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Principles for the design of system of systems exemplified using modularisation

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Abstract

In the context of system of systems (SoS) engineering, the incorporation of design principles is critical to guide the engineering process. This paper presents a systematic literature review to synthesize a list of principles tailored for SoS. 26 principles were identified as generic principles and 39 were mapped to the specific challenges in SoS engineering. Through an evaluation using the principle of modularisation in the design of a charging infrastructure, the study offers insights into the real-world effectiveness of these principles, showing their relevance in SoS engineering tasks.

Keywords: design principles, system of systems, systems engineering (SE), modularisation

1. Introduction

The transformation of society and technical systems is driven by numerous technological advances. A key driver is digitalization, which is expanding both the functionality and the connectivity of technical systems (Dumitrescu *et al.*, 2021). The INCOSE SE Vision 2035 lists multiple future use cases such as "Connected World", "Industry 4.0" or "Smart Systems" that are driven by the technical possibilities of today and enabled by systems collaborating with another (INCOSE, 2021). Multiple systems interacting with each other in networks to achieve a goal that cannot be achieved by a single system is called System of Systems (SoS) (ISO/IEC/IEEE, 2019). One example is the collaboration of transport systems in a fleet. Communication between the transport systems enable them to drive in short distances which results in energy savings across the network that cannot be achieved by a single transport system. SoS exist wherever systems interact with each other. Exemplary areas of application are intelligent transportation, smart city, smart production, or air defence (ISO/IEC/IEEE, 2019).

The challenges for companies to realise system of systems are manifold. Increasing cooperation across company boundaries, including the resolution of conflicting goals and the coordination of interfaces, is just one aspect that need to be solved in this context (Jamshidi, 2008). System of Systems Engineering (SoSE) addresses the planning, analysing, developing and integration of new and existing systems in a SoS (ISO/IEC/IEEE, 2019). The goal is e.g., to optimize the performance, interoperability, and sustainability of the SoS by considering the interactions and dependencies between the individual systems.

Coordinating systems for which different companies are responsible is a challenge in SoSE especially when there is no central authority to issue instructions (Sage and Biemer, 2007). Different goals, IP protection or even competing market strategies mean that cooperation between companies is often difficult. In addition, the different life cycle phases and speeds in which companies design their systems in a SoS as described by Kossmann et al. (2020) are obstacles for successful collaboration between companies. There are other factors that contribute to the complexity of SoS. Characteristics such as the emergent behaviour illustrate the complex task engineers are facing when working with SoS. Emergent behaviour describes the occurrence of novel behaviour and properties through interaction and self-organization of complex systems (Azani, 2008).

As an established approach in engineering, design principles are used to guide engineers during complex tasks in many disciplines, for example software engineering as described by Davis (1994) or mechanical engineering as described by Feldhusen and Grote (2013). A principle is *"a fundamental idea or rule that can provide guidance for making a judgment or taking action*" (Rousseau, 2018). In the context of design, principles are rules, guidelines, concepts, or methods for the design of products, systems, or processes. They are derived from and confirmed by experience and knowledge. Principles are generic and form a theoretical basis for the design but can be adopted and applied for a special application (Balzert, 2011). An example for a design principle is modularisation. Modularisation is a guideline during design to unify interfaces between independent parts and enable cross module interoperability. Modularisation refers to the separation of an overall system into independent and interchangeable components or modules (Baldwin and Clark, 2006). This makes it easier to develop, maintain and change the system, as individual modules can be viewed separate from each other. Modularisation can therefore be viewed as a potential principle for SoS, especially for evolutionary SoS that are under constant change. But as described by Azani (2008), "*modularity should play a more important role in design and development of an engineered SoS.*"

Design principles play an important role in engineering by providing valuable guidance. In this paper, we aim to contribute to a deeper understanding and practical application of design principles within the context of SoS engineering. With modularisation being just one of many design principles it should be investigated if there are other principles, which support SoS engineering and can guide engineers to tackle SoS challenges. This leads to the following two research questions as basis for this contribution:

> *RQ1: Which design principles described in the literature address the unique characteristics of SoS?*
>
> *RQ2: How do design principles such as modularization support the challenges of SoS engineering?*

First, we will give a brief overview of the research and related work in the context of SoS Engineering. We then describe the research methodology and how we proceeded to answer the research questions. In the main part we present the results and findings of a systematic literature review and characterise the results according to the main characteristics of system of systems engineering. We evaluate the results using the example of a SoS built around an electric fast ferry.

