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Modeling data flows in a complex stakeholder network - a case study on autonomous public transportation

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ABSTRACT: Advances in information and communication technology (ICT) foster smart systems. Seamless data flows between stakeholders are crucial for their functioning. Designing communication systems to manage data exchange in distributed multi-stakeholder networks is challenged by the complexity of diverse stakeholders with varying interests and data needs. This requires a comprehensive understanding of data flows and communication dynamics. This paper investigates methods for modeling and analyzing data-related links between stakeholders in complex systems. After defining requirements and reviewing available methods, an approach combining dependency and structure modeling (DSM) and systems modeling language (SysML) is identified as most suitable. This is applied to a case study of autonomous buses in public transport, demonstrating its applicability and providing a foundation for further work.

KEYWORDS: product-service systems (PSS), systems engineering (SE), complexity, modeling method, data- and information flows

1. Introduction and problem clarification

Advances in information and communication technology (ICT) have enabled unprecedented levels of communication and data exchange across the globe. These improvements have facilitated the rise of new business models and changed the way enterprises interact with their stakeholders. As the importance and availability of data grows, so too does the importance and complexity of the related digital infrastructure for data communication. This requires suitable approaches for effectively managing the interactions involved in data exchange. (Pentland et al., 2020)

In the field of engineering, cyber-physical systems (CPS) and product-service systems (PSS) are examples of this trend toward ICT-based concepts. CPS integrate software-based smart elements with physical components, allowing for real-time data collection and analysis, while PSS emphasize the delivery of value through a combination of products and services. These concepts highlight the need for enterprises to leverage ICT capabilities in order to enhance their value propositions, thereby fostering competitive advantages in an increasingly digital marketplace. (Machchhar et al., 2022)

However, designing communication systems for managing communication paths and data exchange within distributed multi-stakeholder networks is challenged by the complexity of these networks, characterized by diverse stakeholders with varying interests and data requirements (Rak et al., 2020; Tipper, 2014). This necessitates a comprehensive understanding of data flows and communication dynamics within the system. Only if the information flow within a system or organization is modeled correctly can insightful analysis be conducted, which in turn makes it possible to adjust the structure for the purpose of optimizing and facilitating the proper flows. (Eppinger & Browning, 2012)

An example of these observations is found in the field of autonomous driving and in the efforts to introduce systems such as autonomous buses in public transport so as to make mobility more efficient and sustainable. In addition to the regulatory challenges and the lack of further experience in real-world operation that is essential for retrieving empirical values and reliable data, the design of digital communication and data management systems for operating an autonomous bus is another important task since such systems are not yet available. (Langner et al., 2024)

In the research field of psychology, it is well-known that communication between two persons can be misunderstood since the exchange of information through spoken or written language is open to various interpretations, e.g., as described by Schulz von Thun (2010). It is therefore indispensable to describe communication on an unambiguous technical level for functioning data flows. Frameworks like the model by Shannon and Weaver (1998) describe the interaction between a sender and a receiver on a factual level by defining certain parameters, such as the transmission channel or coding method used. Yet this only describes one interaction and not numerous interactions in a complex system. In contrast, several methods and approaches to modeling complex systems in general exist in literature. However, it has not yet been thoroughly investigated which methods/approaches are suitable for modeling the data-related links and dependencies in a complex stakeholder network, particularly in light of the growing role of data exchange resulting from advances in ICT.

This paper therefore aims to develop a concept for modeling the communication-related links between stakeholders in a complex network to support the system's design via a data-centric analysis. The research question (RQ) to be answered is thus: *Which methods are suitable for modeling and analyzing the data-related links between stakeholders in a multi-domain value network with distributed stakeholders and data flows?*

2. Approach to research

The research begins with a comprehensive literature review covering several domains essential for understanding complex systems and data communication. This includes an examination of theoretical frameworks and practical methodologies in systems engineering, PSS, and data communication within stakeholder networks. This aims to identify the current gaps in modeling data flows within complex stakeholder networks and to compile a broad understanding of existing methods, challenges, and best practices. Following, the research problem is clarified in the context of the identified knowledge gaps and practical needs. This involves a focused assessment of challenges related to modeling data flows in multi-stakeholder environments, particularly in areas with a high degree of complexity.

