOA paradigm is particularly relevant for SoS because each system within the SoS is designed and operated independently, and thus managed as a separate concern. Loose coupling between systems is necessary to facilitate flexible interactions among them, and the forming and evolution of SoS organically. At the current level of technology development, the SOA paradigm is an effective and efficient approach to designing complex systems that need to interact with each other in a loosely coupled manner.

While not directly related to the SoS models discussed above, it's important to note that the term "service" has another important dimension in the business model of offering and using capabilities in an SoS. An increasing trend is to offer capabilities as a service to its consumers, with fees charged based on subscription (as in the case of video conferencing services) or actual usage (as in the case of virtual machines in a cloud computing environment). This trend is evident in the Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS) models.

As SoS continues to evolve, it's foreseeable that the concept of Capability as a Service (CaaS) will gain traction and become more prevalent. This model will build on other "As a Service" models and enable organizations to leverage external capabilities as services, much like they leverage external software services today. By using CaaS, organizations can focus on their core competencies while relying on external providers for specialized capabilities, creating a more flexible and agile approach to delivering solutions within an SoS. The emergence of CaaS as a value-driven business model in SoS is a game-changer for organizations, as it enables them to create value and achieve high levels of alignment in collaboration.

In the CaaS model, value creation is the primary driver, as providers of capabilities focus on delivering value to their consumers; consumers of capabilities focus on creating new value in their business domains and may in turn become capability providers themselves. This value-driven approach:

- ensures that the capabilities offered are relevant and aligned with the needs of the consumers, enabling them to achieve their objectives efficiently.
- fosters collaboration among different organizations, as they can leverage each other’s capabilities to achieve their goals without having to invest in building those capabilities themselves.
- drives organizations to achieve a higher level of specialization, as they can leverage external providers for specialized capabilities. However, an organization will always be

wary of creating critical dependencies on external parties and want to make sure these dependencies are stable and secure.

- enables organizations to focus on their core competencies, thereby improving their overall efficiency and effectiveness.
- promotes flexibility and agility, as organizations can easily adapt to changing business requirements and market conditions by leveraging external capabilities.

In an SoS, the value-driven business alignment enabled by the CaaS model can extend beyond a pairing relationship between a capability provider and a consumer. The consumer of a capability as a service can enhance or extend the capability they have acquired and provide it to downstream consumers as a value-added service, as illustrated in Figure 2-4. This can create value streams that are formed by chains of capabilities, where each capability provider adds value to those they receive and passes it on to the next consumer. A final consumer may benefit from the aggregated and enhanced capabilities along a value chain (denoted by red arrows in Figure 2-4). Many value chains can be formed within an SoS.

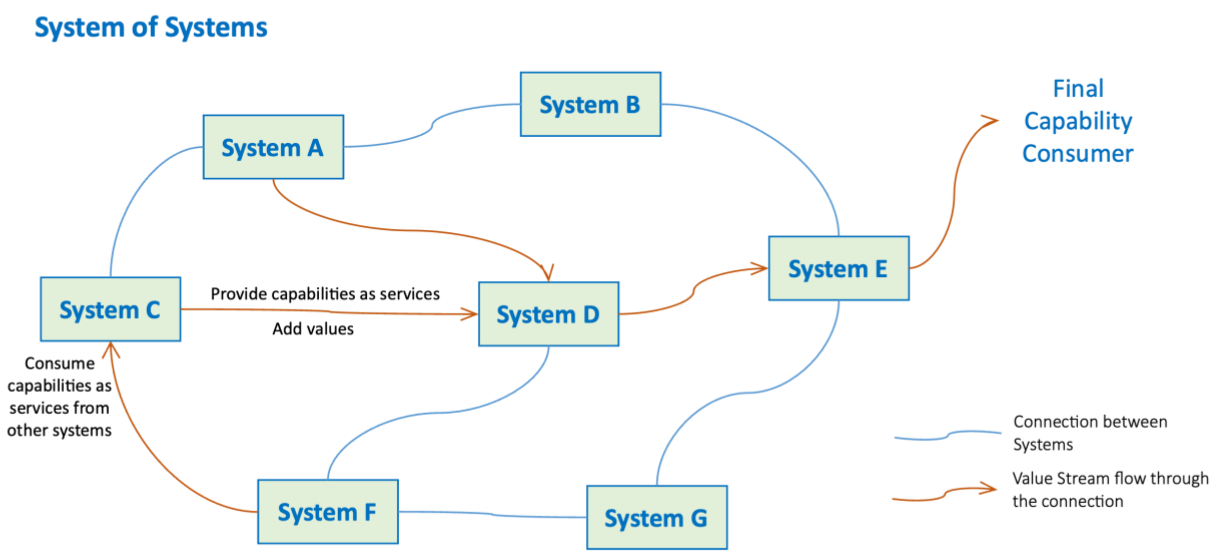

Figure 2-4: Value stream in a System of Systems.

This chain of value creation can be seen as a form of value stream, where value is added at each stage of the chain. The value stream can start from the creation of a basic capability, such as data storage or processing, which can be provided as a service to other capabilities. Each downstream capability can then add value by leveraging the basic capability and providing its own specialized service, such as data analysis or visualization. This value-added service can then be provided to other downstream capabilities, creating a chain of value creation.

The chain of value creation can be extended further by enabling downstream capabilities to provide feedback to the upstream providers. This feedback can help the upstream providers improve their capabilities and create more value, which can, in turn, benefit the downstream consumers. This feedback loop can drive continuous improvement and innovation in the SoS.

Overall, the chain of value creation enabled by the CaaS model in an SoS can create a network of capabilities that are aligned with the needs and interests of the organizations involved. This network of capabilities can foster collaboration, specialization, flexibility, and agility, thereby enabling organizations to achieve their objectives more effectively and efficiently. The feedback loop created by the network can drive continuous improvement and innovation, ensuring that the capability network remains relevant and valuable to its participants.

2.2.4 System Relation Model

To facilitate value stream creation through capability chains enabled by CaaS requires trusted, standardized, and interoperable methods of connection and interaction. This paper introduces the concept of a “Relation” between the systems, serving as a foundation for these connections and interactions. For trustworthy and reliable connections and interactions, a system must understand its peer system’s identity (who), the reasons for connecting (why), safe and effective connection methods (how), and engagement activities (what), and timing and conditions for engagement (when), etc.

Each system should provide essential information in a standardized manner, ensuring consistent and even automated interactions, thereby enhancing interoperability. Such interoperability, essential for the organic growth and dynamic evolution of an SoS, is optimized through established, agreed-upon standards. At the heart of these interoperable connections lies the "System Relation Model", which each system offers. This model encompasses the following details (Figure 2-5):

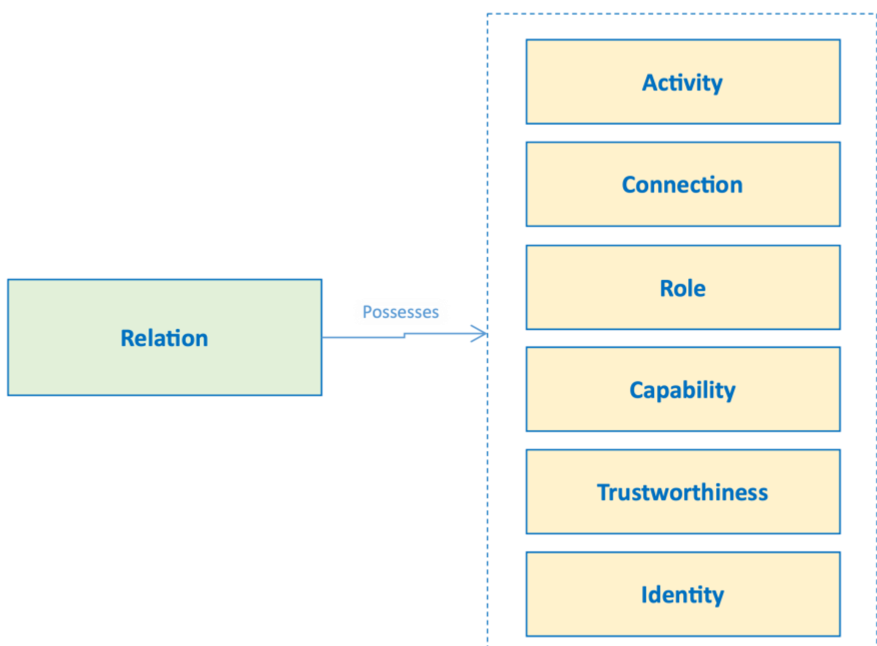

Figure 2-5: System relation model.

- **Identity**: it uniquely and unambiguously identifies a system, and it is the basic attribute for establishing a relation between systems. It answers the "who" question.
- **Trustworthiness**: based on the identity description, it elaborates on a system's trustworthiness. It highlights characteristics like its legitimacy, credibility (ensuring it's not fraudulent), adherence to the SoS community standards and business standing. Additionally, it assesses if the system is secure against digital and other threats, safeguarding not only itself but also peer systems connected to it. It also characterizes the system's stability, reliability, and resilience in delivering capabilities and services to the SoS community.
- **Capability**: it describes its capabilities to be offered to other systems or the capabilities it desires from other systems.
- **State**: it describes the operational state of the system in offering the capabilities.
- **Role**: it describes the role a system plays in establishing connections, providing or consuming capabilities or services.
- **Connection**: it describes the technical means for establishing connections between the connecting systems.
- **Activity**: it describes the type of interactions or transactions between the systems for one system to use capabilities offered by another, including data exchanges.