2. State of research and related work

The first major contributions on SoS development were published in early 2000 (Gorod *et al.*, 2008). Since then, it is a dynamic research field with an evolving interest. In this section we give a brief overview on some approaches, laying the foundation for the subsequent discussion of our research contribution. As one of the early approaches, Selberg and Austin (2008) described a framework for the synthesis, evaluation and managed evolution of SoS. The framework consists of four steps - requirements, synthesis, design of system architecture and implementation. It considers the evolution characteristic of SoS by modelling existing systems that are input for the synthesis phase. Also, the framework is described as a cyclical process that considers changes in requirements.

Another approach is the wave model as described by Dahman et al. (2011). This approach considers the evolution and continuous changes in SoS through iterative steps. In a first phase, the SoS initialization is described that defines the basis for the SoS, such as the key users, core systems and SoS capability objectives. Once the basic structure exists, SoS updates are described to iteratively contribute to the SoS evolution as waves that continuously evolve.

Both approaches are focussing on the evolutionary characteristic of SoS. Other approaches such as the model-based engineering of collaborative embedded systems by Boehm et al. (2021) are tailored to one of the four types of SoS. The four types, namely directed, acknowledged, collaborative and virtual SoS, differ in the degree of independence and belonging (ISO/IEC/IEEE, 2019). Boehm et al. describe methods, such as a goal model to handle the different goals of the independent constituent systems.

Given the broad landscape of different SoS applications and designs, many researchers consider the characteristics of SoS as part of their research. In a prior work, we consolidated the main characteristics of SoS based on a systematic literature review (Anacker *et al.*, 2022). Therefore, the following eight characteristics describe SoS:

1. Managerial Independence: The interacting systems behave according to their own rules, which are set by independent managements. (Maier, 1998; Boardman and Sauser, 2006)
2. Operational independence: As described by Maier, the operational independence describes the capacity of the constituent systems to operate when being detached from the SoS. (Maier, 1998)
3. Distribution: The (geographic) distribution describes the spatial distance between interacting systems, which to the greatest extent possible can represent an information-only interaction over long distances. (Maier, 1998)
4. Evolution: The majority of SoS exist over a long period of time and change. On the one hand, the functionalities and their quality can change, and on the other hand, the structure and composition of a SoS changes as new systems are integrated or existing systems are updated or removed. (Maier, 1998; Abbott, 2006)
5. Dynamic reconfiguration: The ability to change the structure and composition of the SoS without any external intervention is described by the dynamic reconfiguration. (Boardman and Sauser, 2006)
6. Emergence behaviour: In the context of SoS, emergence refers to the behaviour that results from the interaction of interacting systems. The resulting behaviour enables intended or unintended higher functionality than the interacting systems can provide independently. (Maier, 1998; Boardman and Sauser, 2006; Abbott, 2006)
7. Interdependence: Interdependence describes the interdependence between interacting systems to fulfil the goal of the SoS. If the individual goal of each system deviates from the overall goal of the SoS, the interacting systems forgo some of their own behaviour to meet the requirements of the SoS. (Boardman and Sauser, 2006)
8. Interoperability: To form a federation of systems, the SoS must be able to integrate a selection of heterogeneous systems. This includes the integration and adaptation of interfaces, standards, and protocols to connect old and new systems. (Boardman and Sauser, 2006; Abbott, 2006)

In a survey by Uday and Marais (2015) the usage of design principles is discussed to leverage SoS resilience. Resilience is the ability to maintain functionality despite unexpected disruptions, which can occur multiple times in an SoS lifetime. As described by Uday and Marais, design principles can effectively guide engineering design. Design principles, such as physical redundancy, can for example contribute to the challenge of dynamic reconfiguration as a characteristic of SoS.

The presented approaches focus on selected challenges of SoS. A broader research approach is needed for more general procedures and techniques for the design, analysis, evaluation, and evolution of system of systems (Klein and van Vliet, 2013). Using design principles to address the challenges of SoS as in the work of Uday and Marais (2015) is promising. However, it is important to acknowledge that this approach does not encompass all characteristics of SoS.

