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Multi-domain data integration and management for enhancing service-oriented digital twin for infrastructure operation and maintenance

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A R T I C L E I N F O

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A B S T R A C T

The evolution from Building Information Modelling (BIM) to Digital Twins (DT) marks a shift from static models to dynamic data-centric representations. Using DT can improve Infrastructure Operation and Maintenance (IOM) through prompt and comprehensive data, especially by providing services and value-added features. However, developing this service-oriented digital twin (SoDT) for IOM faces challenges due to data heterogeneity, fragmentation, and interoperability issues across various systems used by different asset authorities. This paper develops a service-oriented digital twin framework for IOM (SoDT-IOM), which focuses on multi-domain data integration and IOM service-oriented design. Service-oriented DT components and data integration mechanisms are developed, and an individual-multiple interacted data repository for IOM services is designed. Two-stage industrial interviews are conducted, and two use cases are illustrated to evaluate the functionality and efficacy of the framework. The evaluation results reveal that implementing a SoDT-IOM framework encounters challenges related to cost and data security; however, it is appreciated for its capacity to improve decision-making and collaboration with linked, accurate and timely data. This paper proposes further design requirements and implementation recommendations for SoDT of asset management from both technical and managerial perspectives.

1. Introduction

Despite the continual advancement of emerging digital technologies and the escalating complexity of infrastructure systems, Infrastructure Operations and Maintenance (IOM) is still lagging in integrating novel technologies into their routine operations. This deficiency significantly hinders the ability of asset managers to effectively harness available data management to better inform decision-making. With the growing adoption of information and communication technologies in the late 20th century, asset management systems for Infrastructure Operations and Maintenance (IOM) have been mostly established in developed countries using relational database management systems (Halfaway et al., 2006). Since the last decade, Building Information Modelling (BIM) has been considered a promising method for improving data-based infrastructure operation and maintenance (Pocock et al., 2014; Kivits and Furneaux, 2013). Different aspects of using the BIM model with the extension of domain-specific information, e.g., safety risk, quality control, inspection, etc., are proposed in the literature (Costin et al., 2018). However, despite the increasing deployment of BIM for IOM, many issues still need to be fully addressed, such as data incompleteness, lack of real-time data integration, limited integration with operational systems, the complexity of model updates, and standardization and interoperability (Bradley et al., 2016; Parlikad and Jafari, 2016; Ozturk, 2020).

More recently, the concept of Digital Twin (DT) has proposed to improve the management of the built environment through the integration of static BIM data with real-time data from sensors, video cameras, and other sources to create a dynamic model of the asset. The transition from BIM to DT represents an evolution in the level of sophistication and functionality of virtual representations of physical assets from a static, model-centric approach to a dynamic, data-centric approach (Deng et al., 2021; bSI, 2022). A digital twin captures not only the geometry and attributes of the asset but also its real-time behavior, performance, and operational data. It enables continuous monitoring of

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asset conditions and performance using sensor data. Accordingly, real-time monitoring allows for proactive maintenance and predictive analytics, identifying potential issues and optimizing asset performance.

Using Digital twins by focusing on providing services and value-added functionalities to various stakeholders for IOM, can offer advanced simulation capabilities to analyze different scenarios, and enable what-if analysis and predictive simulations, which contribute to the effectiveness of planning, decision-making, and collaboration. Developing such service-oriented digital twins (SoDTs) is proving beneficial for providing services to the manufacturing industry, accompanying the improvement of the technological maturity of the Industrial Internet of Things (IIoT) (Kritzinger et al., 2018; Liu et al., 2021; Longo et al., 2019). Unlike traditional digital twins that primarily focus on replicating the physical characteristics and behavior of an object or system, a service-oriented digital twin extends its capabilities to deliver specific services and insights to users or customers. It acts as a platform for integrating data, analytics, and services.

However, there are still significant challenges in developing a service-oriented digital twin for IOM. First, a great variety of heterogeneous data must be considered for recording IOM activities, including a wide range of data formats from damage fotos to point clouds or BIM models. Second, the asset authorities have already established different and specific management to cover the major demands of IOM. In addition, the ability and managed asset type of each authority are strongly different to adopt, extend, or connect further implementation considering the current technology development (e.g., BIM). All the issues require adequate data management to overcome the unstructured data from data silos and to provide relevant information for the service-oriented digital twin.

Therefore, this paper proposes a service-oriented digital twin framework with a systematic data integration method to improve IOM. The Service-oriented Digital Twin for Infrastructure Operation and Maintenance (SoDT-IOM) is conceptualized to provide comprehensive information linked from various data sources for IOM. The DT components for data integration and service support are defined considering the requirements of industrial experts. The proposed concept design and the industrial concept evaluation through expert interviews focus on the following research aims:

- How to design a service-oriented digital twin to improve IOM?
- How to design a data integration and exchange mechanism to realize SoDT-IOM?

In this paper, the challenges in IOM were first captured by a systematic literature review and a series of industrial engagement activities. Then the objectives of the digital twin-enabled solution for IOM were defined based on current research and industrial practices. Under the problem-oriented objectives and industrial requirements, the SoDT-IOM framework was designed and developed iteratively, mainly focusing on multi-data integration and IOM service-oriented design. To evaluate the proposed framework, two use cases were illustrated and the functionality and efficacy of the proposed SoDT-IOM framework and the research methodology were both evaluated. In the end, theoretical contributions, practical implications, and future research directions are elaborated.

2. Related work

2.1. Trends in digital twins in the AECO industry

The idea of the digital twin was presented in 2003 for product lifecycle management by Grieves at the University of Michigan (Grieves, 2014). Digital twins are virtual replicas of physical objects, processes, or systems that exist in the digital realm. With the rapid development of related technology, e.g., Internet-of-Thing (IoT), multi-physical simulation, and real-time sensors and sensor networks, industrial needs and research efforts in the digital twin have become more urgent in various industry sectors since 2017 (Tao et al., 2019; Jones et al., 2020). Industrial digital twins are created by collecting and integrating real-time data from various sources, such as sensors, IoT devices, and other data streams, which enable the representation, analysis, and manipulation of their physical counterparts (Qi et al., 2021; Rasheed et al., 2020). Following the trend in manufacturing, researchers in the construction sector have begun to pay more attention to the digital twin due to its abilities and benefits since 2018 recognized by Madubuike et al. (Madubuike et al., 2022; Opoku et al., 2021) and Opoku et al. (2021). In the Architecture, Engineering, Construction, and Operation (AECO) industry, digital twins have gained significant attention and are primarily classified into the following three categories:

1) Comprehensive management service-oriented digital twins: These digital twins are designed to provide comprehensive management functions for various aspects of construction projects. For example, urban digital twins replicate entire cities, including their infrastructure, buildings, transportation systems, and utilities (Bauer et al., 2021; Deren et al., 2021). These digital twins help city planners, architects, and engineers visualize, analyze, and optimize urban development projects (Dembski et al., 2020). Similarly, construction site digital twins represent construction projects in their entirety, allowing project managers to monitor progress, simulate scenarios, and identify potential issues before they occur (Pan and Zhang, 2021; Greif et al., 2020).
2) Numerical simulation-oriented digital twins: These digital twins focus on simulating physical rules and change mechanisms associated with construction processes. For instance, digital twins can simulate the mechanical deformation of buildings under various conditions, such as earthquakes or extreme weather events (Levine and Spencer, 2022). By incorporating data on the structural properties of buildings, material characteristics, and external factors, these digital twins provide insights into how structures behave in different scenarios (Lai et al., 2023; Kang et al., 2021). Such simulations help architects, engineers, and construction professionals optimize designs, enhance safety measures, and predict potential structural vulnerabilities.
3) Human-Computer Interaction (HCI)-oriented digital twins: This category of digital twins integrates advanced computer technologies to create immersive and interactive experiences, especially by integrating Mixed Reality (Mix-R) visualization technology (Yin et al., 2023; Coupry et al., 2021). These digital twins enable human-computer interaction and provide a more intuitive understanding of construction processes. For example, digital twins can be used for on-site safety training, where workers can immerse themselves in a virtual environment that replicates real construction sites (Harichandran et al., 2021). They can practice safety procedures, identify hazards, and gain hands-on experience in a risk-free environment. By combining virtual elements with the real world, these digital twins enhance training effectiveness, improve worker competence, and mitigate potential on-site risks.

From the perspective of the whole life cycle of the construction project, digital twins offer different capabilities at various stages (Deng et al., 2021; Jiang et al., 2021). In the construction phase, a digital twin combined with the lean construction method is used to monitor the project process (Sacks et al., 2020). In this research, five kinds of monitoring and control loops were analyzed to improve construction processes with feedback, that were provided in different time frames such as real-time through the digital twin. A comparison between cyber-physical systems and digital twins is introduced, exploring potential scenarios (Akanmu et al., 2021). Additionally, a digital twin concept combined with Geographic Information System (GIS) is used for logistics simulation, transportation risk detection, and route optimization in supply chain coordination for construction projects (Lee and Lee, 2021).

During the operational phase, a digital twin framework combined with a BIM model is employed for the risk-based inspection of bridges (Kaewunruen et al., 2021). Risks are classified based on their causes, and the digital twin focuses on processing detected risks to assess bridge structures and determine inspection needs. For building maintenance, a comprehensive data listing and integration with the building model support a building digital twin (Lu et al., 2020; Zhao et al., 2022). The study outlines process flows for building operation and maintenance, leveraging the BIM model as the basis for the virtual asset.