3 SYSTEM OF SYSTEMS INTEROPERABILITY

SoS interoperability refers to the ability of multiple independent and heterogeneous systems to work together effectively and efficiently as a cohesive whole. According to ISO/IEC 25010, interoperability is the "degree to which two or more systems, products or components can exchange information and use the information that has been exchanged."[14]

Interoperability is critical in SoS because these systems are often built independently, using tools from different vendors, each having diverse architectures, using various technologies, and often serving distinct purposes. Ensuring secure, smooth connections to enable collaboration among these systems is essential for the successful operation of the larger SoS. In other words, the demand for interoperability is especially strong when taking into account the independence of each of the constituent systems and the dynamic nature of these systems joining together to form the SoS.

However, achieving SoS interoperability can be challenging, as it requires coordination and cooperation among multiple stakeholders, including technology providers, system developers, integrators, and end-users. It often involves the use of standards and best practices to ensure seamless "plug and play" and collaboration among the systems within the SoS. The benefits of successful SoS interoperability include improved efficiency, increased capabilities, reduced duplication of efforts, and better adaptability to changing requirements.

Key aspects of SoS interoperability include:

- Data interoperability, which is the ability of different systems to exchange and understand data in a standardized and consistent manner. Standardized formats, protocols, and interfaces ensure that data can be easily shared across different platforms. Examples of such standards include JSON, XML, or MTConnect[16] for machine tool data, OPC-UA[17] for industrial automation, and ISO 10303 (STEP)[18] for product data exchange. Data interoperability supports SoS composition, connection, completeness, and construction (as discussed in Section 2.1).
- Communication interoperability, which is to ensure that the communication infrastructure between the systems supports seamless information sharing. It may involve establishing compatible communication protocols, data transmission rates, and security mechanisms. Standards such as HTTP, MQTT[19], and WebSockets can facilitate communication interoperability by providing common rules for data exchange across different platforms and systems. Communication interoperability supports the SoS composition, connection, construction, and continuance.
- Functional interoperability, which is the capability of various systems to work together to achieve a new goal. It requires defining standardized interfaces and Application Programming Interfaces (APIs) that allow the systems to interact with each other. For example, in manufacturing, it refers to the capability of different machines, processes, or systems to work together harmoniously and perform their intended functions collaboratively. Examples of functional interoperability standards include PLCopen[33] for industrial automation control, OPC-UA[17] for secure data exchange, DNP3 in IEC 62351-5[31], IEEE C37.118 for Synchrophasor Measurements[32][31], and ISO 22400[20] for manufacturing operations management. Functional interoperability supports SoS continuance and capability.
- Semantic interoperability, which is to ensure that the exchanged data and information are interpreted correctly by all the systems involved. It involves using standardized data models such as Resource Description Framework (RDF), JSON schema, and ontologies that provide common vocabularies and relationships to achieve a common understanding of data and its meaning. Semantic interoperability supports the SoS composition, connection, and continuance.
- Conceptual interoperability, which focuses on achieving a shared understanding and common conceptualization of information or data between different systems. It emphasizes the alignment of the meaning and semantics of exchanged information, rather than merely the technical aspects of data exchange. This level of interoperability

often requires defining common concepts, taxonomies, and reference models. In manufacturing, relevant standards help prevent misunderstandings and misinterpretations during collaboration by providing a common framework for communication. Examples include ISO 15926[21] for process plant data, Product Lifecycle Management (PLM) standards, and Industry Foundation Classes (IFC) for building and construction. Conceptual interoperability supports the SoS composition, connection, completeness, and construction.

- Dynamic interoperability, which refers to the ability of different systems to exchange and understand information in real-time or on-the-fly, without requiring extensive pre-configuration or static interfaces. It enables seamless communication and collaboration between heterogeneous systems by allowing them to adapt and interact with each other dynamically. For example, in manufacturing, dynamic interoperability might involve adjusting production processes based on changing demand, optimizing resource allocation, and responding to unexpected events. Standards and technologies for Industrial IoT (IIoT), edge computing, and adaptive control systems play a crucial role in achieving dynamic interoperability by enabling flexible and responsive interactions between interconnected systems. Dynamic interoperability supports SoS composition, connection, completeness, construction, continuance, and capability.
- Performance interoperability, which is to ensure that the overall performance of the SoS meets the desired objectives and doesn't degrade due to interactions among the individual systems. It involves ensuring that different systems can work together efficiently and effectively and focuses on how well integrated systems can collectively meet specific performance criteria, such as speed, accuracy, throughput, or reliability. Relevant standards define benchmarks, metrics, and guidelines for evaluating and optimizing the combined performance of interconnected systems. In manufacturing, it could relate to the coordination of machines, sensors, and control systems to achieve high-quality production at desired speeds while maintaining safety and reliability. Performance interoperability supports SoS connection, completeness, continuance, and capability.
- Security interoperability, which is to address the security concerns that arise when integrating multiple systems. It involves implementing standardized security protocols and mechanisms that allow interconnected systems to authenticate, authorize, and protect data during transmission and processing. It is important to prevent systems with weak or inadequate security to jeopardize the whole SoS. Standards and protocols such as OAuth, OpenID Connect, and PKI (Public Key Infrastructure) based authentication and authorization protocols such as SSL/TLS (Secure Sockets Layer/Transport Layer Security) can help achieve security interoperability by providing common methods for secure authentication, authorization, and encryption. Security interoperability supports SoS composition, connection, completeness, and continuance.

- Lifecycle interoperability, which covers interoperability throughout the entire lifecycle of the systems in an SoS, from design and development to deployment, operation, and maintenance. This type of interoperability ensures that information is consistently and accurately shared between various systems throughout the entire lifecycle. For example, standards such as PLM and Building Information Modeling (BIM) help facilitate lifecycle interoperability by providing a structured framework for managing and sharing data across different stages of a product's or project's lifecycle. Lifecycle interoperability supports SoS composition, connection, completeness, construction, continuance, and capability.

The key aspects of interoperability listed above are concerns mostly in the technical domains. However, there are also interoperability concerns in the business domains. For example, in order to realize true value creation by an SoS, there must be corresponding monetization and value distribution mechanisms among the participating systems. If different systems adapt various business models, such as subscription or charge per use, it is important to make sure these systems can realize their fair share of revenue from the value creation with the capabilities they collectively enable by the SoS as a whole.

On the other hand, in the regulation and governance area, when an SoS is composed of systems from different governmental jurisdictions, another problem is ensuring as a whole the SoS functions satisfying various regulatory and governance requirements.

The characteristics of an SoS are crucially dependent on data exchange and sharing among its constituent systems owned and operated by various entities. Therefore, a trustworthy data ecosystem is important for SoS development. The concept and application of dataspaces [15], recently garnering strong interest worldwide, appears to be strongly relevant in SoS. Dataspace is understood to be a decentralized infrastructure for trustworthy data sharing and exchange in data ecosystems based on commonly agreed principles. A data ecosystem is defined to be the overall system created by the activities and connections of a set of actors and infrastructure, interacting according to a common set of rules. Multiple ecosystems can exist, overlap, and collaborate. A dataspace has the following characteristics:

- Enables a data ecosystem with defined identity, access, and usage rules, possibly with mechanisms to enforce policy rules on data sharing and governance
- Facilitates access to and use of data from multiple data sources
- Imported data may be ingested (or fused) with other data to generate new data sets
- Supports data analytics and ML in compliance with data protection requirements
- Enables business models based on the data
- Has data lifecycle management

These dataspace characteristics may help to facilitate the forming of an SoS. On the other hand, the characteristics of SoS may also be beneficial in building a viable dataspace ecosystem.

4 DIGITAL TWINS AS SOS

The economy of the world relies heavily on a vast and intricate network of production and distribution systems, encompassing energy, materials, components, and finished products. These systems consist of vast quantities of real-world entities, such as equipment, production machines and the products they manufacture and distribute.

Currently, the world is at a pivotal point where these real-world entities are rapidly connected to the digital world and represented as digital twins, aiming for enhancing the management and coordination of production and distribution. Consequently, just as their real-world counterparts are interconnected, digital twin systems across the globe are increasingly interlinked together, forming ever-expanding connected systems.

This interconnectedness in the digital world is posed to be more extensible than that in the physical world. This is evident by the expansive information flow in the digital world as compared to that in the physical world, which is typically limited by the movement of energy, materials or products. This movement, whether it is within a production setting or from producers to consumers, has been traditionally facilitated by processes and documentation with human involvement.

However, as the network of digital twin systems grow, forming larger conglomerates, the concept of SoS becomes ever more relevant, leading to the emergence of digital twin SoS.

4.1 DIGITAL TWIN SOS – OVERLAYING STRUCTURE OF VIRTUAL AND PHYSICAL SOS

In a conceptual view depicted in Figure 4-1, a digital twin SoS formed by the network of interconnected digital twin systems overlays on its corresponding real-world SoS formed by the network of interconnected cyber-physical systems[7].

A cyber-physical system can be seen as consisting of physical entities and its corresponding digital services for sense, actuate and control; a digital twin system encompassing the digital models representing the corresponding physical entities and digital services for manage, simulate and predict the state and behavior of its real-world counterparts. The layered structure of the SoS, which overlays a virtual SoS onto a physical SoS, is a crucial aspect involving digital twin SoS.