3. Research methodology

The overall research methodology for this paper is based on the design science research approach according to Hevner et al. (2004). The framework consists of three cycles: relevance cycle, rigor cycle and design cycle. In the relevance cycle, the application context is defined and examined based on a problem. The relevance is discussed in chapter 1. Chapter 2 aligns with the rigor cycle, in which literature is investigated and used as a knowledge base. The contribution of this paper is a broad and structured knowledge base for designing SoS as explained in Chapter 4. It is based on a systematic

literature review on design principles and extended by mapping it to SoS characteristics during the design cycle.
The systematic literature review was conducted according to Webster and Watson (2002) and Xiao and Watson (2019). The process consists of three steps, (1) planning the review, (2) conducting the review and (3) reporting the review. The goal of the review is to identify principles in the context of SoS as described in chapter 1 and 2. As a data base SCOPUS was used to identify the most relevant principles from the relevant scientific research areas. As the term *principle* is a common concept and used across many disciplines, the SCOPUS search was limited to systems engineering conferences and journals.

Search string: TITLE-ABS-KEY (("system of systems" OR "systems of systems" OR "SoS") AND ("principle")) SRCTITLE ("systems engineering")

Using the initial set of 133 sources, the data set was narrowed down to the most relevant ones using three filters. First, we filtered the data by scanning the title and removing the sources with no citations. Afterwards we filtered the data by reading through the abstract and as a last step reading the full text. Figure 1 illustrates, how the review was conducted.

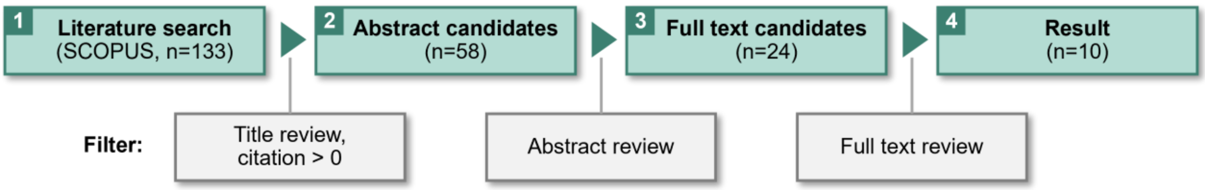

Figure 1. Systematic literature review procedure on design principles for SoS

4. Results

In this study, we aim to provide guidance for engineers in the development of SoS by consolidating and analysing a set of design principles. Based on the ten research papers identified in the systematic literature review, an initial set of 84 design principles for SoSE were identified. After reviewing the listed principles, 19 principles were identified as principles with similar meanings. If two principles had a similar meaning, we consolidated them into one principle. One example is 'interface management' mentioned by Meentemeyer (2009), which was marked as a similar meaning to the 'leverage at the interfaces' principle by Maier (1998).
After consolidating the principles, a final set of 65 principles were taken into further analysis. These principles were then mapped to their corresponding SoS characteristics, enabling engineers to identify design principles that are specifically relevant to their SoS design challenges. Through this mapping process, we identified 26 design principles that were universally applicable to all SoS characteristics, categorized as generic principles. As a result, we derived 39 specific design principles and 26 generic design principles. The analysis process with the number of principles related to each step is illustrated in Figure 2.
The results of the analysis process are listed in tables with each principle related to its source. If a principle appeared in multiple contributions, we named the authors in brackets. The SoS characteristics are numbered according to Chapter 2. As mentioned before, some principles are generic and contribute to all SoS characteristics. Therefore, we consolidated the generic principles in Table 1 and the specific principles in Table 2. As the generic design principles are general in nature and can be assigned to all SoS characteristics in the broadest sense, the mapping was not included in Table 1. The design principles by White and Jean (2011) are only numbered in the original contribution. Therefore we have added a title for the principles in the list.