In terms of lifecycle management, a cognitive digital twin framework with knowledge graph data is introduced, highlighting the potential for generically creating use cases within the digital twin (Yitmen et al., 2021). Addressing the handling of construction material for recycling and demolition, another digital twin concept is presented for simulating and evaluating different material flow scenarios (Züst et al., 2021). The digital twin system analyzes scenarios using predefined real-world parameters that impact material flows, supporting decision-making and visualizing results based on GIS. However, scalability for infrastructure assets requires further data integration and visualization beyond the asset element level, and a technical approach is still needed to connect and integrate the data effectively.

2.2. Digital twins for infrastructure operation and maintenance

IOM activities play a crucial role in ensuring safe and reliable infrastructure. Managing these activities relies heavily on using Asset Management Systems (AMS). Serving as a backbone, these systems are widespread globally to support decision-making for the asset authorities and asset managers. This importance of a robust and efficient AMS is underscored by international standards ISO 55000 ff (ISO 55000, 2014; ISO 55001, 2014), which provide guidance and introduce general requirements for establishing asset management strategies, manuals, and digital systems. In IOM practice, a wide range of AMS solutions are available considering the specific needs of different infrastructure domains and countries. Table 1 presents examples from Germany, the USA, and the UK, showcasing the managed assets, data, and key features offered by different systems.

Concluding current AMSs shows that system solutions are typically segmented based on asset types, such as bridges or pavement. Aligned with national standards and engineering requisites, the systems generally manage data on inventory, inspection records, planned and executed maintenance measures and are usually implemented with relational databases (SIB- Bauwerke et al.; ZEB Server; AASHTOWare; FHWA and PWA). Although these established solutions effectively support conventional IOM by organizing well-structured data, certain limitations persist. From a management perspective, current IOM activities remain heavily reliant on traditional methods and the restricted scope of data, such as visual bridge inspections. This reliance limits the awareness and utilization of advanced technologies. It is also consistent with the technological constraints observed in existing AMSs, where extending functionalities beyond established systems presents a significant challenge. These limitations necessitate advanced, integrated solutions capable of integrating diverse data sources and novel technologies.

Recognized as the feasible concept for enhancing the efficiency of managing IOM, digital twins for IOM are virtual replicas or digital representations of physical infrastructure assets such as bridges, roads, and utility systems (Gao et al., 2021). They differ from construction digital twins in several key aspects, particularly in terms of their features and emphasis on multi-source heterogeneous data integration and specialized service-oriented design for IOM purposes. Digital twins for IOM have transitioned from the rapid proliferation of data to the stage of data accumulation and further application. This implies that the focus has shifted from simply collecting and storing data to effectively utilizing accumulated data for advanced analytics, predictive modeling, and optimization in the context of operation and maintenance.

As for the operation and maintenance specialized service-oriented design, digital twins are developed to cater to the specific needs of engineers and decision-makers involved in asset management for transportation infrastructure (see Table 2). They offer specialized applications and services that align with the requirements of IOM activities, such as time, space and human resource conditions for periodical inspections and emergency management (Kaewunruen et al., 2021; Nicoletti et al., 2023; Mahmoodian et al., 2022; Yu et al., 2021). Another kind of digital twin is tailored to support tasks such as real-time monitoring, object detection, self-driving vehicle support, and workflow management (Gao et al., 2023; Dang et al., 2022; Wenner et al., 2021). For example, the presented digital twin by Marai et al. (2021) focuses on real-time monitoring using live streams for object detection and recognition of entities like people and cars. This emphasis on real-time data enables proactive decision-making, maintenance planning, and the support of emerging technologies like autonomous vehicles. To support the development of digital twins in infrastructure management, research investigates use cases through literature reviews, defining standardized terminology, use case scenarios, and specifying the dimensions and characteristics of the proposed digital twin (Al-Sehrawy et al., 2021).

Reviewing the literature on the digital twins for IOM, current research highlights the varying levels of conceptualization and application of digital twins in infrastructure management (shown in Table 2). The studies proposed digital twin development starting with framework definition. While a few studies primarily dealt with framework development at the conceptual level (Hakimi et al., 2023), most of the studies were based on the groundwork with the framework, followed by detailed case studies (Kaewunruen et al., 2021; Nicoletti et al., 2023; Mahmoodian et al., 2022; Yu et al., 2021; Dang et al., 2022; Marai et al., 2021) and even prototypical implementations (Gao et al., 2023; Wenner et al., 2021). Notably, current efforts prioritize frameworks for single asset types like bridges or tunnels. In terms of IOM activities, bridge inspection and Structural Health Monitoring (SHM) have garnered significant attention from diverse perspectives: integration of Artificial intelligence (AI) (Gao et al., 2023; Dang et al., 2022), leveraging IoT and sensors (Mahmoodian et al., 2022; Wenner et al., 2021), combining various engineering methods and perspectives (Kaewunruen et al., 2021; Nicoletti et al., 2023; Mahmoodian et al., 2022).

However, studies exploring digital twins for broader infrastructure

Table 1
Examples of AMS solutions for IOM across different countries.

Solution name	Country	Managed Asset	Managed data	Key Features
SIB-Bauwerke (SIB- Bauwerke et al.)	Germany	Bridge & Structure	Inventory, inspection & maintenance data	Plan and record inspection and maintenance, assess condition
IT-ZEB Server (ZEB Server)	Germany	Highway pavement	Road network, inspection data	Record assess condition
AASHTOWare Bridge Management (AASHTOWare)	USA	Bridge	Inventory, condition data & maintenance data	Plan, support and record inspection and maintenance
PMS-FHWA (FHWA and PWA; FHWA)	USA	Pavement	Road network, pavement type, traffic information, condition data	Record and assess condition, analyze performance
HAPMS (HAPMS 2024)	UK	Pavement	Road network, road type, condition data	Record condition, support maintenance

Table 2
Examples of current studies for infrastructure digital twin.

Study	Key Description	Methodology	Additional Finding
Hakimi et al. (2023) (Hakimi et al., 2023)	Define a conceptual digital twin framework that emphasizes data fusion and open BIM integration for efficient infrastructure management throughout the lifecycle.	Literature review, framework development	Identify gaps in data fusion and the potential of digital twin for civil infrastructure management
Nicoletti et al. (2023) (Nicoletti et al., 2023)	Define a digital twin model for bridge structural assessment that integrates a specific non-destructive test and operational modal analysis to update the digital twin model	Framework development, case study	Outline the advantage of using dynamic testing and numerical modeling in digital twins to evaluate real-world structural performance
Gao et al. (2023) (Gao et al., 2023)	Define an AIoT-informed digital twin framework for smart bridge operation and maintenance (e.g., SHM), integrating AI-based edge computing and low-cost cyber-physical communications.	Framework and prototype development	Outline the importance of physical-virtual communications resilience in digital twin implementations
Mahmoodian et al. (2022) (Mahmoodian et al., 2022)	Define a digital twin architecture for intelligent infrastructure management, practically for bridge SHM that integrates semantic modeling to organize data.	Framework development, case study	Outline the interoperability challenges of collecting dynamic external conditions and connecting them to virtual models
Yu et al. (2021) (Yu et al., 2021)	Define a digital twin-based decision analysis framework for the operation and maintenance of tunnels, combining COBie standard-based method for tunnel data and Semantic Web Technology to achieve data fusion	Framework development, case study	Demonstrating capabilities of Semantic Web Technologies for data fusion in digital twin implementation
Dang et al. (2021) (Dang et al., 2022)	Define a digital twin framework based on cloud computing and deep learning for bridge SHM	Framework development, case study	Outline the high accuracy of damage detection for real bridge structures using deep learning
Brucherseifer et al. (2021) (Brucherseifer et al., 2021)	Define a digital twin conceptual framework to improve the resilience of critical infrastructures that consists of three major components: virtual replicas, toolboxes, and control centers.	Requirement analysis, framework development	Outline the ability of the digital tools to improve infrastructure resilience
Marai et al. (2021) (Marai et al., 2021)	Define a Digital Twin Box integrating camera and IoTs to create a real-time digital twin of road asset, and demonstrate with experiments	Concept definition, experimental study	Demonstrate the effectiveness of Digital Twin Box in creating a digital twin of roads, object detection and recognition accuracy
Keawunruen et al. (2021) (Kaewunruen et al., 2021)	Define a digital twin framework combining BIM and bridge risk inspection model for bridge inspections, and demonstrate digital twin application for three predefined risk types	Framework definition, case study	Outline the importance of applying BIM to bridge structural monitoring
Wenner et al. (2021) (Wenner et al., 2021)	Implement a prototypical digital twin as a smart bridge (e.g., SHM) with a focus on monitoring structural condition through sensors,	Concept definition, prototype development	Outline the importance of data fusion and aggregation processes for assessing bridge condition

assets (such as smart city (Hakimi et al., 2023) or critical infrastructures (Brucherseifer et al., 2021)) often lack in-depth investigation into specific operation and maintenance demands and detailed framework specifications. Specifically, in the context of linear infrastructures, such as bridges and roads, the characteristics of these assets focusing on effective asset management have not been adequately considered (Hakimi et al., 2023). Although mature concepts for infrastructure monitoring using digital twins combined with BIM and geospatial data have been proposed, the focus has often been on modeling the physical structure rather than addressing broader data integration and specialized service requirements (Brucherseifer et al., 2021). Furthermore, while certain road infrastructure digital twins have been developed for real-time monitoring and object detection, there remains a need to define clear workflow processes and integrate them with practical demands, such as supporting self-driving vehicles (Marai et al., 2021).