[7] *A digital twin SoS may contain systems that are not digital twin systems.*

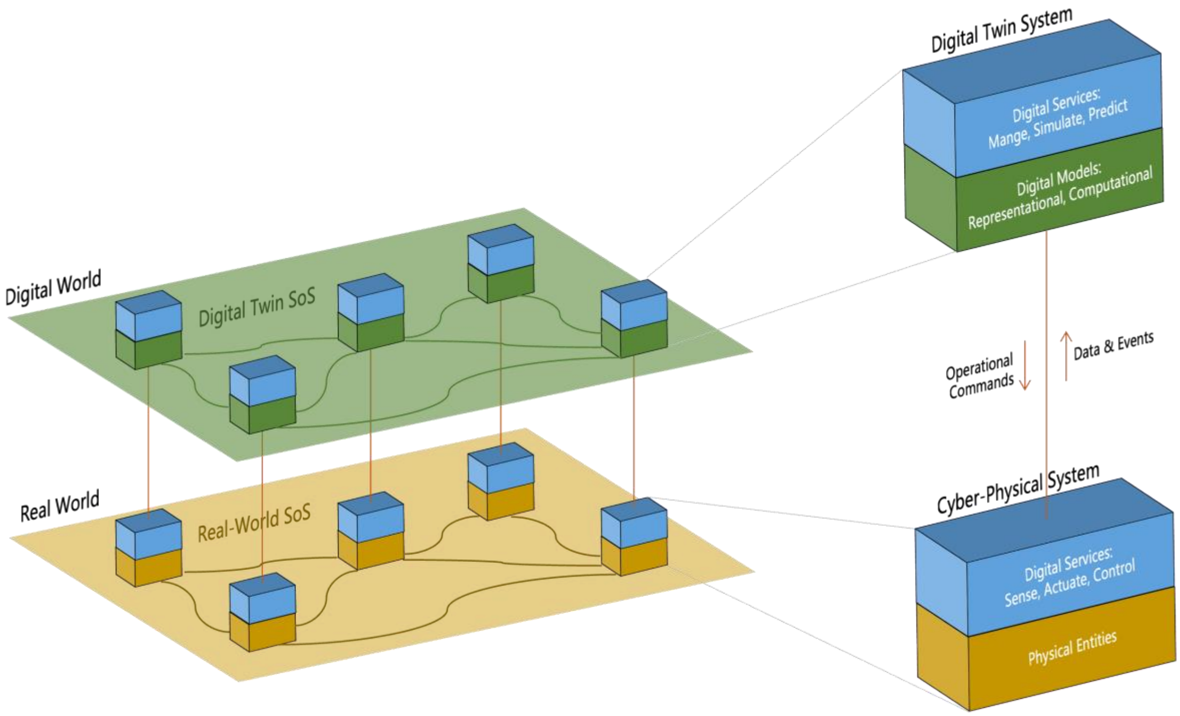

Figure 4-1: Digital twin System of Systems.

4.2 ADAPTING SOS PRINCIPLES TO DIGITAL TWIN SYSTEMS

A key aspect of constructing extensive digital twin systems that traverse organizational boundaries is the independent design, creation, and operation of constituent digital twin systems by each organization. The integration of these autonomously operated digital twin systems to establish cohesive larger systems necessitates the recognition and application of the SoS concept, including the 6C Dimensions criteria. Within the scope of assembling these expansive digital twin systems—effectively forming a digital twin SoS—the application of the SoS 6C Dimensions, as outlined earlier in this document, to digital twin systems is briefly elaborated as follows:

Composition: The composition is organic, meaning systems can join and interact dynamically, not strictly by initial design. Each digital twin represents a system that can operate independently but, when combined with others, contributes to a more significant, more capable digital twin systems.

Connection: The digital twins within an SoS require interoperable connections, meaning they can communicate and interact seamlessly despite being created independently, not through system-by-system integration. This interoperability is vital for the effective function of the SoS, ensuring various systems can collaborate and operate cohesively.

Completeness: Unlike a standalone system, a digital twin SoS is nondeterministic in its completeness. It can evolve, with digital twins joining or leaving the SoS. This requires the SoS to be flexible and adaptable, capable of maintaining operations despite changes in its constituents.

Construction: The forming of a digital twin SoS is achieved by multiple collaborating independent stakeholders, each contributing different digital twin systems to the whole. This decentralized construction necessitates clear protocols and standards for interaction within the SoS, ensuring that the SoS functions effectively despite the absence of a single controlling entity.

Continuance: Digital twin systems typically operate independently and when they join together to form a digital twin SoS, they collaborate to ensure the overall operations in the lifespan of the SoS.

Capability: The capabilities of a digital twin SoS are largely not predetermined and emerge from the interactions between the constituent systems. The fact that it is not predetermined is a strength, allowing the SoS to provide innovative solutions and adapt to new challenges or conditions.

Additionally, the dynamic characteristics in forming an SoS, is inherent in a digital twin SoS. It is reflected in the organic and evolving nature of the SoS composition and the nondeterministic aspect of its completeness. Furthermore, the interoperability is crucial for the connection dimension enables these dynamic characteristics, allowing for flexible and adaptive configurations.

The Construction and Continuance dimensions highlight the unique "ownership" and "controls" within a digital twin SoS. Each digital twin system within the SoS may have different owners and operators, contributing to a federated structure. This federation requires a shared vision and agreed-upon rules to ensure that the independent systems can cohesively achieve their collective goals. The emphasis here is on the collaborative operation and the interoperability that allows these independent digital twins to connect, interact, and collaborate to create value within the SoS.

One unique potential of a digital twin SoS is the ability to perform large-scale, more reality-grounding simulations that isolated digital twins cannot achieve. Imagine a network of digital twins, each modeling different aspects of the real world, including simulations that outpace real-time, projecting future behaviors and outcomes of various "what-if" scenarios. When these digital twins exchange messages, they collectively enable a comprehensive simulation on a grand scale, making the digital twin SoS especially powerful.

Consider a food supply chain SoS that integrates digital twins from farms, agricultural equipment, transportation systems, and distribution centers. This interconnected system can simulate a range of unpredictable conditions, such as droughts, floods, severe weather disruptions, and geopolitical events, across different regions. Such realistic simulations facilitate quicker and more effective responses to disasters, minimizing their impact. The benefits of these large-scale, reality-based simulations extend to other scenarios too, including managing airport congestion during peak seasons and enhancing smart city responses to disasters.

4.3 Usage Examples of Digital Twin SoS

Here is a high-level description of a few specific examples of how the SoS concept and the 6C Dimensions can be used to build large and complex digital twin systems, as an aid for understanding the concepts:

Smart Cities: A digital twin SoS representing a smart city may encompass various digital twin systems corresponding to distinct city infrastructures, such as transportation, energy, water, waste, and emergency management systems. These systems, primarily operated autonomously by various city departments and organizational entities, cater to specific citizen needs. Despite their independent operation, there exists an interdependence among these systems. By interconnecting with each other and forming a city-wide digital twin SoS, these systems can exchange and share data, enhancing the visibility of each system's activities to the others and improving coordination in their collective service delivery. This interconnected approach not only ensures a holistic delivery of capabilities but also fosters the development of emergent capabilities.

An emergent capability in a city-wide digital twin SoS could be proactive crisis management during disasters. In an interconnected system, real-time data sharing among digital twin systems—encompassing transportation, energy, and emergency services—allows for a unified response to anticipated threats like severe storms. For example, such SoS could predict flood-prone areas and automatically adjust public transportation routes, redistribute energy to prevent outages, and strategically position emergency resources based on the most current data. This coordinated, anticipatory approach minimizes damage and enhances citizen safety. This new proactive, adaptive crisis response represents an emergent holistic capability born from the digital twin SoS's interconnected nature which is not achievable by the individual systems operating in isolation.

Manufacturing Supply Chains: A digital twin system within a manufacturing plant generally encompasses individual digital twins of various plant components, including production lines, machines, and robots, and typically designed, constructed, and managed by the plant itself. Nonetheless, in expansive manufacturing settings, the production of final products may necessitate the collaborative efforts of multiple plants within a single enterprise or multiple enterprises. Moreover, manufacturing supply chains are inherently complex, encompassing numerous upstream and downstream partnering enterprises, each potentially operating their own digital twin systems. Herein lies the applicability of the SoS concepts, which facilitate the interconnection of these diverse digital twin systems, forming a manufacturing SoS. By implementing SoS principles, these autonomous systems can achieve a level of interoperability, enabling them to communicate and exchange data, thereby enhancing coordination and efficiency across the entire manufacturing network.

An emergent capability in a manufacturing supply chain SoS, facilitated by interconnected digital twin systems, could be real-time, multi-tier supply chain optimization. Traditionally, each entity in a supply chain plans its operations based on forecasts and buffers, leading to inefficiencies like excess inventory, wasted production capacity, and extended lead times. Real-time supply chain optimization and automated exception or crisis management capabilities can emerge from the interconnectedness, data-sharing, and collective intelligence of the SoS, optimizing the entire network's efficiency, responsiveness, and resilience against the volatility inherent in the environment.

Power Grids: The fact that the Independent Power Producers, the transmission utilities, the distribution utilities, and the energy markets are all typically different business entities with their own operating and control systems reinforces the need for the SoS approach. Within a digital twin SoS framework, the constituent digital twin systems can communicate and exchange data with each other. This interaction and data-sharing facilitates a comprehensive understanding of the grid's behavior, enabling holistic simulations under diverse conditions. It also streamlines the optimization of grid operations and aids in predictive diagnostics, ensuring the entire grid's efficient and proactive management, particularly during exceptional operational scenarios.

One important emergent capability in a power grid SoS is the demand-response optimization with renewable Integration and climate resilience. The power grid's evolution to incorporate a higher proportion of decentralized renewable energy sources, from independent power producers (such as solar and wind), brings forth the challenge of variability. These sources exhibit fluctuations over the day and under changing weather conditions. Moreover, with the increasing occurrence of severe weather events, there's a potential for electricity demand to surge well beyond the norm, especially during extreme cold or heat waves.

Under these conditions, the interconnected digital twin SoS of the power grid becomes critically valuable. The emergent capability of the SoS facilitates synchronization of real-time data on renewable energy generation with escalating demand patterns during severe weather events. This holistic approach enables dynamic balancing of energy supply against its inherent volatility, especially during periods when renewable generation may be dampened due to adverse weather, or when demand spikes unpredictably.