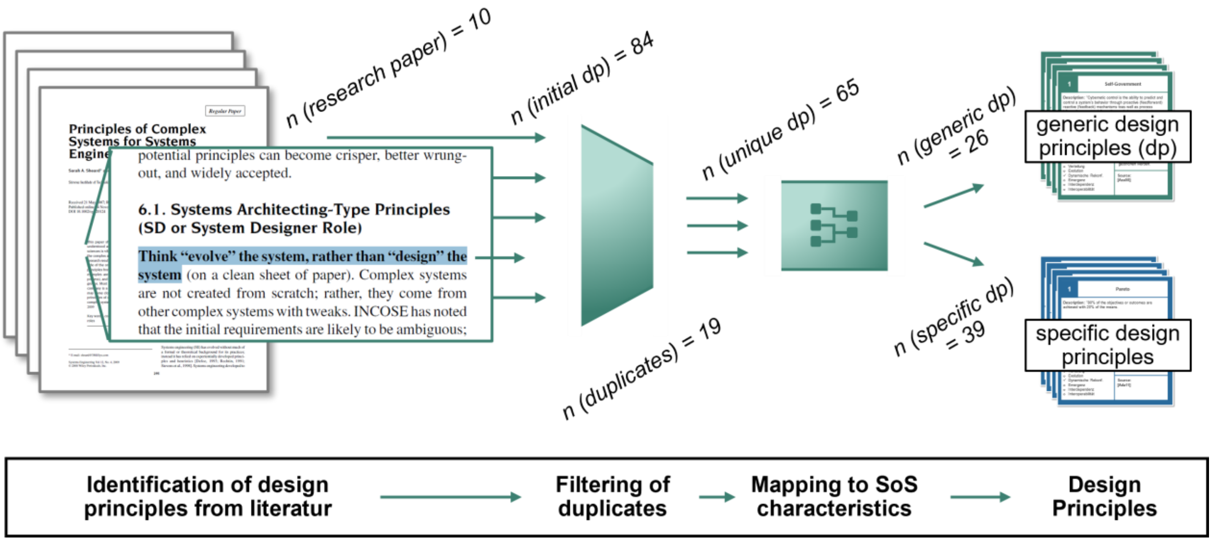

Figure 2. Overview of the analysis procedure

Table 1. Generic design principles

No	Source	Principle
1	Sheard and Mostashari, 2009	Use decision tree to determine where four design approaches work best
2		"Forgo the last bit of optimization"
3		Establish rich mental models to understand the problem space
4		Presume a system is complex until proven otherwise
5		Coordinate the people
6		Establish the right kind of coordination
7		Find the right experts
8		Focus engineering efforts and resources on central product development tasks
9		Understand that Pareto charts derive from power laws
10		Base decisions on data
11	Adams, 2011	Pareto
12		Requisite parsimony
13		Requisite saliency
14		Minimum critical specification
15	Hester, 2012	Principle of multifinality
16		Circular causality
17	White and Jean, 2011	1 - *Humility centered*(*title by author)*
18		2 - *Comprehensive Systems Perspective**
19		4 - *Transdisciplinary Integration**
20		5 - *POET Factor Consideration**
21		6 - *Semantic Convergence Approach**
22		7 - *Opportunity-Risk Synergy**
23		8 - *Heuristic Decision Support**
24	Meentemeyer et al., 2009	Utilization of Systemigrams
25		Paradoxical Thinking
26	Choi, 2016	Employing the right information technologies

Table 2. Specific design principles and their contribution to SoS characteristics

			SoS characteristic							
No	**Source**	**Principle**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	Maier, 1998	Stable Intermediate Forms (Choi 2016)				x				
2		Policy triage (Choi 2016)				x				
3		Leverage at the Interfaces (Meentemeyer 2009, Choi 2016)								x
4		Ensuring Cooperation (Choi 2016)	x							
5	Sheard and Mostashari, 2009	Think "evolve" the system, rather than "design" the system				x				
6		Look for local actions that can have global consequences						x		
7		Keep multiple possibilities viable	x	x			x	x	x	x
8		Explicitly impose variety on the system		x				x		x
9		Architect in layers that isolate elements with different rates of change from each other.				x				
10		Consider creating swarms to perform some tasks.						x		
11		Allow for off-label utilization of modules				x	x	x		x
12		Model when needed. (Meentemeyer 2009)		x				x	x	
13		Analyze system networks						x	x	x
14		During system development, prepare for and accommodate expected design changes				x				
15		Connect people and groups as much as possible	x							
16		Explicitly manage the development environment.	x			x				
17		Build capable organizations	x							
18		Judge actual results	x			x		x		
19		Make business rules of interaction explicit	x							
20		Take steps to reduce catastrophes	x	x		x		x		x
21	Jamshidi, 2017, Azani, 2008	Standardized interfaces (Meentemeyer 2009)								x
22		Self-Government (White 2011)	x			x	x			
23		Conservation				x			x	
24		Reconfiguration					x			x
25		Symbiosis	x							
26		Modularity (Sheard and Mostashari 2009)	x	x		x	x			x
27	Hsu *et al.*, 2009	Condition of Emergence (Meentemeyer et al. 2009)						x		
28		Emergent Behaviour is Inversely Proportional to the Degree of Bondage between Systems						x		
29		Emergent Behaviour is Non-linear						x		
30		Emergent Behaviour is Self-organized						x		
31	White and Jean, 2011	3 - *Systemic Balance Principle* (*title by author)*	x	x						
32		9 - *Trust-Centric Collaboration**	x							
33		12 - *Simple Element Design Philosophy**		x		x	x		x	x
34		13 - *Layered, Loosely Coupled Architecture**		x		x	x		x	x
35	Meentemeyer *et al.*, 2009	Integrated Product Teams	x							
36		Global risk management and Decision Analysis	x		x	x				
37		Interface Management								x
38		Agile Development Concepts: Plug-n-Play Architecture Scalability					x	x		
39	Choi, 2016	Including uncertainty					x	x		