Furthermore, digital twins for construction and infrastructure reveal significant disparities in technical maturity and application development (Opoku et al., 2021; Gao et al., 2021). The absence of an overall concept for digital twins for IOM with technical solutions is evident. The development of digital twins for IOM needs to consider three essential demands: 1) integration mechanisms for existing information systems like bridge or pavement management systems and BIM systems; 2) IOM-oriented digital twin functions and interface designs aligned with practical demands; and 3) automation mechanisms that enable digital twin processes.

2.3. Data integration towards digital twin for infrastructure operation and maintenance

For service-oriented digital twins, data integration is essential to provide value-added data to support comprehensive management functions efficiently and reliably. In particular for infrastructure operation and maintenance, the current research recognizes the importance of data fusion to develop digital twins (Yu et al., 2021; Wenner et al., 2021; Hakimi et al., 2023). From the technical perspective, data integration as the broader context of data fusion plays a crucial role in the implementation of digital twins integrating novel technologies. It involves the process of retrieving data from various sources and combining the data to provide a unified view of information (Lenzerini et al., 2002; Bleiholder and Naumann, 2009).

Considering the transition from BIM to digital twin in construction, the established standards such as ISO 55000ff (ISO 55000, 2014; ISO

55001, 2014), ISO 19650-1 (ISO 19650-1, 2018) provide a high-level concept of data management to achieve federated data with a Common Data Environment (CDE). Further BIM-related standards provide technical methods facing various aspects, such as ISO 29481-1 (ISO 29481-1, 2016) to specify information delivery, ISO 21597-1 (ISO 21597, 2020) to introduce information containers for information delivery using Semantic Web Technology (SWT). These standards provide a comprehensive framework for managing asset data throughout the lifecycle, ensuring consistency and interoperability across various systems and stakeholders. Previous research has also investigated, that open BIM (such as IFC) provides a crucial backbone both to present physical environment and to support data integration in digital twin (Yan et al., 2022). Given the advantages of BIM in facilitating data integration and information sharing (Kivits and Furneaux, 2013; Costin et al., 2018), these standards should be adopted within the digital twin environment.

A further promising technical approach for data integration in digital twin is the SWT. Boje et al. (2020) presented the benefits of a fully semantic data environment of construction digital twin, which enables the design and construction supply chain to leverage web-based linked data. For infrastructure operation and maintenance, SWT-based information containers were used to collect, retrieve, and update data from the AMS system into a CDE-similar platform (Liu et al., 2022; Hagedorn et al., 2023). Linking heterogenous data to provide a uniform view of information for bridge and pavement inspection was demonstrated using ontological datasets. For the operation and maintenance of tunnels and supporting decisions efficiently, digital twin has been developed using ontology and SWT capabilities are demonstrated for data integration (Yu et al., 2021).

Despite various efforts in research, achieving data integration for digital twin in IOM remains several challenges. From the management and technical standpoint, the adoption of available international standards leads to broader acceptance. Still, the integration of different levels of standards, such as the high-level concept for asset management and CDE, into digital twins is a challenge needs to be addressed. Another challenge is the complexity of integrating data from heterogeneous sources, such as sensor networks, measured data, and legacy systems for inventory data. Research which also mentioned the importance of data integration (Yu et al., 2021; Wenner et al., 2021; Hakimi et al., 2023), mostly lacks generic technical methods for complex multi-asset data integration. In addition, research (Liu et al., 2022) focusing on the technical method to link heterogeneous data lacks mostly clear procedures in the context of data processing to ensure data quality and consistency, which is a further critical challenge needs to be addressed.

Therefore, the digital twin development needs to address the challenges of data integration. Especially, for the provision of specialized management services to continuously support infrastructure operation and maintenance, an overall digital twin concept for multi assets is required, that combines the technical approach to data integration with the needs of infrastructure practices.

It should be noted that while digital twins for structure assets like airports (Keskin et al., 2022) or buildings (Lu et al., 2020) have received more detailed system design, various use case scenarios, and comprehensive data, the development of digital twins for linear infrastructure assets remains challenging and largely unexplored. Actually, operation and maintenance of infrastructure assets such as roads and bridges is more complex and dynamic compared to buildings. They are subject to various external factors, such as weather conditions, heavy loads, and traffic patterns. Digital twins allow for a detailed understanding of the behavior, performance, and deterioration patterns of these assets, enabling proactive maintenance and efficient operation. The merging of different assets, such as bridges and roads, and the consideration of key infrastructure features pose significant challenges that require further investigation.

3. Methodology

This study employs an exploratory research methodological approach, i.e., design science research (DSR), to analyze the problems and investigate the potential solutions to develop knowledge and contribute to the body of theory in IOM. The adoption of the DSR paradigm ensures rigor across the research steps of problem identification, artifact development, demonstration, and validation (Patacas et al., 2020). In this study, DSR guides the overall development of the proposed framework for its ability to embrace 'artifact' creation and improve it through its iterations (Peffers et al., 2007). The research methodology is illustrated in Fig. 1.

As suggested by Peffers et al. (2007), the entry point for this study is problem identification. The challenges in IOM were captured by a systematic literature review and a series of industrial engagement activities, e.g., observations and interviews. Meanwhile, current digital techniques and solutions were explored, and the emerging technological environment was clarified. The challenges and supporting technical conditions were explained in the Introduction section. In the second stage, the objectives of the digital twin-enabled solution for IOM were defined based on current research focus and industrial practices, and this is a problem-oriented and hypothesis-based proposal. The first interaction with industry experts aimed to capture the requirements of the framework, which was achieved by conducting semi-structured interviews (see Table 3). Under the problem-oriented objectives and industrial requirements presented in the Requirement Analysis section, the framework was designed and developed iteratively. The prototype was developed and tested in a technical demonstration using two use cases from road and bridge projects in the fourth stage. In the evaluation stage, the functionality and usability were first evaluated through existing criteria, e.g., Erri Pradeep et al. (2021). Then a structured interview with experts (see Table 4) was conducted, and 5 industrial experts were invited to evaluate the proposed framework and prototype from both technical and managerial perspectives. Within the research process, there are interactions between stages. Especially the development of the framework is iterative, both inter-stage and cross-stage.

4. Requirement analysis of SoDT-IOM

4.1. Subdivision of the original DT component for IOM

Following the methodology, this section describes the requirements analysis from stage three. The development of SoDT-IOM is based on the original digital twin approach. Four primary DT components are first identified based on the pieces of literature on digital twins in the construction industry: ***physical environment***, ***physical and virtual connections***, ***virtual environment,*** and ***data repository***. For the achievement of supporting services and performing data integration from multiple domains for IOM, the primary components are divided into detailed levels in Table 5. The detailed components of the ***virtual environment***: ***visualization service***, ***digital Twin service***, and ***data management service*** provide the main functionalities for the realization of the digital twin. The subdivided SoDT-IOM components are presented to the experts in interviews for requirements analysis.

4.2. Practice-oriented digital twin requirements for IOM

The five semi-structured interviews are conducted with experts from IOM engineering to construction-specific software development (see Table 3). In order to identify the practice demands of data management in IOM, interviews began with general questions about satisfaction with data management in IOM practice activities and its issues. In addition, the experts were also asked to assess the use of existing data management systems. The key statements are summarized and categorized according to management and technology aspects, in which the identified issues are classified in Table 6. The digital twin approach is then

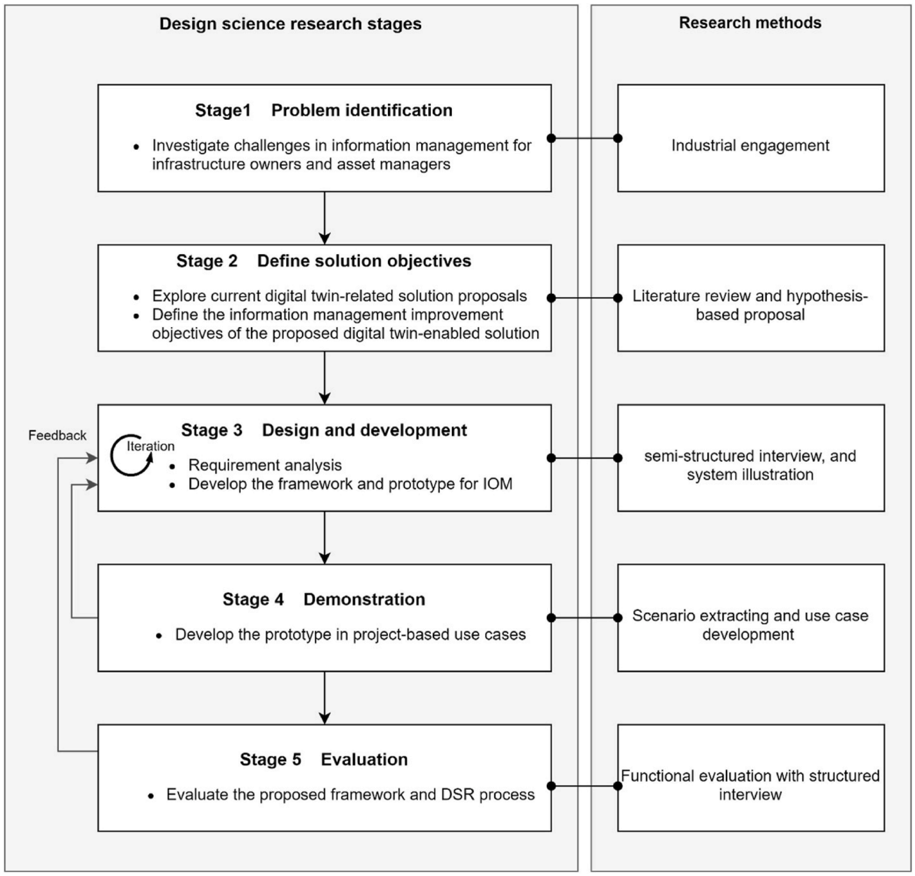

Fig. 1. Methodology for development SoDT-IOM.