Furthermore, the SoS can aid in dynamic pricing strategies based on renewable energy availability, allow real-time power rerouting to harness areas with peak renewable generation, and even orchestrate signals to smart devices for adjusting consumption in response to both renewable supply and weather-induced demand surges. The advanced demand-response optimization, underpinned by the SoS, ensures not only efficient energy distribution and optimized renewable source utilization but also enhances grid resilience against the dual challenges of renewable energy variability and the intensifying impact of severe weather conditions. This seamless communication between individual digital twin systems of various grid components and renewable sources within the power grid SoS is paramount for this adaptive and proactive grid management.

Another important concept involved is value stream. As an example, a power grid can fundamentally amplify value; it transforms various resources into electricity at the generation level, carries it across vast territories through transmission lines to meet distant demands, and finally, through distribution stations, channels it directly to consumers. However, this traditionally hardwired large and complex system, while robust, lacks the flexibility to nimbly navigate the rapidly evolving dynamics of energy generation and consumption. By integrating a digital overlay, the power grid's digital twin SoS, atop this physical infrastructure, the system acquires the essential adaptability to adeptly manage these dynamic shifts in the energy landscape. With digital twin optimization enabled at multiple tiers , a loosely coupled but highly effective balancing function under an overall governing policy across the grid may become practical.

A digital twin SoS, as outlined above, superimposed on the traditional power grid, introduces agility into a historically static value stream. By harnessing real-time data on power generation and consumption, this SoS can facilitate dynamic pricing models as a new business capability supported by the technical capability in dynamically balancing supply and demand. During peak demands or supply surpluses, the pricing fluctuates to guide consumption behavior and usage patterns, ensuring optimal energy utilization. This proactive approach, steered by data-driven insights, streamlines operations across the grid, from power producers to consumers, transforming the static value stream into a dynamic one, fostering a more efficient, responsive, and resilient energy ecosystem.

Overall, the SoS concept and the 6C Dimensions (see Section 2.1) can be used to build large and complex digital twin systems that are effective, efficient, and adaptable.

4.4 Synergizing Frameworks: Architectural Foundations for Digital Twin SoS

The Digital Twin Consortium (DTC) recently released a technical brief, the "Platform Stack Architectural Framework"[3], illuminating digital twin system fundamentals and introducing an architectural framework. This framework provides a blueprint for creating composable and federated digital twin systems. The approach simplifies system complexities and enhances integration, synchronization, security, trust, and governance of digital twins.

Shortly after, the Industry IoT Consortium (IIC) published a technical report, “Digital Twin Core Conceptual Models and Services”[4]. This report introduces Digital Twin Core models, encapsulating important conceptual models and services, bridging the foundational IT infrastructure and industry-specific applications, thereby facilitating the construction of digital twin systems and reducing the complexity in their standardization.

The IIC technical report emphasizes digital twin core models and services to optimize interoperability in building digital twin systems. It corresponds and aligns with the Virtual Representation layer of the Platform Stack Architectural Framework, which has a strong emphasis on creating composable and federated digital twin systems. The complementarity of these two documents provides a comprehensive understanding of creating interoperable, composable, and federated digital twin systems. From the SoS viewpoints articulated here in this paper, large scale and more complex digital twin SoS can be formed by connecting the individual digital twin systems built based on concepts and models from the previous two documents, while addressing the concerns regarding interoperability, composability, and federated nature in a broader scope.

The composition and the context models, as outlined previously, are inherently suited for the development of the digital twin SoS in supporting large and complex interoperable, composable, and federated digital twin systems. Specifically, the concept that an SoS displays overarching capabilities—including emergent capabilities offered as services by its constituent systems—is pivotal. What is conveyed in these two models ensures that the digital twin SoS is not only a representation of individual systems but also captures the dynamic interactions and emergent behaviors that arise from their combined operation. This holistic approach is essential for accurate simulation, prediction, and optimization in complex environments, which are all important for digital twin systems as demonstrated in the examples given above.

Finally, the system relation model introduced in the general SoS conceptual models section defines the characteristics of the relations between the systems in an SoS at a more technical level. They are generally applicable to digital twin SoS as well, clearly including the aspect of addressing the trustworthiness issues in the connections and interactions.

5 SoS Application Use Cases

In this section, a few use cases are introduced to exemplify the applications of the SoS conceptual models across diverse domains. These domain include energy, manufacturing, supply chains, buildings, cities, and airports. Each use case explores the complexity, challenges, and value creation inherent in the SoS, as well as its connections, services, capabilities, and interoperability.

In each use case presented in the following subsections, an SoS is formed to address problems specific to the application domain. Even though these SoS domain applications are discussed separately, it is important to note that they may be interconnected, with systems in one domain potentially connecting to those in others, forming overlapping SoS. For instance, supply chains and digital commerce ecosystems are complex, multi-level SoS in their own right. This is also true for smart manufacturing which features intricate, multi-level SoS within individual manufacturing environments and across inter-manufacturer ecosystems, including their manufacturing supply chains.

From raw material and energy sources to parts, components, and final products, these elements traverse the entire mega ecosystem, linking resource extraction, manufacturing to commerce, forming an ever-larger SoS. Therefore, the SoS concepts and applications are expected to ultimately envelop the entire economic system.

5.1 SMART ENERGY

Energy systems are challenged with external issues such as climate change, natural resource disruptions, and regional regulatory changes. In response to these challenges, energy microgrids have emerged worldwide to provide electrical generation to localized utility grids and operate separately from major regional grids. Many of these microgrids are powered from renewable energy sources. However, these sources are more unpredictable than conventional sources (e.g., gas/coal plants) and therefore need to store energy for balancing the demand and supply. These energy storage systems are called Distributed Energy Resources (DER) and they provide demand response to an electricity grid by storing excess energy during generation times and delivering that stored energy during peak demand times (this process is known as peak-shift).

The renewable energy microgrid, paired with sufficient energy storage, can add resiliency to local areas during major disasters (e.g., severe weather conditions) that would otherwise disrupt regional grids. However, they face difficulty to compete at the scale of larger energy producers due to each microgrid's limited capacity. One solution to this issue is to combine these renewable energy resources and DERs together and form a single "virtual" power plant (VPP). This solution allows multiple renewable resource providers to collectively optimize their energy production and minimize energy imbalances, making their renewable energy grid more stable and predictable.

To enable a VPP, an SoS approach is essential. The assets in renewable energy resources and DERS are typically owned and operated by various providers, exhibiting a strong SoS characteristic. An SoS approach offers a natural solutions in addressing challenges come with this multi-ownership issue. A VPP SoS involves many physical assets that can be modeled under a digital twin SoS to enable effective real time analytics and dynamic response.

As illustrated in Figure 5-1, the key constituent systems for the VPP SoS are composed of distributed renewable energy assets (e.g., wind, battery, solar, biomass, and geothermal), a weather prediction system, and a demand-side response system. The VPP Orchestrator is a forecast optimization system that serves to collect and store data from the constituent systems, provide balancing and trading capabilities supporting an energy exchange market, and provide regulatory data to a regional governing agency. Each of these systems can be connected to form a VPP SoS, offering their capabilities to serve the overall SoS, and ultimately the consumers, by providing stable and resilient power.

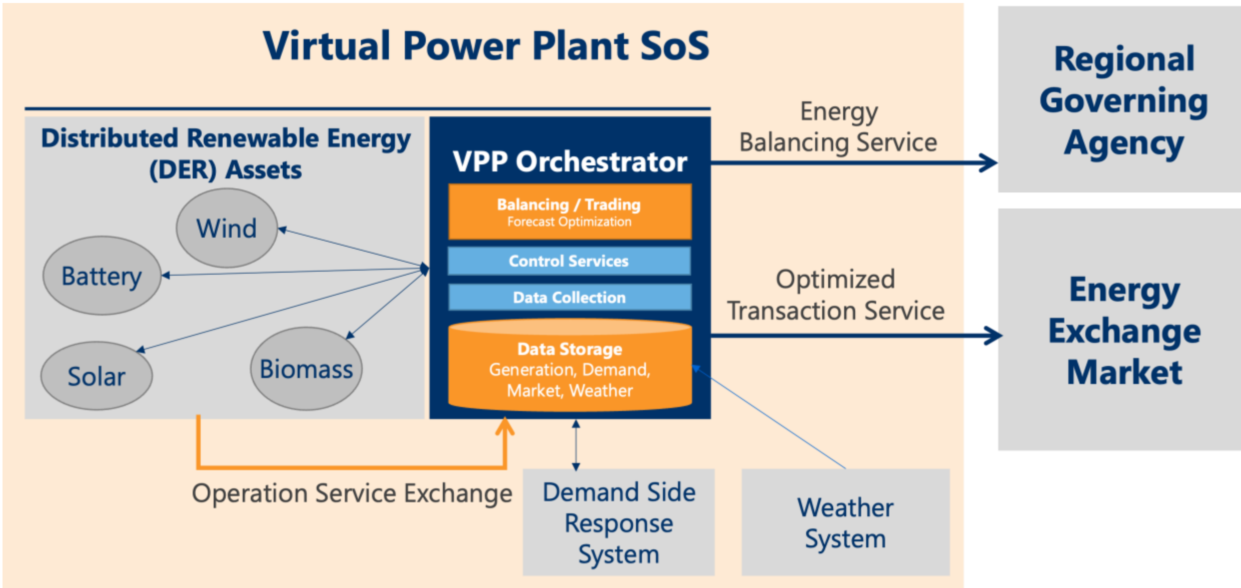

Figure 5-1: Virtual power plant of System of Systems.

5.1.1 Complexity

Energy systems are composed of a variety of constituent systems, which are operated independently by various groups such as regional electrical producers, distributors, and governance bodies. They also consist of many different types of energy sources and other supporting facilities such as those in DERs.