The next step involves deriving and defining specific requirements that the model must meet. Based on a synthesis of findings from the literature and problem clarification, these requirements outline essential characteristics for the model. The requirements are informed by established requirement definitions from prior works, especially those focusing on modeling languages and system design, to ensure a robust and academically grounded foundation. Existing modeling approaches and methods are then analyzed to assess their strengths and limitations within the context of the research problem and the defined requirements. This includes evaluating established frameworks and methodologies in data communication, systems engineering, and stakeholder management. Each method is systematically examined for its capacity to represent complex data flows, support multiple stakeholders, and maintain flexibility for different application scenarios. By cross-referencing these methods with the defined requirements, insights are gained into how well current approaches meet the needs identified in the problem clarification phase, highlighting areas for potential integration and improvement.

A novel modeling concept is subsequently designed on the basis of the insights from the literature and method analysis. This concept consolidates the strengths of investigated approaches, addressing any gaps identified in their applicability to complex stakeholder networks. The design focuses on creating a comprehensive, flexible, and understandable model that aligns with the established requirements. The modeling concept is validated by applying it to a real-life case study specifically within the domain of autonomous public transportation. Multiple industry workshops (WS) are conducted with selected stakeholders from this sector, namely a bus operating company (WS1 with 5 participants; WS2 w. 4 p.), a transportation association (WS1 w. 5 p.; WS2 w. 4 p.), and a manufacturer (WS w. 8 p.) in order to gather the needed data for building a model with the selected concept. In addition, data from relevant industry standards and related literature is screened and included in the model. This application tests the model's capability to accurately represent complex data flows and interactions among multiple stakeholders, such as transportation agencies, municipal governments, technology providers, and end users. This allows to derive further needed steps in the development of the novel modeling concept.

2.1. State of the art (available modeling methods)

Our research approach established a solid foundation for identifying and examining existing modeling methods and approaches. Table 1 presents a comprehensive overview of approaches for modeling complex, data-driven networks. Each approach is briefly described, with the key findings highlighted, and example real-world scenarios for practical applications are illustrated. In subsequent sections of this paper, we will delve into a more detailed analysis of these modeling methods, examining their strengths, limitations, and specific contexts where they provide optimal value.

Table 1. Modeling methods retrieved from literature

Dependency and Structure Modeling (DSM) (Eppinger & Browning, 2012)

Description: DSM methods are used to describe the interactions between elements in a system. The basis forms an NxN matrix describing the dependencies between N components. Three main types of DSM have occurred: mapping of components, process steps, and people/stakeholders to analyze the product, process, or organization architecture respectively. Each of those domains is described in a single matrix. Multi-domain matrices (MDM) combine single matrices to allow for a comprehensive analysis. Mathematical operations allow mainly for the clustering and sequencing of the model to derive recommendations for its optimization, e.g., an optimized workflow or team composition.*Key findings*: DSM enables clear visualizations and mathematical analysis of various complex system types, including any domains of interest. It is a proven method with numerous applications.*Application*: Engine development: redesigning organization architecture for enhanced communication and integration; multinational energy project stakeholders: analyzing the stakeholder value network and identifying channels of stakeholder influence. (Eppinger & Browning, 2012)

Model-Based Systems Engineering (MBSE) (Weilkiens, 2014)

Description: MBSE is a methodology for holistic system development based on the use of models. It utilizes a variety of interconnected models to depict different aspects of a system and form a cohesive overarching model. Systems modeling language (SysML) is often used for MBSE. Activity diagrams and internal block diagrams are particularly suitable for modeling data flows.*Key findings*: This is a universal modeling technique for data flows within systems and offers numerous applications across diverse domains. In particular, MBSE has seen frequent application in the context of PSS or CPS. SysML is commonly used within MBSE, providing a structured approach to capture, visualize, and manage the requirements and interactions that are characteristic of systems.*Application*: Numerous applications focused on defining the architectures of circular PSS and engaging key stakeholders within these systems. These applications support the identification and analysis of critical life-cycle stages, facilitating and enhancing collaboration and integration among diverse domain experts. (Halstenberg, 2022; Orellano, 2019)

Business Process Model and Notation (BPMN) (OMG, 2011)