Table 3
Requirements analysis: profile of participants.

Expert code	Background	Organization	Role/Activity	Experience (years)
R1	Civil engineer	Highway authority	Asset manager for the highway operation and maintenance	29
R2	Civil engineer	Engineering agency for infrastructure	Consultant and digital solution supplier for infrastructure management	20
R3	Civil engineer	Engineering agency for infrastructure	Consultant for engineering performance in pavement management	8
R4	Civil engineer	Engineering transfer institute	Coordinator of product development on research-based digital solutions in construction	4
R5	Applied computer scientist	Engineering transfer institute	Software developer on research-based solutions for infrastructure construction management	3

Table 4
Framework evaluation: profile of participants.

Expert code	Background	Organization	Role/Activity	Experience (years)
E1	Civil engineer	Infrastructure construction company	Contractor for infrastructure construction projects	12
E2	Civil engineer	Infrastructure construction company	Contractor for infrastructure construction projects	7
E3	Civil engineer	Airport authority	BIM manager from asset owner for the airport construction, operation, and maintenance	7
E4	Civil engineer	Engineering agency for infrastructure	Consultant for engineering performance in pavement and bridge management	5
E5	Civil engineer	Engineering agency for infrastructure	Construction safety manager of municipal infrastructure projects	3

presented with the descriptions of the components identified through the literature review. The experts' assessment of digital twin and the requirements for the components are documented and concluded for the development of SoDT-IOM.

From the management aspect of the existing IOM data management in practice, unequal worker skills are a major human factor affecting data management. It hinders the use of novel technologies such as BIM or other digital systems. It leads also then to part issues of data management, such as paper-based documentation, inconsistent documents,

Table 5
SoDT-IOM components based on literature reviews.

Components based on literature reviews	Components for SoDT-IOM		Component relevance for data integration and service support
	Primary level	Detailed level	
Physical entity, environment, physical processes acting (Jones et al., 2020; Qi et al., 2021) **Building, IoT devices, and construction projects** (Deng et al., 2021; Jiang et al., 2021)	Physical environment	Infrastructure entity, IoT devices, etc.	Prerequisite: IOM service support & Multi-domain data integration
Physical-to-virtual data connection (Jones et al., 2020; Qi et al., 2021) **Data captured by sensors, laser scanners, cameras, etc. to virtual parts** (Jones et al., 2020; Qi et al., 2021)	Physical and virtual connections	P–V connection for data transmission	Prerequisite: IOM service support & Multi-domain data integration
Virtual-to-physical data connection (Jones et al., 2020; Qi et al., 2021)		V–P connection for data transmission	
Virtual entity and virtual environment (Jones et al., 2020; Qi et al., 2021)	Virtual environment	Visualization service: functions for visualizing virtual entities & diverse data	IOM service support
Virtual processes acting or services (Jones et al., 2020; Qi et al., 2021) (Deng et al., 2021; Jiang et al., 2021)		Digital twin service: functions for IOM-associated use cases	
Connections between data, service, and virtual entities (Jones et al., 2020; Qi et al., 2021) (Deng et al., 2021; Jiang et al., 2021)		Data management service: functions for data transmission and interaction with digital twin service	Multi-domain data integration
Cloud-based data center (Jones et al., 2020; Qi et al., 2021) (Deng et al., 2021; Jiang et al., 2021)	Data Repository	Centralized data storage: asset data, measurement data, etc.	Foundation: IOM service support & Multi-domain data integration

etc. as shown in Table 6. Furthermore, qualified data management also misses a clear definition of the responsibility and requirements of information delivery. On the technology aspect, the reality in practice shows that data is mostly heterogeneous and recorded in separate systems. The individually developed systems are not linked to each other. Lack of standardized methods, data exchange and integration need individual solutions for different systems. Therefore, it is difficult to efficiently provide comprehensive data to the IOM activities.

The experts' assessment of the digital twin approach has shown that its adoption is expected to bring various improvements to IOM activities and data management (Table 6 – SoDT-IOM). Increasing automation and optimization for IOM is most often associated with the use of the digital twin. Enhanced automation should also include data delivery and processing in data management to improve data sufficiency and transparency. For using digital twin, virtual assets are considered as another asset type that also needs to be managed in IOM. Given the wide range of infrastructure asset data, virtual assets should aggregate information in a reasonable way that mirrors physical assets.

Table 6
Interview summary for general IOM and overview SoDT-IOM.[a]

Aspects		Summary of interviewees' responses
IOM	Management	The unequal skills of workers: R1: difficulties in creation, modifying or reusing comprehensive information models during the life cycle, especially taking BIM models into account R3: different levels of acceptance and maturity in the use of digital systems or solutions Lack of qualified data management: R2: delayed and inadequate information delivery without clear responsibilities and requirements R2: inadequate historical data R3: manual, paper-based documentation R3: inconsistent level of detail of the delivered documents
	Technology	Heterogeneous information with isolated systems: R2: separate bridge and pavement management systems R3: individual-developed und hosted data management systems from traffic authorities R4: distributed data silos and heterogeneous information missing standardized data exchange methods R4: discontinuous data integration using individual solutions
SoDT-IOM	Improvement of IOM: R1 & R2 & R3 & R4: increasing optimization and automation of IOM activities Improvement of data management: R2: timely and sufficient information transfer R3: increasing data transparency R5: automated process of information delivery General aspect: R1 & R2: management of two types of assets: physical and virtual assets. R1 & R2 & R3: the virtual asset should be a reasonable information aggregation considering the soft- & hardware abilities.	

[a] R1-R5 represent five industrial experts (see Table 3).

In addition, the experts mentioned that the components of SoDT-IOM should meet IOM-relevant demand to enable the improvement of day-to-day service support. The essential requirements from experts mainly concern DT components related to data integration and service support. These are summarized below:

IOM service support**:** The level of detail in the visualization of the virtual asset information depends on different aspects: the shape of the physical asset (e.g., road vs. bridge), the information type (e.g., BIM model vs. images), the IOM activities (e.g., normal inspection vs. renewal). Therefore, the service should provide several levels of visualization to show the digital environment, from an overview to a particular asset. In addition, the DT needs to provide service from the conventional IOM activities (e.g., regular inspection, maintenance), to advanced services such as 1) real-time monitoring in different fields (e.g., structural health, maintenance activity, and traffic); 2) forecasts of inspection or maintenance. The SoDT functionality should basically be identified through use case definition based on the IOM activities. The definition includes the scope, the intended IoT devices, and the related working process.

Data integration: The SoDT-IOM functionality should provide a data integration mechanism to effectively export and timely update the comprehensive data to support the digital twin service, as the interview result required. Linking relevant data from different sources, maintaining the linked data, and automating the data processing at an achievable level of detail are important for leveraging integrated data to provide service for IOM.

5. Development of SoDT-IOM

5.1. Overall framework

Based on the requirement analysis of the digital twin form the IOM practice, a framework of SoDT-IOM is developed as shown in Fig. 2. To achieve the essential requirements, the framework provides a data integration mechanism from multiple domains and functionalities for IOM service support with an automation mechanism for the IOM processes and interface design. It includes primary components, i.e., ***Physical Environment, Physical and Virtual Connections and Enhanced Virtual Environment,*** which form the prerequisites for the SoDT-IOM framework. As shown in Fig. 2, all components can be sorted into three parts related to data integration and service support:

1. Prerequisite components: given the IOM activities of the built entities using IoT devices retrofitted or newly installed are mostly based on the practical demands. The physical and virtual environment and bilateral relationships provide preconditions for the intended IOM service support and the way of data transmission.
2. Multi-domain data integration components: the ***Hybrid Data Repository*** provides relevant data required for the service support, and the technical structure of the repository is crucial for developing the data integration mechanism. The ***Data Management Service*** in the ***Enhanced Virtual Environment*** provides mechanisms for linking and processing heterogeneous data from multiple domains.
3. IOM service-oriented components within ***Enhanced Virtual Environment***: in addition to ***Data Management service,*** the components ***Visualization Service with User Interface*** and ***Digital Twin Service*** provide relevant functionalities to enable the IOM service-oriented digital twin. On the central point, the ***Digital Twin Service*** considers different IOM activity types for supporting advanced services for IOM activities. In this component, the service workflow combined with the dataflow is illustrated. The requirements of SoDT-IOM from experts for more automation of IOM activities, especially on the automation of data management process, e.g., data verification, for efficient and timely data management, are also considered in the component design.