5.1.2 Challenges

Energy systems face traditional challenges, such as natural disasters, that can disrupt regional grids. Driven by sustainability goals, energy is increasingly generated from renewable sources. Unlike their conventional counterparts, the generation level from these sources is less stable and typically requires new energy storage strategies. This leads to the need for new approaches to dynamically balance supply with demand.

5.1.3 Value Creation

For energy systems, a fundamental requirement is stability and resilience. Therefore, energy supply balancing and improved disaster prevention planning and handling are essential. Additionally, offering incentives for efficient energy usage brings a key benefit to the society.

A VPP SoS offers optimization of energy management strategies, revenue generation through participation in energy markets, and grid support for enhanced reliability and resilience. It enables DERs to dynamically coordinate together to minimize energy costs, maximize revenue streams, and improve their overall energy efficiency; moreover, it allows DER operators to further monetize their assets by selling excess renewable energy generation. VPP operators can provide ancillary services to help with electric grid stabilization and enable participation in demand response programs, thereby diversifying revenue streams and mitigating financial risks associated with market uncertainties and regulatory controls.

5.1.4 System Connections

A VPP SoS can adhere to the SoS Orchestrator Architecture System Pattern, as described in IIRA[12]. It collects energy generation data from multiple DER assets and connects to other systems and services such as demand response, predictive weather systems, and distribution system operators (DSOs), as well as regulatory agency services and an energy exchange market.

5.1.5 Services

Services offered by a VPP SoS include demand response that stores excess energy during over-generation periods and delivers that energy during peak demand times. The VPP SoS also provides energy trading services that buys and sells electricity on an energy exchange market, while supplying regulatory data to a regional governing agency. The end goal is to provide stable, resilient, efficient, and sustainable energy services to the energy consumers.

5.1.6 Capabilities

A VPP SoS allows multiple renewable resource providers to collectively optimize their energy production and minimize energy imbalances, making their renewable energy grid more stable and predictable. It also offers pricing incentives to electricity customers to alter their electricity usage.

Virtual power plants exhibit a wide range of technical capabilities that empower users to efficiently manage and optimize distributed energy resources in real-time.

One key capability of a VPP SoS is their ability to aggregate and integrate multiple DERs and demand response assets into a unified virtual platform, where each asset can be modeled as a digital twin. This provides seamless coordination and orchestration, allowing DER owners to effectively balance supply and demand, mitigate grid congestion, and optimize energy usage patterns. Additionally, a VPP SoS supports predictive analytics and machine learning techniques to forecast energy generation, demand patterns, and market dynamics, thereby facilitating proactive decision-making and optimization of energy trading strategies.

A VPP SoS also offers robust monitoring, control, and optimization capabilities to enhance grid reliability, resilience, and stability. By leveraging real-time data streams and grid monitoring devices, it enables detection of grid disturbances and response to dynamic load changes. The VPP SoS also provides ancillary grid services such as frequency regulation, voltage support, and grid balancing. Moreover, it facilitates bidirectional communication and interoperability with grid operators and utility systems, enabling seamless integration with existing infrastructure and adherence to regulatory requirements.

The VPP SoS can operate at a city-wide distribution level for utility interests, but it can also operate “behind the meter” on a campus-wide level, for example: a military base, university campus, transportation centers, or an industrial complex.

5.1.7 INTEROPERABILITY

A VPP SoS uses international protocols such as OpenADR (IEC 62746-10-1) for automatic demand response control of energy equipment and BACnet (ISO 16484) for building systems control and automation. This creates interoperable system connections from power transmission and distribution operators to offer power savings requests and incentivized services to customer sites.

5.1.8 SUSTAINABILITY

A VPP SoS contributes to environmental sustainability objectives by facilitating the integration of renewable energy sources and promoting decarbonization in the energy sector. By leveraging clean energy resources such as solar, wind, hydro-electric power, and even hydrogen, energy users can reduce greenhouse gas emissions, mitigate environmental impact, and support the transition to a low-carbon economy. Furthermore, a VPP SoS empowers users with energy independence and resilience by reducing reliance on centralized power sources. This diversifies energy supply sources and increases adaptability to evolving energy landscapes and customer demands.

5.2 SMART MANUFACTURING AND SUPPLY CHAINS

Smart manufacturing leverages advanced technologies to enhance production processes, improve efficiency, minimize the environmental impacts, and foster innovation in the sector. It also enables an agile approach to fulfilling manufacturing demands with strong adaptability to achieve mass customization and rapid market responsiveness.

Smart manufacturing is supported by a multitude of diverse and heterogeneous systems, often owned and operated by different stakeholders, often across organization and enterprise boundaries. Within the complex landscape in smart manufacturing, the SoS and digital twin SoS concepts and models can play a crucial role in unifying and orchestrating these disparate elements, virtual and physical. They can also foster more cohesive integration between operational technologies and information systems. By more effectively encapsulating this extensive range of systems and capabilities into a cohesive whole, smart manufacturing can be better equipped to realize its full potential, enabling a tailored and efficient production ecosystem.

5.2.1 COMPLEXITY

The complexity within smart manufacturing arises from the myriad of physical and IT systems operating within and across manufacturing plants. Physical systems such as machine tools, robotics, and autonomous systems must work in harmony with IT systems like Enterprise

Resource Planning (ERP), Manufacturing Execution Systems (MES), Manufacturing Operations Management (MOM), Supply Chain Management (SCM), and Product Lifecycle Management (PLM). These are bolstered by technological enablers like the Internet of Things (IoT), cloud computing, artificial intelligence, and augmented reality, which not only provide the digital infrastructure for enhanced interconnectivity but also facilitate data-driven decision-making.

Moreover, smart manufacturing extends beyond individual plants, incorporating systems and engineering processes from multiple plants within diverse supply chains for product components. This necessitates that systems are not only adaptable and composable to meet the evolving demands of production but also capable of integrating seamlessly over a product's lifecycle.

Addressing this multifaceted complexity requires a systemic approach. Instead of performing the conventional costly and brittle, tightly coupled hardwired, system to system integration, the SoS and digital twin SoS concepts and models offer a strategic vision for constructing, operating, and evolving these systems. By enabling each stakeholder to independently manage their systems while still aligning with an overarching SoS framework, a dynamic and loosely coupled engagement between systems is achieved. This approach allows for individual systems to efficiently meet their internal needs while also participating in a larger, interconnected ecosystem, ensuring adaptability and resilience in the face of changing production requirements and market conditions.

5.2.2 CHALLENGES

Scaling smart manufacturing systems sustainably poses considerable challenges that necessitate sophisticated system engineering. This engineering must ensure that all subsystems are fully interoperable, capable of seamless communication and coordination, even as parts of the overall system are swapped, reconfigured, or expanded. Such dynamic conditions are typical in smart manufacturing environments, reflecting the need for systems to adapt to new processes or technologies quickly.

The incorporation of artificial intelligence and machine learning algorithms and the utilization of large-scale, variable data sources (big data) have become increasingly prevalent in analytics applications within smart manufacturing, offering substantial business advantages. However, these technologies also escalate the demands placed on system engineering. They require robust, flexible frameworks that can handle the complexity and rapid change inherent in these environments.

The principles of SoS provide a solution to these challenges. By adopting SoS concepts, smart manufacturing can ensure that even as individual subsystems evolve, the overarching system maintains coherence and continues to function effectively. The digital twin SoS model, in particular, enables the creation of a virtual representation of manufacturing systems that can be used for testing and validation before they are implemented, modified or commissioned in the real world. This preemptive approach allows for anticipating and addressing real-world issues, thus ensuring the continuous and efficient operation of the manufacturing system as a whole. Moreover, SoS models facilitate the alignment of artificial intelligence and machine learning, and big data analytics with manufacturing processes, possibly presented as different levels of capabilities, ensuring that these advanced tools can be integrated seamlessly and leveraged to their full potential to optimize production and drive innovation.

5.2.3 Value Creation

The ambition of smart manufacturing extends beyond operational efficiency to the generation of innovative value chains and the opening of new business frontiers. One illustrative advancement is Manufacturing as a Service (MaaS), where an internet platform facilitates the connection between suppliers and buyers, offering customized products and manufacturing services. This model leverages artificial intelligence for predictive maintenance, product process design, and process analysis and optimization, collectively enhancing business prospects and operational effectiveness.

The SoS framework is pivotal in realizing these new value streams. It provides the architectural underpinning for stakeholders within the complex manufacturing supply chain to transform their internal systems into service offerings. By adopting SoS principles, these stakeholders can align their capabilities with the demands of the larger ecosystem, ensuring that each interaction adds value. This creates dynamic, market-competitive value streams where contributions from various entities—be they large-scale manufacturers or niche service providers—are integrated into a seamless flow of offerings.

Such a collaborative ecosystem, underpinned by SoS, is characterized by its fluidity and the ability of stakeholders to rapidly adapt and reconfigure their contributions in response to market signals and opportunities. It fosters an environment where value creation is not just a linear process but a multi-dimensional network of interactions, with each node capable of innovating, scaling, and optimizing in concert with the evolving landscape. This dynamic interplay, facilitated by the SoS approach, ensures that the entire manufacturing sector can thrive, with each participant capable of unlocking new efficiencies, exploring novel business models, and contributing to a collective surge in value creation.

5.2.4 System Connections

In smart manufacturing, system connections are central to the integration of a myriad of stakeholders' diverse systems, spanning across the manufacturing ecosystem. The conventional approach to integration—often costly, inflexible, and brittle—struggles to keep pace with the dynamic nature of modern manufacturing practices. Smart manufacturing demands a framework that is not only robust and cost-effective but also dynamically adaptive to continuous changes in market demands and technology. These systems are best to be described according to their capabilities so that they can be identified and integrated into value-added chains across plant and vendor boundaries dynamically and adaptively.