Description: BPMN is a method for the graphical representation of business processes. It uses activities, events, gateways, and flows to represent processes and decisions during a process. The responsibilities and outcomes of each activity in the process can also be shown, thus providing insight and grounds for communicating workflows across different domains and organizational boundaries.*Key findings*: Focus on business workflows, process description, and value creation with an emphasis on visual representation, aiming to provide a common understanding across the stakeholders involved.*Application*: Applied in various business areas, i.e., commissioning, sales, order fulfillment, and many others, structuring and documenting underlying work and information flows. (OMG, 2011)

GEMINI Method (Echterhoff, 2018)

Description: A method for developing the service offering and structure for innovative business models. The method can depict enterprises, resources, and activities needed for value creation. The relationships between entities are described as cash, service, and information flows.*Key findings*: Focuses on the development of business cases on a multiple stakeholder network level, not in terms of the related data/information flow.*Application*: This approach has been applied to the design of complex systems, such as smart PSS and CPS. For example, Paliyenko et al. (2023b) provide a detailed analysis of stakeholder interactions within the value creation network of a smart PSS. They identified five key clusters of actors and described the interactions between these clusters, particularly in terms of system flows.

(*Continued*)

Table 1. Continued.

Meta Model of a Cyber-Physical Product Service System (CPPSS) (Rizvi & Chew, 2018) *Description*: Comprises two meta models. The first focuses on the interaction between CPS and PSS, emphasizing how interactions generate value through integrated solutions. The second meta model outlines the development process of CPPSS, covering its entire lifecycle. This includes key considerations such as business models, service types, and the integration of feedback mechanisms.*Key findings*: This model emphasizes the continuous feedback of information from the system's operation back to the provider, which feeds insights into the design process and supports innovation.*Application*: Its application has been demonstrated in a limited scope, primarily through multiple case studies conducted by the authors themselves.
Knowledge Modeling and Description Language (KMDL) (Gronau et al., 2010) *Description*: KMDL is a specialized method for modeling, analyzing, and optimizing knowledge-intensive processes within organizations. It emphasizes the capture of both explicit knowledge, such as documented information, and tacit knowledge, which includes insights, skills, and experiences. KMDL provides a holistic view of how knowledge moves through an organization, creating a model that illustrates the transformation processes of knowledge creation, sharing, and application.*Key findings*: KMDL facilitates the modeling of interrelations among knowledge workers, organizational processes, and the knowledge resources involved. By mapping these interdependencies, KMDL identifies opportunities to enhance knowledge-intensive processes. This approach is particularly valuable in contexts where knowledge serves as a critical resource.*Application*: The modeling of information flows within organizations aids in enhancing knowledge and information management (Bastos et al., 2014). KMDL is also utilized for managing knowledge in Industry 4.0 environments. (Gronau, 2021)
Stakeholder Value Network Analysis (SVN) (Feng et al., 2013) *Description*: Approach that models relationships between stakeholders in a network as the exchange of value. It allows the inclusion of both social and economic dependencies. After identifying the stakeholders, the value flows are mapped, quantified, and analyzed to derive strategic insights, e.g., in terms of optimizing the interactions.*Key findings*: SVN is suitable for identifying critical stakeholders and communication paths. It uses DSM methods as its analysis tool. The possibility of identifying indirect relationships is a key aspect.*Application*: This approach can be applied in various networks/systems to map and analyze stakeholder interactions through value flows, making it suitable for social, business, or economic contexts regardless of sector or subject. A prerequisite for successful application is detailed knowledge of the stakeholders involved, ensuring they are at the same relational level and that their direct relationships are clearly understood.
Graph Theory (Tabassum et al., 2018; Diestel 2024) *Description*: Graph theory is a mathematical framework designed to study networks and the relationships between connected entities. This framework represents networks as graphs that consist of nodes symbolizing individual entities and edges, which in turn represent the connections or relationships between these entities. Key concepts within graph theory include paths (sequences of connected nodes), cycles (closed loops within the network), connectedness (whether nodes are reachable from one another), and centrality (nodes with positions of influence).*Key findings*: Graph theory provides robust analytical tools for interpreting and understanding network structures and connectivity patterns, facilitating applications such as search algorithms, optimization techniques, and broader network analyses. It makes it possible to uncover patterns, optimize processes, and make informed decisions based on the structure and connectivity of networks.*Application*: Analysis of social networks, particularly in capturing and understanding relationships within economic and organizational networks. In social network analysis, graph theory enables the detection of clusters or communities within a network, revealing groups of closely linked entities such as collaborative teams within organizations or customer communities within a business network.