5.2. Prerequisite components: physical environment and bidirectional connection

5.2.1. Physical environment

In the physical environment, two types of entities need to be considered in the framework. One includes a bundle of built infrastructure assets (e.g., bridge, road, tunnel). These are the actual entities that need to be observed. The other one includes the IoT devices (e.g., sensors, RGB cameras) that are used to track the physical condition or act as physical actuators to respond to commands from the virtual environment. In the framework, the permanently installed IoT devices are considered to support the IOM activities.

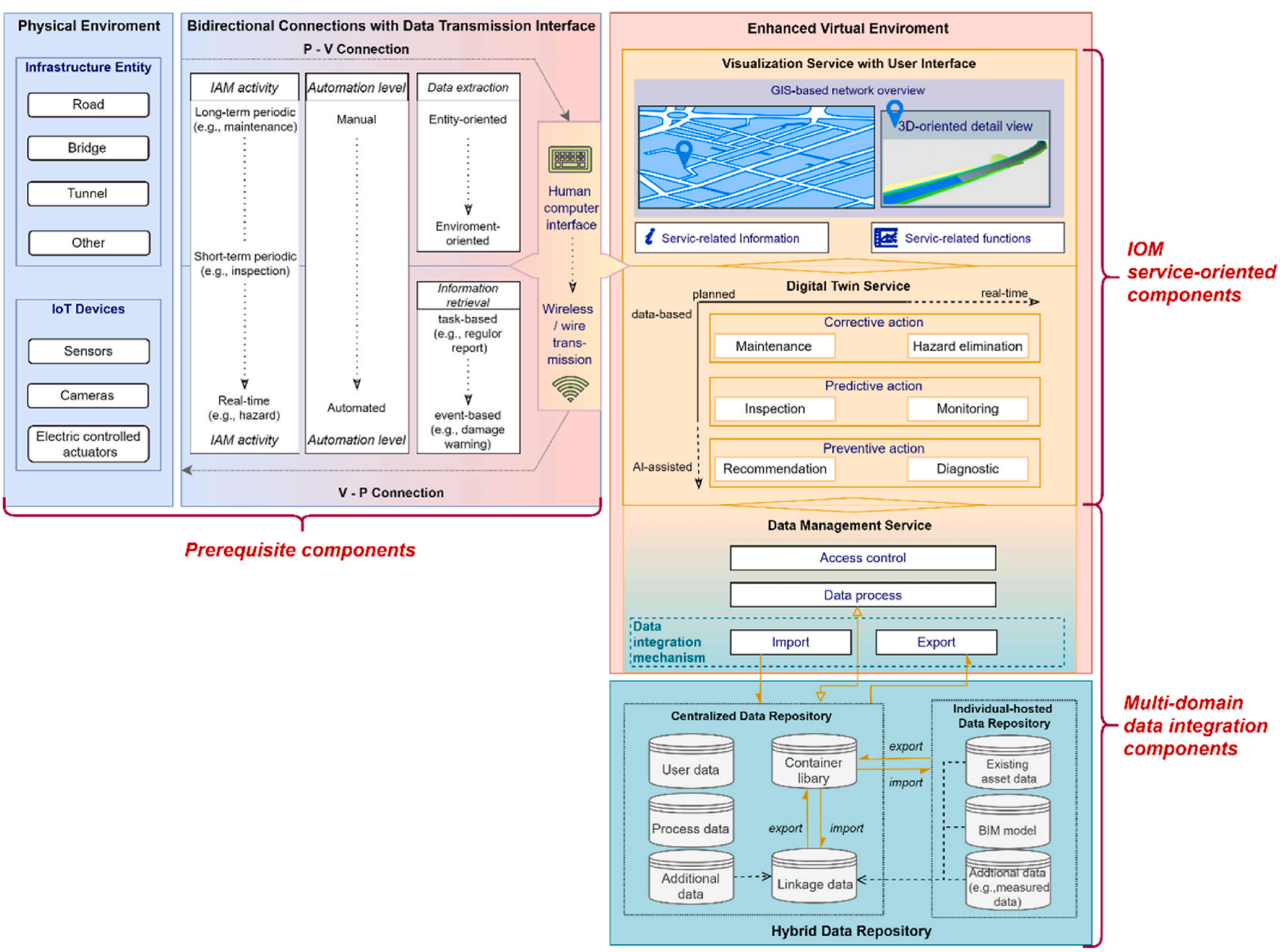

Fig. 2. SoDT-IOM Framework with specification considering the interview outcomes.

5.2.2. Bidirectional connection with data transmission interface

In the overall framework, the connections between physical and virtual environments are summarized, the two directions still must be observed separately in the whole digital twin workflow. The connection from the physical to the virtual environment (P–V connection) is mainly caused by a detected changing of the physical assets or the environment. The connection accompanies the transmission process from the data extraction of the physical environment to the data integration into the digital environment. The automated level of the transmission process depends on the type and cause of the data to be transmitted. While the data extraction and transfer by sensors can be realized fully automated, manual data collection and integration of some human activities (e.g., maintenance) still need to be considered. In the SoDT-IOM, this connection is to be realized on a semi-automated level up to a fully automated level using IoT. The connection from the virtual to the physical environment (V–P connection) is to deliver the information processed through a digital twin service, which results in a change of the physical environment. The executed activities and the changed state of the physical environment should also be recorded in the virtual environment in the last step. Compared with the P–V connection, the automation of V–P connection is rarely possible for most IOM activities.

Considering the different levels of automated connection for data transmission, the interface between P and V provides two opportunities for receiving and sending the data. For manual data transmission, the interface provides download and upload possibilities for humans. With an automated data transmission, e.g., connecting the IoT devices, the interface embeds common communication standards, such as Message Queuing Telemetry Transport (MQTT) (IBM and Eurotech, 2016).

5.3. Multi-domain data integration components: hybrid data repository

As an essential requirement, information of the infrastructure assets from multiple data sources must be seamlessly generated, stored, and updated to realize the DT service. For this reason, the data repository of SoDT-IOM includes an individually-hosted and a centralized part of data storage, which provides a hybrid system for 1.) enabling the Common Data Environment (CDE) conceptualized by (ISO 19650-1, 2018) and 2.) further using the existing information management systems distributed into different asset owners. Both data repositories must be connected. The data transfer between the centralized data repository and individually hosted data repository is operated by the data management service considering the associated digital twin process. During the individually-hosted data repository provides the required information at the beginning of the digital twin service process, the centralized data repository is used to store the data during the service process. At the end of the service process, the individually hosted data repository is updated. Therefore, both parts of data are kept in sync to ensure data consistency.

5.3.1. Centralized data repository for integrated multi-domain data

The centralized data repository stores and manages a variety of data: the process data (e.g., time of a physical change), the observation data (e.g., data measured by IoT devices), the asset data (e.g., the asset observed by IoT devices), the links between the observation data and asset data, etc. Considering the comprehensive data required for an IOM activity, information should be provided in a data package with linked information using the information containers according to (ISO 21597, 2020). This standardized information container is based on SWT, that is encouraging for collection and linking of heterogeneous data. A container library is then defined as a storage for the information containers. The predefined container templates can be saved with the content of the data definition (e.g., data type, data source, etc.) required for the related digital twin service. Within the container, information or documents can be collected and linked with each other. A linkage mechanism operates based on storing "linkage data". It includes links between various data among the data sources and supports the interconnection of information from the multiple domains distributed in the individually hosted data repositories. Furthermore, the crucial information of the process steps is recorded in an additional data source, for instance, in the case of hazard elimination, the tasks preformed may be essential to the investigation and these require therefore a traceable process log.

5.3.2. Individually-hosted data repository and the connection with the centralized data repository

The individually hosted data repository considers mostly the databases of available data management systems organized by different traffic authorities. The distributed responsibility with different data ownership and privacy can complicate accessing, using, and updating data during collaboration. To ensure the SoDT-IOM, data processing must response timely, which requires to facilitate the data management process. Therefore, the centralized data repository is used as the primary data source of truth during the digital twin service, ensuring efficient, synchronous data management.

Keeping the data consistency between both data repositories, the distributed, heterogeneous data is exported from individually-hosted data repository into the information container at the begin of digital twin service. The linkage data is used to extract and update relevant data about inventory, condition etc. from the individually hosted data sources, and link these data within an information container. The specified containers are managed in the container library. For a certain DT-service, the predefined container template can be fulfilled with existing information from the distributed databases. For data integration, the definition of the required information and the related target data source are defined in the container.

5.3.3. Mapping approach for linkage mechanism

To achieve data integration, a reliable mapping approach is the backbone for selecting and unifying data from different data sources (Lenzerini et al., 2002; Bleiholder and Naumann, 2009). Regarding infrastructure, in addition to selecting and unifying data to provide a comprehensive view to support the intended activities, it is crucial to consider the interrelations among the data, incorporating both the topological connections between physical assets and asset elements, and the semantic associations between assets and additional measured or descriptive data. This ensures that the unified data retains pertinent contextual meaning.

To realize the selection of data and linking them considering the relevant contextual relationships, a linkage mechanism for mapping is essential. Given the nature of infrastructure assets and the established systems like bridge classification system ASB-ING (BAST, 2013), an object-centric mapping approach is deemed the most feasible. Theoretically, three primary types of linkage data must be considered: (1) the association of data with their originating data source, which is usually realized based on predefined classification systems; (2) the topological alignment of diverse data representing the asset at the object or element level; and (3) the detailed specification of an asset or its constituent elements, including data on condition record and planned maintenance measures.