The SoS concepts introduce a paradigm shift from tightly integrated systems to a loosely coupled, service-oriented, and capability-centric framework. This approach allows for more flexible and resilient connections, where systems interact with each other through standardized services and interfaces rather than through rigid, direct integrations. It fosters an environment where stakeholders can more easily plug in or swap out their systems, services, or components as needed, without disrupting the overall manufacturing process.

In this context, the System Relation Model becomes particularly significant. It provides the necessary structure for these dynamic connections by defining the relationships between systems in terms of identity, trustworthiness, capabilities, state, role, connection, and activity. This model ensures that the various systems can interact with one another in a way that is not just interoperable but also aligned with the overarching goals and standards of the manufacturing SoS.

5.2.5 Services

The service-oriented approach promoted by the SoS framework emphasizes the exposure and utilization of manufacturing capabilities within the ecosystem. This approach allows for a more granular and flexible way of orchestrating production processes and supply chains.

Smart manufacturing services encapsulate the collective capabilities of a network of plants and engineering firms, enabling them to offer their unique strengths as modular services within the supply chain. These services range from design and fabrication to assembly and logistics, each contributing to the creation of product components across different stages of the supply chain.

By adopting a service oriented SoS model, these capabilities are not just internally leveraged but are also offered externally, allowing for the creation of a dynamic marketplace of services. This marketplace operates on the principles of modularity and reusability, where services are consumed and provided in a plug-and-play fashion, mirroring the flexibility of digital services in the IT domain.

This shift toward a service-oriented ecosystem facilitates greater collaboration among stakeholders. It allows them to expose and monetize their capabilities, leading to a more responsive and adaptable manufacturing landscape. Manufacturers can quickly scale up or down, pivot in response to market shifts, and introduce new services without the need for extensive reconfiguration of the physical production infrastructure.

In essence, the SoS approach in smart manufacturing transforms traditional production lines into agile service providers, where the capabilities of each entity are both an internal asset and an external service offering. This not only streamlines the production process but also opens up new business models and revenue streams, thereby enhancing the overall value of the manufacturing SoS.

5.2.6 Capabilities

The capabilities within smart manufacturing are a reimagining of core assets—namely, manufacturing equipment and process know-how. Traditionally viewed as static assets, the SoS approach advocated in this paper encourages a new view through the lens of dynamic capabilities: not just for what they are, but for what they can produce and the value they can create when interconnected within a large ecosystem. This mindset shift, from static assets to dynamic capabilities, transforms the manufacturing landscape into a responsive, adaptable, and continually evolving system.

In this transformed environment, the capability of a system is not seen in isolation but in how it synchronizes and combines with others within an SoS to create a larger, more complex capability, adaptively. Like building blocks in a pyramid, small individual capabilities can be layered and integrated to construct a comprehensive capability that is far greater than the sum of its parts. This approach harnesses the inherent power of the SoS to not only respond to immediate production needs, such as handling small lot sizes economically, but also to adapt rapidly to broader changes in the supply chain.

The focus on system capabilities within an SoS marks a strategic move away from rigid production lines to a more fluid and flexible arrangement of manufacturing resources. It empowers smart manufacturing facilities to swiftly reconfigure their operations to accommodate new products and processes, aligning with the agile nature of modern supply chains. This capability-centric view is transformational in its thinking and offers a practical pathway to realizing a dynamic, interconnected manufacturing ecosystem with the power to innovate and create value at an unprecedented scale.

In "Information Model for Capabilities, Skills & Services", published by Plattform Industrie 4.0 [26], a model for capabilities, skills, and services (CSS Model) is outlined in the context of flexible manufacturing systems as part of Industry 4.0. In this model capabilities are defined as abstract descriptions of the potential actions or functions a system can perform, without specifying how these actions are executed. They represent the "what" aspect, focusing on the outcomes rather than the process. Services, on the other hand, are more concrete and operational, detailing the "how" aspect by specifying the steps or processes to achieve a particular capability.

Services are tied to the implementation and provide the execution path for a capability, making it actionable within a system. These definitions are similar to what are defined in the SoS conceptual models and help in modularizing functions and allows for flexibility in how capabilities are fulfilled by different services, supporting adaptability in manufacturing systems. When adapting the SoS conceptual models in the manufacturing environments, the CSS Model can be considered a complementary model that provides detailed structures for implementation.

5.2.7 INTEROPERABILITY

Interoperability in smart manufacturing is essential, serving as a means to achieve the dynamic and adaptive formation of an SoS. It enables systems within the SoS to effectively communicate and operate together at the level of semantics and functions. This is crucial, particularly under conditions where systems within the SoS may need to be replaced, re-configured, or new systems added.

To harness the full potential of interoperability, systematic SoS approaches are indispensable, drawing upon decades of collective insights and innovations. Standards and models such as SysML (System Modeling Language) developed by the Object Management Group (OMG) offer a general language for describing and modeling systems in a consistent and standardized way. Additionally, the Asset Administration Shell from Plattform Industrie 4.0 exemplifies an approach that encapsulates production resources, allowing for their management and integration within the SoS.

These methodologies and tools are critical in crafting an interoperable SoS where each system can autonomously function yet collaboratively contribute to the overarching goals of smart manufacturing. Interoperability is thus a pathway that ensures the smart manufacturing SoS remains cohesive, agile, and capable of evolving in response to new demands and technological advancements.

5.2.8 SUSTAINABILITY

Sustainability in smart manufacturing, advanced through an SoS framework, enhances efficiency and minimizes waste. SoS enables smart factories within supply chains to optimize raw material selection and process design, directly reducing energy use and improving recyclability, thereby reducing the carbon footprint and contribute to a circular economy.

The collaborative nature of SoS facilitates the sharing of sustainability-focused data among systems, promoting the adoption of greener practices. It encourages system-wide innovation for sustainability, lowering the barrier of entry for players with efficient eco-friendly manufacturing capability.

By adopting SoS principles, smart factories can benefit from the flexibility in dynamically adjusting operations to prioritize sustainability, achieving a more resource-conservative, environmentally responsible manufacturing approach.

In the context of smart manufacturing for sustainability, the Digital Product Passport (DPP) is a noteworthy concept and technology designed to track products' lifecycle information, promoting transparency and sustainability in supply chains. As a secure record of a product's identity and specifications, it informs purchasers and facilitates recycling and repair, aligning with the EU's push towards a circular economy. The European Union's anticipated regulation foresees the introduction of DPPs, underlining their significance in enhancing product traceability, supporting environmental goals, and enabling adherence to sustainability standards across industries.

The SoS approach for smart manufacturing can potentially bolster the efficacy of DPPs by ensuring seamless integration and communication across various manufacturing stages. By facilitating real-time data exchange and maintaining a comprehensive, updated record of product information across the manufacturing supply chains, SoS could enable the dynamic generation and management of DPPs, essential for meeting regulatory expectations for sustainability and circular economy practices.

5.3 Smart Cities

Cities run various infrastructures from transportation, water supply, and energy to waste management and public safety. A smart city evolution is underway in many cities to connect them to form an integrated urban services. As a result, they are not just collections of independent systems but are interconnected networks that provide efficient, responsive services to city inhabitants. Smart cities harness the capabilities of various infrastructures — by integrating them into a cohesive SoS. This integration enables the city to function more holistically, improving the quality of life for residents, enhancing sustainability, and ensuring more effective governance.

In this new paradigm, the SoS concepts and models allow for an agile response to the changing needs of a smart city. Since smart cities deal with infrastructures in the real world, the concepts of digital twin SoS offer great value. Smart cities can utilize the SoS approaches to streamline urban processes and create more livable environments. These approaches enable the city to adapt to real-time conditions, optimize resource use, and present a unified response to emergencies.

In fact, each type of a city's infrastructure, such as transportation, is complex on their own right, where the SoS or digital twin SoS concepts and models applied. However, within this section we will focus on the larger SoS across these different types of infrastructures.

5.3.1 Complexity

The complexity in smart cities arises from the assortment of infrastructure systems that have historically operated in isolation, each with its own unique set of operational mandates, technologies, and governance structures. For instance, city departments responsible for public transportation might manage intricate networks of buses and subways, using specific technologies for scheduling and tracking, while at the same time transportation services such as taxi and ride-hailing service are offered by for-profits enterprises. On the other hand, private enterprises that oversee energy management systems deploy different technologies and protocols for grid control and energy distribution. The varying technological adoption rates across these sectors add another layer of complexity. Newer systems may incorporate the latest innovations, like IoT devices for real-time monitoring, whereas older systems are often entrenched in legacy technologies resistant to quick changes.

The result is a complex network of infrastructure components, each advancing at its own pace and adhering to its own rules and standards. This diversity reflects the city's organic growth and evolution. The synergy required to unify these elements into a cohesive city-wide system is not simply about connecting different technologies; it demands a comprehensive and strategic approach that takes into account the full array of protocols, system maturity levels, and stakeholder objectives. The concept of a multi-stakeholder, loosely coupled approach inherent in SoS is particularly apt for addressing these complexities, creating a framework that flexibly enables these diverse systems to communicate, collaborate, and collectively contribute to the overarching goals of the smart city.

5.3.2 CHALLENGES

The multitude of infrastructures within a smart city, each serving its unique domain under independent governance structures, presents a significant challenge when these systems are brought together to form a larger, cohesive SoS. Ensuring that each infrastructure maintains its specialized services without compromise, while also contributing to enhanced overall city services, requires a careful alignment of varied objectives. Aligning these objectives must be done in a way that respects the autonomy of each domain while leveraging their interconnectivity for broader benefits.

Continuity, scalability, and adaptability further compound the challenge. As the city grows and evolves, its infrastructures must be able to expand and adapt without disrupting the services they provide. This requires designing systems that are flexible enough to accommodate new technologies and increased demand. They must be capable of evolving alongside the city's growth and the inevitable technological advancements, ensuring long-term resilience and functionality.