2.2. Definition of requirements for the modeling method

After finding multiple modeling methods in the literature, their suitability must be evaluated in detail. To do so, specific requirements for the data communication model must be defined stem from a comprehensive review spanning various fields relevant to complex systems analysis, smart systems modeling, and adjacent developmental methodologies. This foundation integrates insights drawn from an extensive literature survey that includes significant contributions as well as established demands identified by Langner et al. (2024) and Paliyenko et al. (2022) within design disciplines. The derived requirements synthesize distinctive needs for both modeling approaches and methods,

drawing on established and rigorously tested requirement definitions for modeling methods and languages.
Three key publications are instrumental in shaping these requirements due to their grounded and systematic approach to defining needs within developmental processes, modeling languages, and smart system design. Keller & Binz (2009) defined requirements for supportive methods in development processes through a comprehensive meta-analysis. Frank & Laak (2003) derived requirements for modeling languages, emphasizing process description through their meta-analytical approach. Paliyenko et al. (2023a) complement this foundation by detailing requirements derived from extensive industrial surveys, which articulate specific needs in the development of smart systems.
In order to undertake this research endeavor, a synthesized model that bridges these three essential domains is required. The envisioned model for data communication is designed to functionally integrate key insights from developmental processes, process modeling languages, and smart system requirements, ensuring that it is capable of capturing the nuanced demands of each. The synthesis juxtaposes challenges identified within the public transportation sector with those in adjacent fields, extracting and aligning specific requirements to ensure that the model is sufficiently robust, adaptable, and sensitive to complex, real-world data flows. By synthesizing the requirements as shown in Table 2, the proposed model for data communication in complex stakeholder networks is positioned to serve as a robust analytical and descriptive tool.

Table 2. Requirements for a suitable modeling approach

Requirement	Description
#1 Comprehensiveness	Allows a representation of all relevant stakeholders and data flows.
#2 Comprehensibility	Designed for ease of understanding and usability by individuals unfamiliar with the model.
#3 Applicability	Suitable for application across a range of problems in the area of complex stakeholder networks, beyond a single specific case.
#4 Usefulness	Supports actionable and practical analyses, e.g., identification of critical relationships.
#5 Extensibility	The core structure allows not only for additional entities within parameters but also accommodates new parameters or aspects to be analyzed.
#6 Adaptivity	Facilitates customization to reflect the unique conditions of the present network, without being confined to specific disciplines.
#7 Complexity reduction	Reduces the complexity of the overall problem by making it possible to break this down into smaller units/tasks.
#8 Objectivity	Provides a consistent, objective framework that yields valid results across different analysts working with the same data set.
#9 Flexibility	Maintains a uniform level of detail but allows some areas to be summarized, ensuring not all components require exhaustive depth.

3. Findings

This section begins with evaluating the presented methods by taking the corresponding requirements into consideration. A suitable modeling approach is derived on this basis and applied to a case study.

3.1. Investigation of available modeling methods

To select a suitable modeling approach, the presented models in Table 1 are evaluated by assessing their fitness to fulfill the requirements posed in Table 2. Table 3 shows the evaluation conducted by the authors who are experts in the research field and have extensive project experience in the industry. A three-step scale is applied: “3” indicates fully fit to meet the requirement, “2” means only a partial fit, and “1” signifies a lack of fitness for this purpose. Each author evaluated the models independently, and the outcomes were discussed in a workshop to derive the final established evaluation.