To make the mapping process more effective, we propose utilizing SWT, specifically ontology. This decision is not only rooted in its advantages for enhancing data interoperability but also grounded in the foundational efforts already undertaken. As depicted in Fig. 3, the theoretically defined linkage data types are illustrated. For linkage data type (1), the DCAT ontology (ontology for describing data in a catalog) (W3C and Data Catalog Vocabulary, 2022) is suggested for representing the origin data source. For type (2), semantic descriptions of topological structures can be facilitated through the utilization of the BOT ontology (ontology for building topology) (Rasmussen et al., 2021). Likewise, for type (3), the EUROTL ontology (ontology of European road object types) (INTERLINK) presents a viable solution for recording conditions or activities. Nonetheless, comprehensive research is necessary for the full

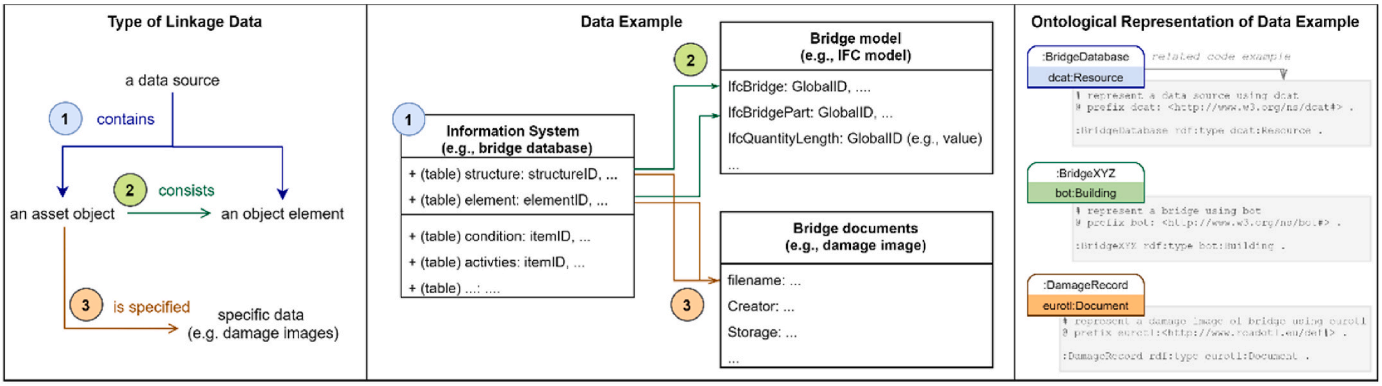

Fig. 3. Categories of the linkage data.

development of the mapping approach in the future. Especially, it is crucial to explore the potential reuse of existing ontologies in the mapping approach.

5.3.4. Technical structure for both data repositories

Given various types of data and historically developed data management systems, the different database types should be used to implement the data repository. It can be summarized into two major types: SQL (structure query language) database and NoSQL database (e.g., BIM Server (Beetz et al., 2010)). Considering the advantages and the existing statutes of the different types of databases, the recommendation of the technical implementation can be realized as shown in Fig. 4. SQL Database is mostly historically developed with certain data scope in the strict structure for alphanumerical information. NoSQL Database concludes other types of databases, that manage data considering the current development of BIM and Linked Building Data, which is not limited to the following three kinds:

- A key-value database is feasible for managing different types of documents. The well-known BIM Server is one realized implementation to manage the BIM model.
- A graph database is feasible for managing ontological data, which is based on triple form and does not have a strict table structure (Angles and Gutierrez, 2008).
- A blockchain database is suitable for transaction data of automated processes using decentralized IoT techniques (Li et al., 2021). They can provide traceability and irreversible modification of data transactions, which can be essential for the use case “hazard elimination”.

5.4. IOM service-oriented components within Enhanced Virtual Environment

The virtual environment contains three components: ***Digital Twin Service***, ***Data Management Service*** and ***User Interface*** for visualization. The entire virtual environment operates under the principle of a common data environment with the connection of hybrid data repository, which enables the data integration to support data for IOM service. The ***Digital Twin Service*** provides functions to manage users, IOM activity as a project with its workflow. An IOM activity is clarified as a service process with data exchange between the physical and virtual environments. ***Data Management Service*** provides the functionalities to enable data integration and processing by authorized stakeholders. The ***User Interface*** represents the information of the appropriate digital twin service and enables user interaction in the virtual environment. The data during an IOM activity is provided through information containers in the centralized data repository. Through the data management service, the individual-hosted data repository is connected to provide data at the begin of an activity project and to update the data at the end of the project.

5.4.1. IOM service-oriented visualization with user interface

The user interface represents relevant information about the virtual asset and provides use the functionality of the appropriate digital twin service. To facilitate the use of SoDT-IOM in the transportation infrastructure network, the representation of infrastructure entities is on a scalable map based on GIS. Further information of the assets, (e.g., bridge or road sections) can be selected and viewed in detail combined with 3D models if it is available. The detail information of the selected entity can also be used to define or perform a particular service further. In addition, the user interface provides functionality for user management such as registration and login to enable authorized user interaction in the SoDT-IOM.

5.4.2. IOM service-oriented module design of digital twin service

As a precondition, the IOM activities supported by the SoDT-IOM should be defined first for identifying its relevant content and process, that need to be executed through functionality driven by digital twin service. Based on the interview results, IOM activities can be listed from planned to real-time, from data-based to AI-assisted activities with increased automation levels. For an asset management relevant

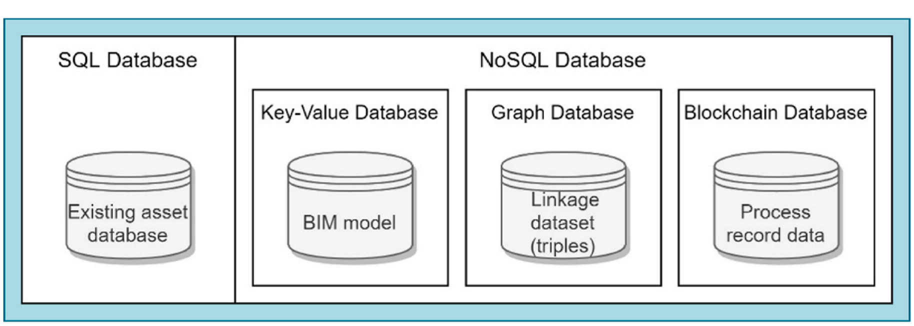

Fig. 4. Categories of the different database types for data repository.

categorization of the activities, three action types are defined considering ISO 55000 (ISO 55000, 2014). These are corrective action (e.g., maintenance), predictive action (e.g., inspection), and preventive action (e.g., diagnostic or forecast) as shown in Fig. 2. Each action contains tasks in the related environment and data exchange between the physical and virtual environments. These are defined as a service workflow to clarify the SoDT-IOM process for more automation.

To explain the service workflow of the three actions, a streamlined sequence diagram illustrates the interaction between both environments with data exchange shown in Fig. 5. The user, which has the role of "asset manager" or "asset engineer" in practice, is defined as an actor for operating the system through the user interface in the virtual environment. Before starting a service on concrete physical entities, the actor must define the activity by specifying relevant content with the required conditions (e.g., the periodic duration for monitoring). During the service execution, the main difference between the action types is the order of tasks between the physical and digital environments. While the corrective and predictive actions execute the task in the physical environment directly after retrieving information in the virtual environment (Fig. 5 – a), the preventive action executes mainly an extensive information analysis in the virtual environment, then follows further actions after decision-making by the user (Fig. 5 – b).

To support the aforementioned services, the purposed functionalities of digital twin service are illustrated with a use case diagram shown in Fig. 6. These are limited only to essential functions with **user management module**, **project management module** and **workflow management module** to specify and execute a service for supporting IOM. The participants in the digital environment are defined as "user (virtual environment)", which is related to the user from the sequence diagram in Fig. 5. The participants or IoT devices for conducting tasks in the physical environments and transferring data are defined both as "actor (physical environment)". The interaction between the user (virtual environment), the actor (physical environment), and the digital twin service are realized through the ***Visualization Service with User Interface*** and ***Connections with Data Transmission Interface***. In addition, interaction with ***Data Management Service*** is required to enable user access control and data processing. The interaction between these two services is specified in the data management service.

The **user management module** shown in Fig. 6 provides functions for user registration and login. A registered user must be assigned a concrete role through the function "assign role" for authorized operation in further functions (e.g., define service). Each role is associated with specific rights to perform tasks through the digital twin service. Therefore, essential roles must be defined for the digital twin service with the corresponding right, such as "system administrator" for operating and maintaining the SoDT-IOM system and "project manager" embodies the asset engineers, which is similar to a BIM manager for managing and conducting a service.

The **project management module** provides functions to define a particular service using a predefined service type considering the different actions. In addition to the "set service type", service information, such as the existing information of the intended service entity, and the required data of the service must be specified using a container template by the function "specify service container". The service container is stored in the centralized data repository and is going to be fulfilled or updated with information via the data management service by running the digital twin service. The service entity is related to the infrastructure entity in the physical environment. The service conditions to be set depend on the selected service type, which includes the condition parameters for each service. For setting service actors, the technical possibility of the data exchange must be considered. If a task can only be performed by humans, the actor must be registered as a user with the associated access right to manually download and upload documents. Alternatively, defining the IoT devices as actors can ensure an automated data transfer and data processing by clear-defined information requirements and well-established connections. The service actor has an important impact on functions of workflow management.