The long list of principles visualizes the significance of design principles within SoS literature. Numerous authors emphasize the relevance and advantages of incorporating design principles into the SoS design process. Some principles, such as *leverage at the interfaces*, seem to be particularly relevant for the design process since they are mentioned by multiple authors. Also, some principles address multiple SoS characteristics and seem to be beneficial when designing SoS. One example is *modularity*. According to Azani (2008) modularity enables modules to evolve more easily and manage complexity. Therefore, principles such as modularity should play a more important role in SoS design.
Most of the principles are explained in more detail in the referenced literature. Authors such as Meentemeyer et al. (2009) or Sheard and Mostashari (2009) describe in short abstracts what the principles are about. Choi (2016) or Maier (1998) also provide examples to further increase understanding of the principle. Overall, each SoS characteristic is supported by at least one specific design principle in addition to the generic design principles in Table 1. Generic design principles such as *forgo the last bit of optimization* help engineers to get the right mindset, when looking at complex SoS engineering tasks. However, they are not able to provide specific guidance for engineers.
In order to demonstrate the benefits and relevance of design principles in the context of SoS engineering, an example is given below. The example describes the development of a network for electric ferries, which is based on the principle of modularization. As already described in chapter 1 and highlighted by the multiple mentions of the authors in the literature study (Table 2), modularization is particularly suitable for addressing characteristic challenges of SoS. The following section outlines how a design principle adresses the challenges in SoS engineering.

5. Evaluation using the modularity principle

In the following section, the identified and categorized design principles are evaluated using the development of the world's first electric fast ferry as an example.
During the project, several challenges arose, such as battery technology, hydrodynamic optimization, and propulsion efficiency. However, these could be solved internally through the combined expertise of the project participants, and the solutions did not depend on other stakeholders. In contrast, the integration of the ferry into the operator's mobility network or the design of charging facilities with a view to future use by other vessels is more complex. These questions deal with the design of the SoS and therefore need to be answered not only based on the individual system, but also considering other systems and applications. An illustration of the resulting SoS is shown in Figure 3.