The SoS concepts and models offer robust solutions to the challenges of integrating multiple infrastructure systems within a smart city. They allow each infrastructure system to continue operating independently, preserving its ability to provide specialized services. Through SoS, these systems can be connected in such a way that they can share resources and information while maintaining their autonomy.

On the other hand, the SoS approach also supports the independent evolution of each infrastructure system. It does so by providing a flexible architecture that can adapt to changes within each system, whether due to technological advancements or shifting user demands. SoS models promote modularity, meaning that individual systems can be upgraded, extended, or replaced as needed without extensive re-engineering of the entire integrated network. The SoS approach allows each system to offer increasingly sophisticated and comprehensive capabilities over time. This incremental approach contrasts with an all-or-nothing system of hard-wired integration, which can be rigid and inflexible. It enables a more fluid, adaptable integration strategy, leading to a smarter, more responsive urban ecosystem.

5.3.3 Value Creation

In the context of smart cities, the value creation fostered by an SoS approach primarily seeks to improve the quality of life of its citizen, rather than direct financial gain. This is particularly evident in emergency management, where connecting various systems to form a city-wide emergency management SoS can lead to a more proactive and informed response to crises. For instance, through the SoS framework, a smart city can utilize predictive analytics to anticipate flood patterns and redirect traffic flow away from high-risk areas, or it can manage energy distribution to ensure critical services remain operational during a power outage.

Smart cities seek to holistically optimize its services through digitalization and connectedness. In this aspect, the SoS approach may help to advance this evolution and elevate a city's operational efficiency in everyday functions, streamlining the provision of services and reducing wasteful practices and can lead to sustainable urban growth and development.

5.3.4 System Connections

In smart cities, connecting the diverse systems across the urban ecosystem to form a cohesive whole is vital. Traditional methods of integration, which tend to be costly and rigid, are not suited to the dynamic and ever-changing landscape of urban life.

The SoS concepts facilitate a shift from tightly integrated, inflexible systems to a more dynamic, service oriented SoS, which emphasizes loose coupling and capability-centric design, allowing for resilient connections between systems such as transportation, energy, waste management, public safety, and emergency services. Such an approach enables various city functional systems to interact through standardized services and interfaces, streamlining the integration process and ensuring that modifications to one system can occur without major disruptions to others. At the same time, it allows flexible adaption to new technologies and the evolving needs of its citizen.

5.3.5 Services

The service-oriented SoS framework facilitates an adaptable orchestration of urban services. The urban capabilities in the city's infrastructures can be exposed as services offered to the SoS that they participate in. These services can then be reassembled at the SoS level to form new services and offer new or emergent capabilities that are not possible in an otherwise siloed configuration, for instance, in emergency response.

5.3.6 Capabilities

In smart cities, the SoS approach can revitalize the concept of urban infrastructure, evolving from isolated functionalities to a network of dynamic, integrated capabilities. Urban assets such as transport networks, energy grids, and water systems are seen not merely as individual entities but as interlinked components that, when combined, magnify the city's operational potential and responsiveness. This interconnectedness, exemplified by the city-wide digital twin SoS, enhances service visibility and coordination, fostering a collaborative ecosystem that transcends traditional urban management.

The real power of this SoS framework manifests in scenarios like proactive crisis management, where integrated systems collaboratively predict and mitigate the impacts of emergencies, such as rerouting transport or managing energy distribution in response to severe weather. This synergy not only streamlines city operations but also cultivates emergent capabilities that significantly elevate citizen safety and urban resilience, showcasing the shift towards a more adaptable and collectively intelligent smart city landscape.

5.3.7 INTEROPERABILITY

Interoperability in smart cities is fundamental for creating a cohesive urban SoS, allowing diverse services like traffic control and emergency management to interlink and operate harmoniously. It facilitates seamless data sharing and functionality across systems, crucial for updating, scaling, or integrating new services into the city's fabric.

To achieve this, smart cities must adopt standardized communication protocols and data models that enable different services to understand and utilize shared information efficiently. Such standardization ensures that whether it's adjusting energy usage or rerouting traffic, each component of the city's infrastructure can respond effectively to changes, maintaining the rhythm of urban life without interruption. Furthermore, standardization in communication and data models will enhance security and elevate the level of trustworthiness in the city's operations.

5.3.8 SUSTAINABILITY

In smart cities, the SoS concepts and models can play a critical role in advancing sustainability, optimizing the efficiency of urban operations, reducing wasteful practices and redundant services, and minimizing environmental impact. By integrating interconnected systems, such as energy, transportation, and waste management, the SoS approach ensures that resources are allocated and managed effectively, leading to a reduction in the overall carbon footprint and support for a circular economy. This integration allows for real-time data sharing on resource consumption and waste generation, enabling city-wide implementation of eco-friendly initiatives and innovative practices for sustainability. To the end by leveraging the SoS approach, cities can offer the best services to its citizen and realize the best value from the tax revenue.

Furthermore, the SoS model lowers the barriers to adopting sustainable solutions, facilitating collaboration among different city services to promote a holistic approach to sustainability. Smart cities, leveraging SoS principles, can nimbly adjust operations to prioritize environmental considerations, fostering a resource-conservative, environmentally responsible urban landscape. This adaptability not only enhances the quality of life for residents but also sets a precedent for sustainable urban development that can dynamically evolve with both technological advances and the changing needs of protecting the environment.

5.4 Smart Airports

Smart airports are evolving to blend the virtual and real worlds seamlessly. This effect aims to optimize airport operations and deliver immersive travel experiences that are enjoyable and less stressful, while also increasing revenue for the airports. By combining 5G connectivity with smart devices at the edge of the network, smart airports are creating a framework for building impactful business solutions. These solutions are designed to digitally transform airports and provide seamless and immersive travel experiences.

5.4.1 Complexity

Airports are one of the most complex public infrastructures. To operate an airport, multiple stakeholders must work together as an SoS (see Figure 5-2) [22]. These stakeholders include:

- government agencies such as immigration authorities and customs,
- operational entities such as airlines, ground handling companies, and security providers, and
- commercial players running retail concessions.

Each system within the airport has multiple components that operate independently and yet interdependently. For instance, efficient passenger processing within a terminal requires check-in, immigration, security, flight information, and baggage handling systems to work seamlessly.

Figure 5-2: Multiple systems and stakeholders involving the operation of an airport.

5.4.2 Challenges

Airports, airlines, and travel retail operators are currently facing unparalleled challenges, both in the way they do business as well as in the aviation industry itself.

A key challenge to digital transformation of airports is the ability to enable end-to-end interoperability across these interdependent domains and use cases. For airports to maximize potential and deliver excellent passenger experiences, people, digital systems, and infrastructures must operate in harmony.

Although increasing digitalization of airports has resulted in a wide variety of systems and IT infrastructures that encourage centralized operations, these systems are often not fully interoperable. This frequently creates work silos, both in land and airside operations, leading to unnecessary delays, sub-optimal solutions, and expensive advanced systems that cannot be used to their full potential.

Airports must deal with many unexpected disruptions. To avoid such severe disruptions, airport operations need advanced planning to handle system entropies and unexpected exceptions, no matter how unforeseeable they may be. This requires decision-making support tools that can analyze dynamic traffic conditions in real-time and facilitate coordination of various activities across multiple stakeholders to respond in a swift and integrated manner.

5.4.3 Value Creation

Adopting a unifying model for interoperability will enable intelligent airport services to work better together to form an SoS, comprising smart systems, that deliver high-value outcomes, adding significant business value. A unified commerce ecosystem based on an SoS framework can drive sustainability, operational efficiency, safety and security, new revenue streams, and optimized customer experiences (see Figure 5-3).

Together with digital twin technology, all contextualized event data can be aggregated and expanded to enable total process simulation of the airport system. This allows airport operators to visualize how individual parts of complex systems work together and can eliminate risks prior to physical system implementations. Airports will greatly benefit from a holistic visual representation to effectively manage day-to-day operations as well as envision future scenarios to optimize processes.

Within the airport ecosystem, airport operators, retailers, airlines, and service providers can model, simulate, and optimize their systems, processes, and infrastructure to identify and address issues before committing time and resources to the real thing. Furthermore, through the simulation of real-world scenarios, applied generative AI systems can make recommendations for innovation.

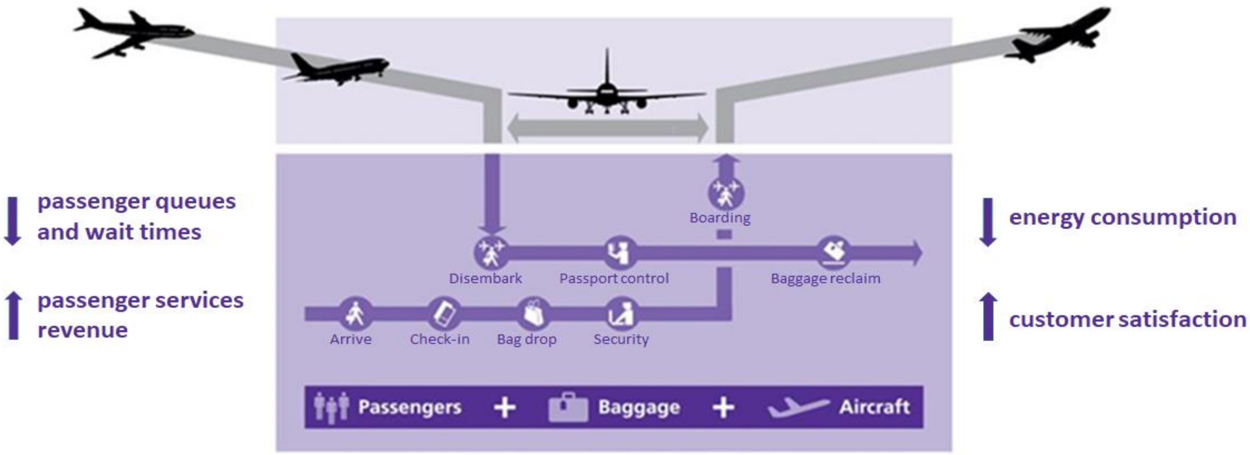

Figure 5-3: The intelligent airport.