The **workflow management module** provides functions for performing a particular service on the selected entities, once all settings of the service are specified. The authorized stakeholders and the associated devices are enabled to interact with the SoDT-IOM by executing tasks, transmission and processing information/data. Based on the foreseen actor type in the physical environment, the data extraction and retrieval can be conducted in two manners both manually and automated. In the virtual environment, the actor can request, view, and confirm the service task, and the related data delivered from the physical environment. To ensure the use, project, and workflow management functions, data handling supported by data management service is necessary.

5.4.3. Multi-domain data integration component: data management service

The holistic data management service provides to align, process and update the linked heterogeneous data in the hybrid data repository for supporting the digital twin service based on the CDE approach. To ensure high data availability, reliability, and sustainability, managing authorized access for delivering and verifying information is the basis of the digital twin services. Three essential parts of data management service are provided as semi-automated processes with the interaction of digital twin service. There are (a) exporting existing data from the distributed data repository into the centralized data repository using a container template and integrating; (b) utilizing and updating the container content during digital twin service with an integrated data validation process; (c) importing the up-to-date data from the container back after a digital twin service or on demand of asset management. The process of export (a) and import (c) illustrate the relevant data integration mechanism.

In addition to managing the authorized access, the management of information container status is considered in the processes. Each container and the documents of the container contain meta-information (e.g., unique name, version, revision, status), which is used for identifying and recording the container content modification. The container goes through three statuses (see Fig. 7) determined by data verification in the service workflow, which is linked to increasing content. The three status addresses increased container content. The accessibility and verifiability of container content depend on its status and the definition of user role. A container with the status "working in progress", which contains data requirements, is created by asset management as a user (virtual environment) and can be provided to an actor (physical environment) for executing the physical tasks. Once the extracted data is delivered and successfully verified, the container changes its status to "shared", ensuring visibility to all involved users of the digital twin service. In case of confirming the end of a service, or updating the information in the hybrid data repository, the container status is changed to "published". The container content cannot be changed anymore, the relevant information is then imported into the individually hosted data repository.

To specify the data management service and the interactions with digital twin service, a process diagram with BPMN is defined in Fig. 7. In the process, the functions of workflow management of the digital twin service (see Fig. 6) refer to high-level tasks executed by the appropriate actors. The data management workflow combined with access control and container status management is illustrated as tasks in data management service. The container status is shown with the related files. The services (a) and (c) can be fully automatic based on the predefinition of digital twin service and the linkage datasets of the virtual entity data. In the scope of "define service" of the digital twin service, the service (a) of information export for the intended entity and service types is illustrated as four steps from "E1" to "E4" in the data management service process. Trough the predefined container template "E1", the information of the physical entity is stored in the container in step "E2". In step "E3", the links related to the existing information of the physical entity can then be imported from the database of linkage data into the container. At last, the result of this service is a prepared "service container" stored in

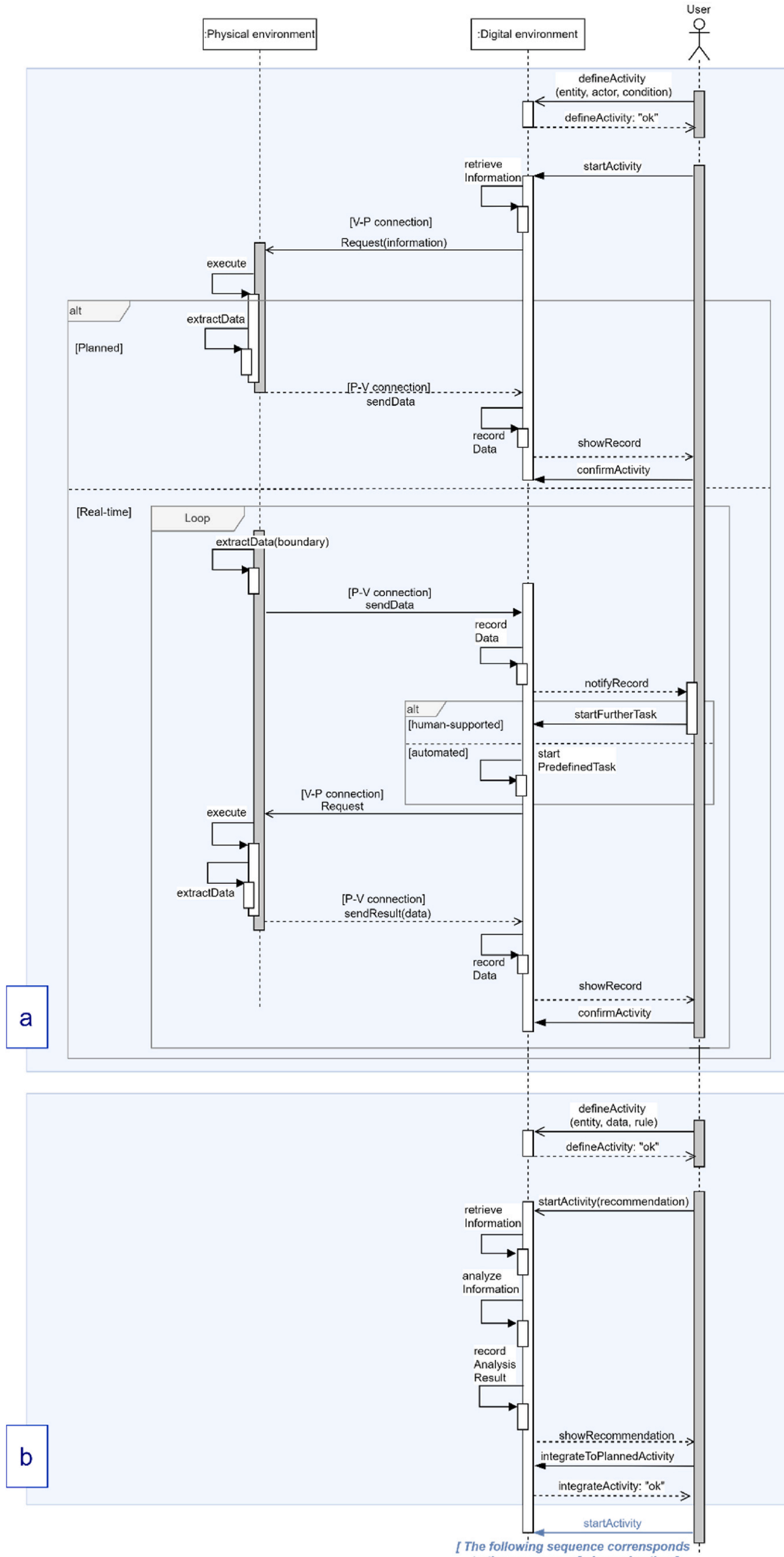

Fig. 5. Sequence diagram of three actions for IOM activity; a. sequence for corrective and predictive action; b. sequence for preventive action.

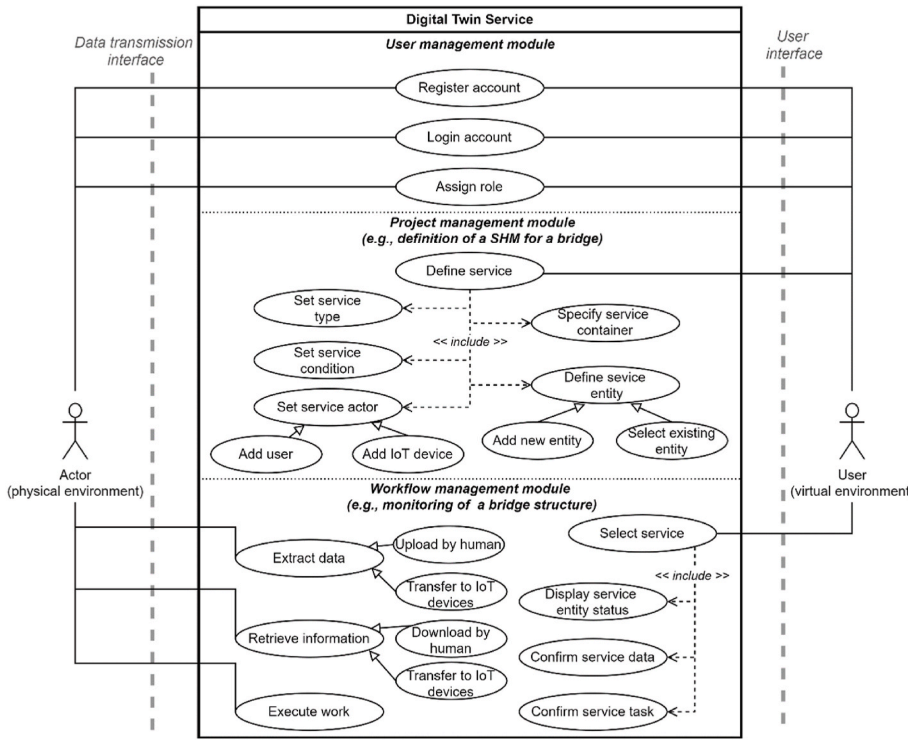

Fig. 6. Use case diagram of main digital twin service functions.

the centralized data repository for the digital twin service later in "E4".