Table 3. Evaluation of the fitness of the investigated models for the given requirements

#	Evaluation of fitness: 3 = fully 2 = only partly 1 = rather not	Comprehen-siveness	Comprehen-sibility	Applica-bility	Usefulness	Extensi-bility	Adaptivity	Complexity reduction	Objectivity	Flexibility	Ø
1	**DSM**	3	3	3	3	3	3	3	2	3	2.89
2	**MBSE (SysML)**	3	2	3	3	3	3	3	3	3	2.89
3	**BPMN**	1	1	1	2	1	2	3	2	3	1.78
4	**GEMINI**	2	2	3	2	2	3	2	2	3	2.33
5	**CPPSS Meta Model**	2	3	1	3	3	3	2	2	3	2.44
6	**KMDL**	3	2	2	3	3	3	2	2	3	2.56
7	**SVN**	3	2	3	3	2	3	3	2	3	2.67
8	**Graph Theory**	3	3	3	3	2	3	3	2	3	2.78

The easy-to-comprehend architecture of **DSM** makes it possible to include any type of entity and domain (Eppinger & Browning, 2012), and be extensible to other parameters of interest. It applies to numerous complexity issues and is adaptable to specific conditions. By dividing into domains, it allows to reduce the complexity, also showing its flexibility: while one domain can be described in detail, others can be summarized, still, a certain depth is required to enable useful analysis. DSM has proven useful in various applications, such as identifying important stakeholders and patterns of interactions (Eppinger & Browning, 2012). However, objectivity concerns arise as interpretation can vary based on the user. **SysML** comprises various diagrams to comprehensively model any aspects of a system, making it both extensible and adaptive to specific conditions. This also enables its vast applicability. By dividing sub-diagrams of the overall system, it reduces complexity and gives room for flexibility, but still requires that modeling is performed with a certain consistency across the levels under consideration. Numerous case studies show the usefulness of analyzing systems with a SysML-based model, e.g., Orellano (2019). Compared to the DSM methods, the strict modeling rules give it an advantage in terms of objectivity, but simultaneously make it more complicated for new users to comprehend. **BPMN** is primarily suited for business processes and struggles with technical representations. While it simplifies business processes effectively, its comprehensibility and applicability beyond this context are limited. Its extensibility and adaptability are also constrained, reducing its usefulness. The **GEMINI** Method focuses on stakeholder interdependencies and system interactions, making it highly applicable in multi-domain settings. While adaptable and flexible, it is more complex to use than DSM or SysML and may require training to be fully understood. Its extensibility is moderate, and some subjectivity remains in how dependencies and relationships are assessed. The **CPPSS Meta Model** is specialized for analyzing cyber-physical product-service systems, offering strong insights into these domains but limiting broader applicability. While it is adaptable and extensible within its domain, comprehensibility is a challenge due to its specialized focus, and complexity reduction is not as effective compared to other modeling techniques. **KMDL** is comprehensively able to represent stakeholders and data flows within a system (Bastos et al., 2014), due to its focus on modeling knowledge-intensive problems, but has limited applicability in multi-domain engineering. It enforces objectivity through strict modeling rules and can simplify knowledge-related systems, but it may not be as effective in reducing complexity in other types of systems. **SVN** integrates DSM and Graph Theory to model stakeholder relationships and interdependencies effectively. It is highly applicable and flexible, allowing for detailed system representations. However, its comprehensibility is lower due to the need to understand both DSM and Graph Theory, and extensibility to new domains such as IT systems requires considerable customization and effort. **Graph Theory** mathematically underpins DSM through adjacency matrices, allowing powerful analyses like clustering and centrality measures. It is highly flexible and applicable across domains, though multi-domain representations can become complex. While comprehensible at a basic level, interpreting results objectively still depends on user expertise.
Resulting, both DSM and SysML seem to pose promising approaches. A combined holistic approach comprising both methods could provide promising outputs for modeling data flows in a complex stakeholder network. To investigate this, both are applied to a case study presented in the next section.

3.2. Example application of selected methods

Autonomous buses play an essential role in advances toward more efficient transportation solutions, since they provide the possibility of extending the transportation offering without needing to combat the general shortage of bus drivers. Previous work has identified the need to conceptualize the data communication systems needed for the operation of these smart PSS, since there are numerous interdependent stakeholders in a complex network (Langner et al., 2024; Paliyenko et al., 2022). To derive recommendations for action, the data-related links in this complex stakeholder network must be analyzed - making this a suitable case study for the research question at hand.

As described, industry workshops were conducted in order to collect the necessary data input. At first, the lifecycle of the autonomous bus is used as a guiding framework to identify all relevant stakeholders in the smart PSS. The necessary data input for the stakeholders and the related data source are then discussed. Further input from discussions with other stakeholders in the system is also considered.