5.4.4 System Connections

A common platform based on a system connection model is critical to enable information to be efficiently shared among all airport agencies and to dynamically compose an adaptable SoS providing continuous decision intelligence.

5.4.5 Services

For the smart airport to reach its full potential, solution providers will need to deliver AI, IoT, and digital twin services at scale. To serve the needs of all airports, from small vertiports to the largest transportation hubs, these solutions must be tailored to specific operator requirements and desired outcomes – by matching customer intent with provider capabilities. This requires a paradigm shift in the way complex systems are composed, tested, and delivered to adapt to business needs. These services may include:

- **Parking Management:** Utilizes smart technology to optimize parking space usage and guide passengers to available spots quickly.
- **Building Management:** Integrates systems within the airport to ensure operational efficiency, energy savings, and optimal environmental conditions.
- **Baggage Management:** Employs advanced systems for tracking and handling luggage, improving the reliability and speed of baggage delivery to passengers.
- **Travel Guide:** Provides passengers with real-time information and navigation assistance within the airport via mobile apps or interactive kiosks.
- **Reservation Management:** Streamlines the booking and check-in processes, allowing passengers to manage their travel plans efficiently.

- **Access Control:** Enhances security by regulating entry and exit points through biometric scanning and automated verification systems.
- **Passenger Management:** Offers personalized travel experiences by analyzing passenger data to improve service delivery and satisfaction.
- **3D Visualization:** Creates detailed visual representations of airport layouts and processes for better management and planning.
- **Anomaly Detection**: Monitors for any unusual patterns or issues within airport operations to quickly address and resolve potential disruptions.
- **Intent Management:** Analyzes passenger flow and behavior to optimize airport resource allocation and improve the overall travel experience.
- Climate Monitoring and Control: Ensures a comfortable climate within the airport facilities by constantly adjusting environmental controls.
- **Queue Monitoring:** Reduces wait times and improves passenger flow through the use of sensors and predictive analytics.
- **Computer Vision:** Supports security and operational tasks by processing and interpreting visual data from cameras and sensors.
- **Object Recognition:** Assists in identifying and tracking items throughout the airport to prevent loss and improve security.
- **Route Optimization:** Enhances the efficiency of aircraft and vehicle movement on the ground, minimizing delays and improving turnaround times.

5.4.6 Capabilities

These services must be described based on common capability models to enable an SoS to be composed from federated marketplaces.

5.4.7 Interoperability

System interoperability is ensured through compliance with open standards that unify concept, capability, and event models for interdependent, commercial domains including aviation, retail, transportation, building, and telecommunications. The Aviation Community Recommended Information Services (ACRIS) Semantic Model managed by the Airports Council International provides a comprehensive foundation for cross-industry semantic interoperability.[22]

6 Conclusion

This paper has examined, as its background, how complex systems have proliferated over the years, often creating silos that constrain the sharing and reuse of information and capabilities across various domains and stakeholders. Traditional integration approaches have proven inefficient, resulting in long-term fragility. This becomes particularly evident with recent advancements like the Internet of Things and digital twins, which bind together a myriad of entities, from people and assets to processes, powering the world's economy. To harness the immense value hidden within these silos and manage the ever-increasing complexity in the totality of the systems, this paper finds that it's essential to bridge these silos to form a cohesive SoS. Conceptual models of the SoS are pivotal in achieving this, ensuring seamless interoperability and connectedness of diverse systems.

This paper subsequently explores the concept, main characteristics, and conceptual models of System of Systems (SoS) and how the SoS approach can help us interconnect different systems seamlessly and dynamically, creating a new vast landscape of SoS that fosters emergent capabilities and value creation at scale. Applying an SoS model for interoperability to connect and compose digital twins into larger systems provides significant value.

6.1 Key Findings

- SoS is an important approach to increase efficiency and reduce waste in the vast network of interwoven digital and cyber-physical systems in the world's economy.
- SoS distinguishes from traditional systems in a number of ways (see Basic Concepts and the 6C Dimensions), which is important to the understanding and formation of SoS.
- The unique characteristics of SoS place strong requirements on interoperability and trustworthiness, especially in collaborative independent participation, organic growth, and dynamic evolution.
- Value creation through emergent capabilities, and value streams through collaboration among systems, are the key drivers for the development and scaling of SoS.
- The forming of SoS benefits from time-tested paradigms such as Service-Oriented Architecture (SOA) that promotes loosely coupling connections and interactions. The successful IaaS, PaaS and SaaS approaches can be further extended as CaaS (capabilities as a service) in SoS.
- Interoperable SoS requires a shared understanding and standardization of basic concepts including models, capability, communication, and interaction between the systems - the conceptual models introduced here can serve as an input for advancing these aspects.
- The relations between systems are key elements in enabling interoperability and trustworthiness in an SoS; the system relation introduced here serves a starting point for further modeling and refinements.

- The general SoS concept and models are readily applicable to digital twin systems, particularly in addressing concerns in building interoperable, composable and federated digital twin systems.
- Interoperability challenges for SoS are not limited to technical aspects, but also extended to business model and governance aspects, all of which require specific standardization efforts.
- The feasibility and values of SoS can be demonstrated in multiple and cross industries, including the use cases as described.

As Albert Einstein said, “you cannot solve a problem with the same mind that created it.” Solving the growing complexities of interwoven systems cannot be done by traditional system-wise thinking alone. What is needed is a flexible, dynamic, and organic approach, as offered by SoS, to allow rigid systems to scale, facilitate new capabilities, and create new values.

6.2 Call to Action

To harness the full value potential of interwoven systems in the world’s economy, including emerging IoT and digital twin technologies, we need to move beyond conventional industrial and disciplinary silos. It's essential to elevate interoperability from a singular system perspective to an SoS viewpoint. Industrial consortia and standards development organizations should re-examine their system models, aiming to build consensus on cross-industry and interdisciplinary SoS models. By aligning their system and data models, ontology concepts, and terminologies, we can establish a unified, scalable mechanism for interoperability among diverse and autonomous systems.

6.2.1 Validate Through Reference Implementations

The application of the SoS concept and models are still in its nascency. Reference implementations that validate specific models, showcasing their feasibility and viability, are highly valuable. Within industry consortium innovation labs, technology vendors can collaborate to develop multi-stakeholder SoS based on common models, fostering value stream creation. In these reference implementations, attention is also needed in transitioning system-specific offerings from feature-based monolithic systems to API-based granular capabilities, allowing for discovery and use by other systems.

Testbeds[8] and Test Drives[9] within the Industrial IoT Consortium and Catalyst[10] projects within TM Forum serve as examples of these innovation labs.

[8] IIC Testbeds: *www.iiconsortium.org/test-beds/*
[9] IIC Test Drives: *www.iiconsortium.org/test-drives/*
[10] TM Forum Catalyst Project: *www.tmforum.org/catalysts/projects/*

These multi-vendor projects, testbeds, and test drives can incorporate varying data models while still adhering to the overall conceptual models. The reference implementations emerging from these efforts can further refine and validate the conceptual models, paving the way for Minimum Viable Products (MVPs) and contributing inputs to formal standards.

Original equipment manufacturers (OEMs) of devices also benefit from participating in the innovation labs and reference implementations that are driven by common conceptual models, as they can gain insights into the customer needs, market trends, and technical challenges.

6.2.2 Evolve an Open Ecosystem

An open ecosystem for developing SoS, including those involving digital twins, is essential for future innovation and collaboration. With open ecosystems, constituent systems can communicate, interoperate, and co-evolve across different domains and platforms using SoS modeling. This paves the way for novel value propositions, business models, and solutions that tackle complex and dynamic challenges across diverse sectors and scenarios.

Device OEMs play a crucial role in open ecosystems, providing physical components and sensors that enable data collection, communication, and actuation. Aligning their capabilities and interests with the ecosystem not only encourages their active participation but fosters broader adoption of diverse hardware configurations.

6.2.3 Standardization

Achieving true interoperability within an SoS hinges on the foundation of common conceptual models. Standardizing these models within the SoS framework is paramount to ensuring the required level of interoperability.

The conceptual models for the SoS as described, especially the system relation model, serve as potential inputs for standard development organizations (SDOs). Such standardization efforts can refine and expand upon these initial models, adding greater depth and detail, or supplement and improve existing ones. This enhancement process not only formalizes the models but also makes them more comprehensive, ensuring their adaptability and widespread adoption. De facto standards may also emerge from successful commercial implementations.

6.2.4 Monetization and Business Model Interoperability

The ability to monetize capabilities from the constituent systems in an SoS is crucial driver to unleash the power of expansive SoS that fosters emergent capabilities and value creation. How to enable monetization and value realization is the key to the success of SoS and must be considered seriously at the forming stage of an SoS. Various systems participating in the capability sharing and value creation may be originally designed for supporting a certain business model in realizing its commercial value.

When joining together to form an SoS, they must solve not only interoperability issues in technology but also in business models as well. Incompatible business models utilized by various systems would impede the value realization of the SoS.

Addressing business model interoperability may require standardized business models and service monetization approaches; this interoperability enables money, a practical measurement of value creation, to flow through an SoS frictionlessly as capabilities are delivered. SoS testbed is another arena where business models should be considered and experimented. Creating mechanisms to facilitate and incentivize data sharing while offering adequate data protection in both privacy and value is a key starting point for achieving full scale capability monetization.

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8 AUTHORS AND LEGAL NOTICE

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