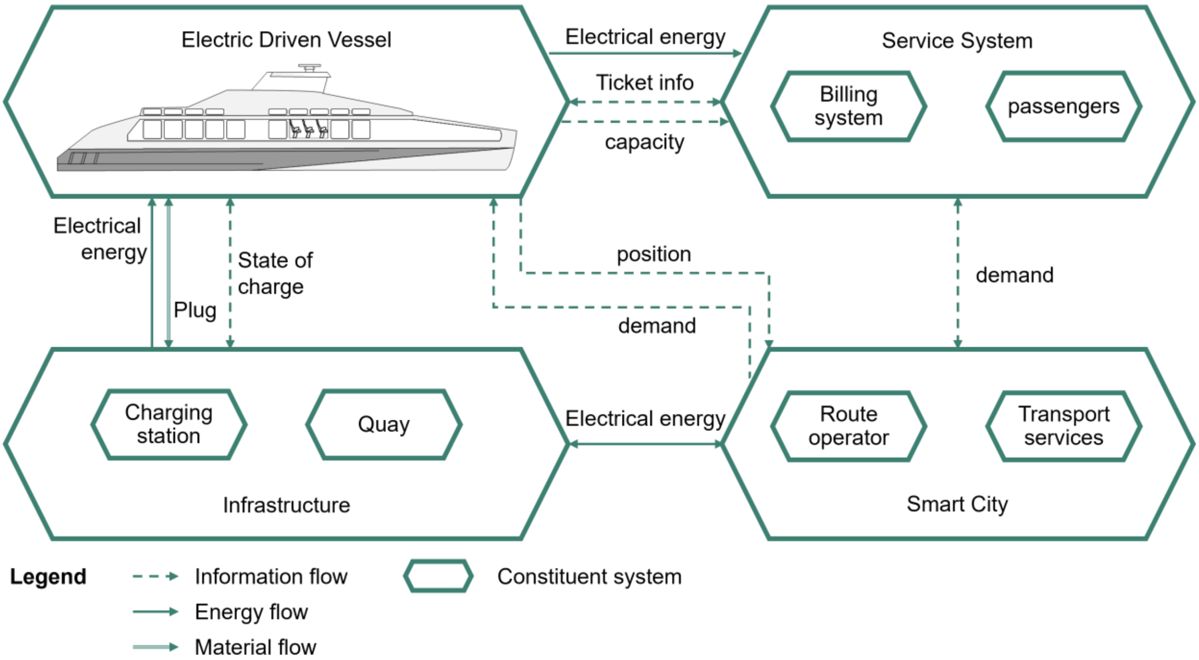

Figure 3. Illustration of the mobility system of systems

In this paper, we focus on the design of the charging infrastructure in the port, which had to be carried out within the project as it was the first time a high-capacity charging solution was needed. The resulting solution needs to orchestrate multiple charging endpoints, different parts of the electrical grid such as high-voltage stations, digital payment and scheduling services, and the different objects being charged. For these charged objects, several ships as well as land-based mobility solutions were considered. The most relevant characteristics to describe this SoS are managerial interdependence (1), evolution (4), and interoperability (8). Following the literature review and considering further economic factors such as reusability and scalability of the selected solution, it was decided to use the design principle of modularisation for the further procedure. Modularisation focuses on standardization of interfaces and the independent realization of functions to allow the exchange of specific parts from a system without effecting other areas.

Following a modular approach such as Seidenberg (2023), the solution adapts components from high-power car charging stations and uses them as standard interfaces. The backend components of the charging system are completely customized to ensure efficient charging, as the maximum power is 20 times higher compared to the latest car charging stations. The plugs and communication protocols that connect the charging infrastructure to the ferry are compatible with the CCS Type 2 standard. Also, the communication between the electrical grid systems and the charging station to request the start of charging or to reduce the charging rate follows the same standard.

Since this public standard is well established and used by most EVs on European roads, designers of other systems that need to charge at this station can easily adapt to it, demonstrating the interoperability (characteristic 8) of the SoS. Since many other charging stations also use the same standard for smart grid communication, future evolutions (characteristic 4) of the grid must be backward compatible to maintain the operation of the charging station in the long term. The standard interfaces also make it possible to replace or upgrade individual components (characteristic 4). Due to the clearly described interfaces, the systems can still operate independently internally and only need to follow the agreed behaviour externally (characteristic 1).

The usage of modularisation as design principle for the SoS has led to a successful design. With many degrees of freedom in the SoS design process it was helpful to find guidance by a well-established design principle, allowing a fast and efficient development.

6. Discussion and conclusion

This contribution aims to provide a more nuanced understanding and practical application of design principles within the dynamic landscape of SoS engineering. Two central research questions were researched on. First, the concept of design principles was investigated in the context of SoS. Through a systematic literature review, a total of 65 design principles were identified. By evaluating the characteristics of SoS, the principles were categorized into specific and generic principles. The 39 specific principles were assigned to the corresponding SoS characteristic, establishing a set of principles for each SoS specific design challenge. This allows engineers to search for design principles that match specific SoS design task.

As a second question we focussed on the contribution of design principles to the SoS design process. During the analysis of an electric fast ferry charging infrastructure, the design principle of modularisation was selected because it addresses SoS-specific challenges, such as interoperability or evolution. Considering the many degrees of freedom that need to be covered during the SoS design, this allows for a faster and more efficient design. Since only one design principle was used for evaluation, the question can only be answered provisionally, and further evaluation is needed.

The design principles presented in this paper are a basis for further refinement. Not all authors provide detailed information on what the principle is about, how to apply it and how a possible example looks like. Standardizing the description and structure of design principles is proposed to enhance accessibility for engineers and researchers. This not only facilitates a more inclusive addition of principles but also encourages collaborative contributions to the evolving list.

However, further guidance is needed to select the most appropriate principle for a given design task. A comprehensive description how the principles address specific SoS characteristics is recommended. In order to increase the quality of the lists of design principles, further research should examine their applicability and relevance for SoS. A proposed strategy involves ranking the principles through the input of a focus group of experts. This way the design principles can further be aligned in order to higher the quality of the design principle lists.

As presented in the paper, modularization offers great potential to address challenges in the context of SoS. In order to increase the applicability for companies, concrete instructions are needed on how the principle of modularization can be applied for SoS.

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