The data available for each information exchange is therefore as follows: information/data, sending stakeholder, and receiving stakeholder. This input is used to create a network model utilizing both a DSM and a SysML approach. Figure 1 shows the structured DSM, which is built with the Lattix software tool for working on DSM-based projects. The stakeholders are shown in the first row and column of the symmetric matrix. The dependency between each other, marked with an entry in the related cell, represents a data/information exchange. All entries in rows represent the input received by this stakeholder, whereas the entries in the column indicate the output generated by the respective stakeholder. The value in the cells is generated by adding the relevant numbers pertaining to the data/information flow: if one item of information is exchanged, "1" is entered, "2" if two, and so on.

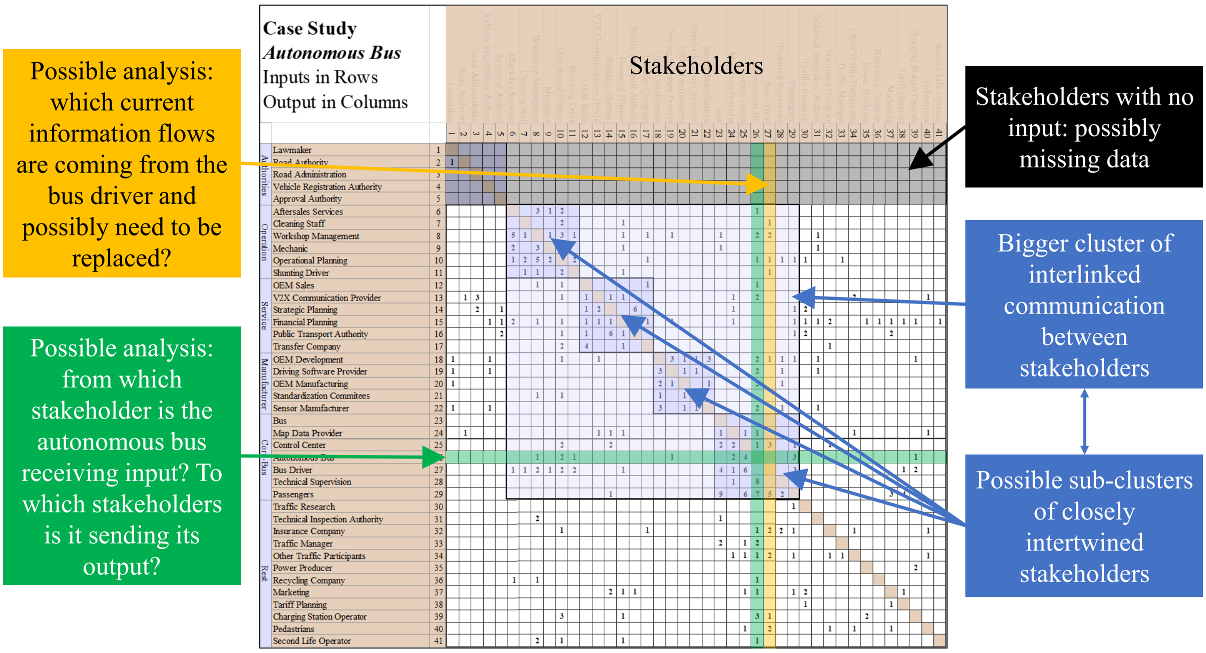

Figure 1. Structured DSM built with Lattix showing possible analysis approaches

Lattix enables users to conduct analysis with pre-implemented algorithms for clustering and sequencing. After being applied, the resulting DSM model shows numerous possibilities for analysis. As shown in Figure 1, clusters of closely intertwined stakeholders were identified by clustering. But since these clusters are also interrelated, strict separation is unsuitable. Furthermore, a group of stakeholders with no required input is identified by sequencing. This forms the basis for more detailed analysis: do these stakeholders really need no input, or is data input for the model missing? In this case, this reflects the group of mainly legal authorities and political entities that were not represented in the workshops.

In addition, the DSM model allows for easy identification of the links between certain stakeholders. For example, the bus driver as a currently important stakeholder will be replaced by the autonomous bus. Two views could be of interest: the first is analyzing the information flows coming from the driver and investigating if those need to be replaced, while the second is retrieving the necessary interfaces of the autonomous bus by looking into the flow of information both received and sent. Overall, the DSM model provided a good understanding of the overall system and showed the autonomous bus as a core stakeholder in the closely intertwined stakeholder group related to its operation. This is used as the basis for modeling the data flows between those stakeholders in more detail with SysML.

Both DSM and SysML are modeling techniques used to represent relationships between entities. DSM matrices can be converted into SysML-based models and vice versa. When an autonomous bus network is modeled using SysML, it enables a higher level of detail and information density. This facilitates the breakdown of DSM clusters and the organization and visualization of underlying information or data flows, along with their corresponding sources and sinks. However, as the granularity of content increases, the model's clarity tends to decrease, primarily due to the overlapping edges between blocks in the two-dimensional representation. To address this limitation, the proposed approach allows for the coexistence of both DSM matrices and SysML models, offering complementary perspectives by utilizing existing software solutions. In the subsequent section, the same network depicted in Figure 1 is modeled using SysML, specifically through an internal block diagram created as a "logical architecture diagram" with the widely used Arcadia Capella software. Capella employs a SysML-like modeling logic, that utilizes modeling principles from UML, SysML and NAF, thus ensuring a high interoperability with other MBSE tools. Figure 2 presents an excerpt from the stakeholder analysis, focusing on data flows, with the autonomous bus as the central point of analysis. The SysML model comprises multiple domains that are divided into subsystems (dark blue) or sub-actors (light blue). Within these subsystems, functions (green) depict how data is processed by the entities. Different types of data and information are transferred between these elements to fulfill the functions of the systems.

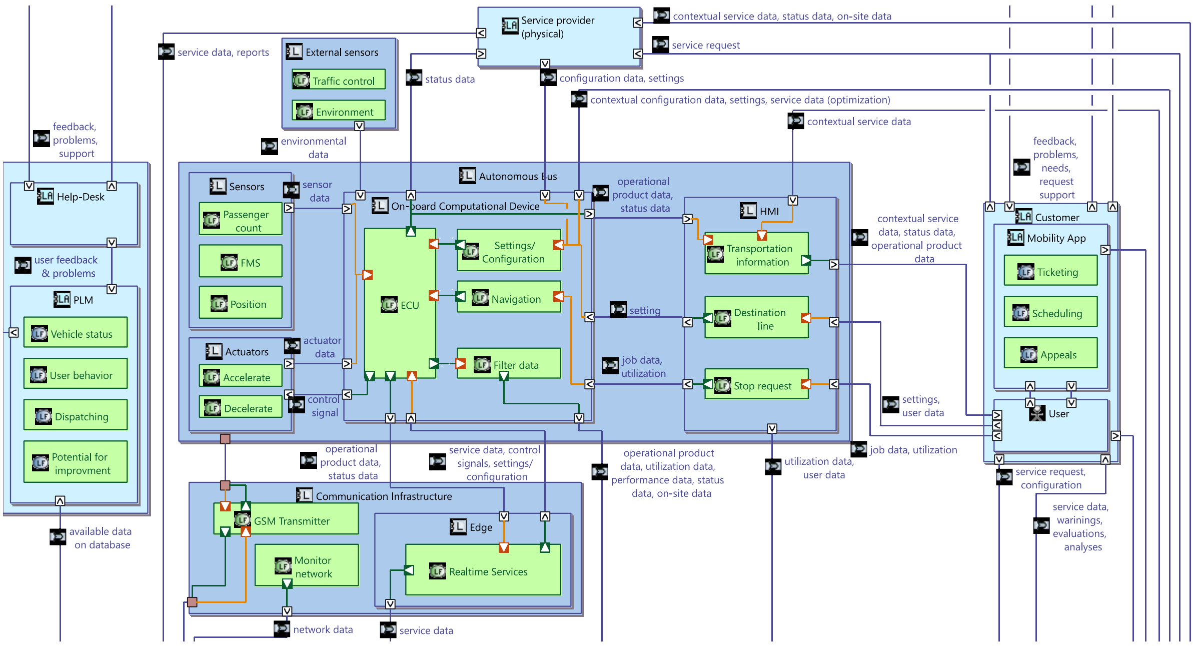

Figure 2. Internal block diagram for the stakeholder network around the autonomous bus (excerpt)

The autonomous bus, characterized as a smart product, integrates key components such as sensors, actuators, software, and a human-machine interface (HMI) to enable autonomous operation and user interaction. Sensors on board the bus collect data about its internal state and external environment, such as passenger occupancy, route conditions, and traffic patterns. This data is processed by an onboard controller, which analyzes it to generate control signals for actuators, enabling real-time decision-making for navigation, safety, and operational adjustments. The bus's behavior can be adapted dynamically through configurable settings that consider factors such as usage patterns, passenger preferences, data insights, and optimization goals. Service providers or data-driven services can implement these changes, ensuring the system evolves with operations and user requirements.

A communication infrastructure supports the autonomous bus network by facilitating seamless data transfer between the smart bus, central systems, and external stakeholders. Pre-processing and filtering of sensor data occur on board the bus to ensure relevance and reduce the volume of raw data transmitted to the cloud. This minimizes communication overhead while maintaining high-quality data for further analysis. The processed and raw data is stored in a service platform where it is enriched with contextual external data, either in a data lake for unprocessed formats or a data warehouse for structured insights. Customers, as key stakeholders, interact with the autonomous bus network through intuitive interfaces, including the bus's HMI and an integrated service platform accessible via mobile apps or web portals. These interfaces allow passengers to view real-time bus information, request services, customize preferences, and receive data-driven insights such as route recommendations or delay alerts. Additionally, APIs enable integration with external systems, such as city traffic management or other transportation networks, fostering a cohesive and interconnected public transportation ecosystem.

4. Discussion and outlook

This paper aims to identify suitable methods for modeling and analyzing data-related links between stakeholders in a complex network. Suitable methods are chosen which have proven to be valuable in numerous applications. A new, innovative approach that integrates DSM and SysML models for both network and system-level analysis is presented. The applied case study comprised a rather small dataset. While making it possible to show the applicability of the combined DSM/SysML approach, it lacks the sophisticated datasets necessary for further, more detailed validation. Therefore, the case study needs to be extended. A more detailed data input could foster greater insights, e.g., by including data formats, frequency of exchange, or a proxy for the importance of one data exchange. It is necessary to detail both approaches and acquire the necessary data input for detailed modeling and analysis.

DSM methods have proven to be an effective representation of a system of organizational units and their relationships (Eppinger & Browning, 2012). However, they offer numerous possibilities for extensions beyond the simple stakeholder-to-stakeholder DSM that has previously been implemented - for example, an extension to MDM. This would enable the inclusion of aspects such as IT systems or a more detailed characterization of the data flow in the model. However, DSM/MDM models can get very complex and overfilled within themselves when trying to include too many aspects in one model. This demands a more detailed look into the concept of an overall modeling approach with DSM methods.

When further looking at DSM methods, given the strong relationship to Graph Theory, their mutual supplementation could provide additional benefits, e.g., in visualizing large networks. Depending on the complexity of the problem, a DSM might grow too large to be intuitively handled. Therefore, in some cases, combining both methods could allow for deeper insights. (Lindemann et al., 2009)

Further research offers significant opportunities for advancing both theoretical frameworks and practical applications. The development of a DSM/SysML approach framework with a generalization of possible analysis and derived insights, as well as describing the required steps to generate the model, also involves further refining the existing approaches to provide greater clarity and adaptability while ensuring applicability across various domains. Consequently, although similar approaches of combining DSM and SysML modeling can be found in the latest literature such as in the work of Feng et al. (2024), the combined approach must be rigorously evaluated through real-world applications.

The ability to accurately capture the dynamics of multi-stakeholder systems through a suitable modeling approach provides a deeper understanding of system behavior and facilitates decision-making at multiple levels. However, the use of sophisticated models introduces trade-offs such as increased design effort and potential loss of clarity at higher levels of granularity. Future research should focus on strategies to balance such trade-offs. In fact, future work should address the broader tensions and opportunities that come with modeling smart multi-stakeholder systems. This includes navigating challenges such as data integration, interdisciplinary collaboration, and the management of competing priorities. By tackling these issues, modeling can continue to play a central role in enabling the development of systems that are not only functionally robust but also socially and economically sustainable, laying a solid foundation for innovation and progress in a wide range of contexts.

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