The service (b) is realized as a semi-automated process based on the two different types of actors (physical environment). For providing the service in run-time, information exchange and update between physical and virtual environments are illustrated as process steps between "select service" and "display service entity status". The data-checking process differs in the two types of physical actors (IoT device and human actor). The step "control user access (advanced)" determines whether the data is sent by an IoT device or sent manually by a person. By IoT device, the required data format, content constraints, execution periodicity and classification with the related virtual IoT entity are preset for the data transfer. The data checking can then be fully automated unless damage has occurred to the IoT device for which maintenance of the IoT device is required. Data submitted by a person is mostly collected and edited manually, which often needs an advanced checking on the content in view of the accuracy, completeness and relevance. This data can first be automatically checked against the defined requirements (e.g., format, constraints). Qualified data checking requires confirmation by an authorized user (virtual environment) based on the pre-checked result. After a successful check, the container is revised with new data.

To import the information using service (c), the digital twin task "confirm service task" can be executed by the user (virtual environment). The interactive data management service follows three steps. With changing the status, the content of the container is fixed in the centralized data repository in step "I1". The container links are stored in the database for linkage dataset for further use in step "I2". The relevant information, which needs to be stored in the individually hosted data repository is then integrated into the last step "I3".

The data management service provides flexible and seamless data creation and collection for each digital twin service by reusing linked information and automatically updating new information. The information requirements defined for each digital twin service enable machine-supported data checking that provides the basis for automatic data handling. Using information containers in the centralized data repository ensures process efficiency during the digital twin service. The data export and integration between the hybrid data repository ensures data reliability. Furthermore, comprehensive and seamless information provides the cornerstone for more preventive services, mostly supported by specifically trained AI for IOM.

5.5. Framework scalability for IOM service support

As the core of SoDT-IOM framework, components of the enhanced digital environment support a series of service actions, integrating three functionality modules and data management service to specify the service detail and to process data with a generic workflow. It ensures service support for multiple assets and offers an overview of the transportation network level. However, due to the nature of digital twin technology in infrastructure operation and maintenance, the framework scalability, especially for data volume and processing can be challenged.

Facing the operational activities, from the traditional inspection to seamless monitoring integrating novel technology, such as sensor networks, and from daily routines to minor repairs and major renewal projects, the complexity of asset performance assessment and maintenance measures has increased significantly. The widely varying complexity leads to a wide variation in information needs, which causes scalability issues when dealing with the data that needs to be required, processed, and exchanged to support an activity. Therefore, to adapt SoDT to the various activities of multiple infrastructure assets, it is necessary to easily add or remove the required information to correctly match the scale of an activity. This can be achieved by the functionality module designed in the proposed framework.

Facing the collaboration demands of an activity, especially maintenance measures, scalability needs to be addressed from a management perspective. For instance, maintenance as regular measures can be managed through SoDT-IOM by assigning tasks and confirming executed work. For large-scale measures, such as comprehensive renewal, SoDT-IOM should be used, with a focus on the process of handing over measure result documents.

Facing the implementation of the proposed framework, the complexity of activities poses challenges to the real system's capability of collaboration and data processing. This requires the leveraging of

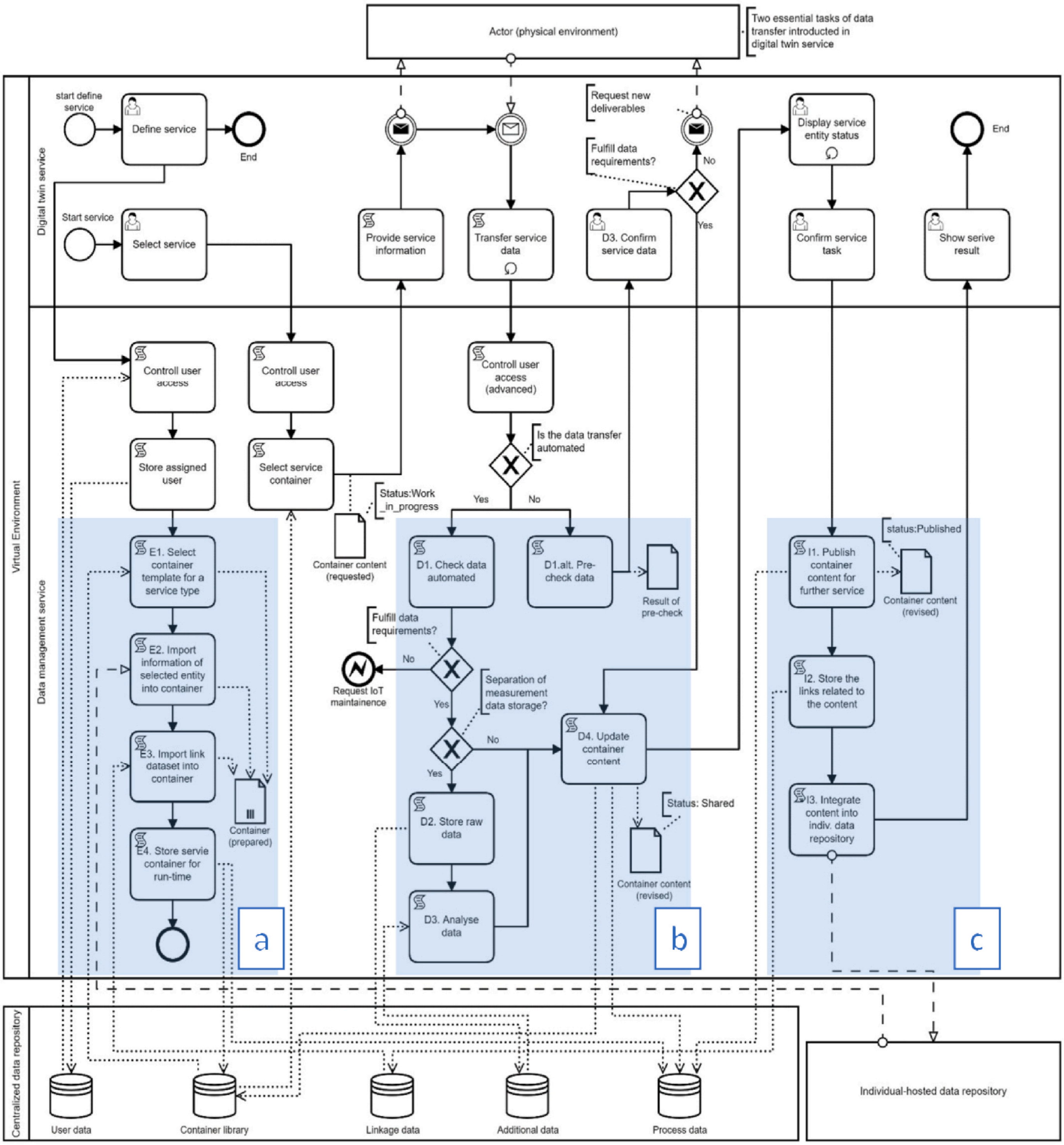

Fig. 7. Workflow of data management service in SoDT-IOM: (a) providing existing data during service definition; (b) collecting and updating data in the information containers during IOM service; (c) storing data in the hybrid data repository.

cloud computing resources to establish the centralized data repository and to enable the data management service defined in the framework. By providing the necessary computational power and storage capacity, cloud computing can efficiently handle large-scale service data. However, this scalability challenge needs to be thoroughly tested once implemented. Such testing helps to identify potential system bottlenecks and optimize performance for infrastructure services at different scales.

6. Use cases

For the demonstration of SoDT-IOM with service-oriented design and data integration mechanism, two use cases are presented for two types of IOM activities: (1) executing a pavement maintenance measure, presenting the conventional day-to-day work, and (2) monitoring a bridge structure with IoT, presenting the increasing use of novel technology. The use case "pavement maintenance measure" shows how service support for IOM can be achieved through SoDT-IOM, in particular by providing relevant and integrated data through advanced data management. The use case "bridge monitoring" shows how a service for supporting IOM in SoDT-IOM can be established and enables an automated condition assessment using multi-domain data. The use cases are introduced with the illustration of the user interface from the virtual environment combined with predefined SoDT-IOM components as background support.

6.1. Pavement maintenance measure

Considering challenges in data management, in particular, collaborative data exchange and automated data integration and update from existing data repositories during the daily work. The use case presents a pavement maintenance measure of a municipal road section with a length of 460 m. The three bituminous pavement layers must be renewed within 7 months, the usability of this road section is limited to a single lane with reduced driving speed (in Fig. 8). Regarding the collaborative workflow, the maintenance detail information is divided into three types: project information, confirmed documentation, and delivered documentation.

The project information includes general contract documents (e.g., technical specifications, schedule) shared with the contractor. It also contains a project dashboard (e.g., for budget information) considering the project's progress (Fig. 8 – a). The delivered documentation includes documents from the contractor that are required and must be confirmed by the client. For instance, the conformity test protocols of asphalt properties, which provide the important as-built information of the pavement material used in the maintenance, must be delivered and saved in a foreseen data repository. Regarding the service container defined at the begin of the service activity (Fig. 7 – a), the contractor should use the "conformity test requirements" file provided by the client to capture the conformity test protocol machine-readable, and deliver the protocol linked with the associated pavement section of the maintenance model and the requirements through "interface of data transmission". Then, the conformity test protocol is verified against the requirements automated considering the task "D1.alt. Pre-check data" (Fig. 7 – c). After reviewing the details of the conformity test protocol and the related verification result, the client can request a revision of the

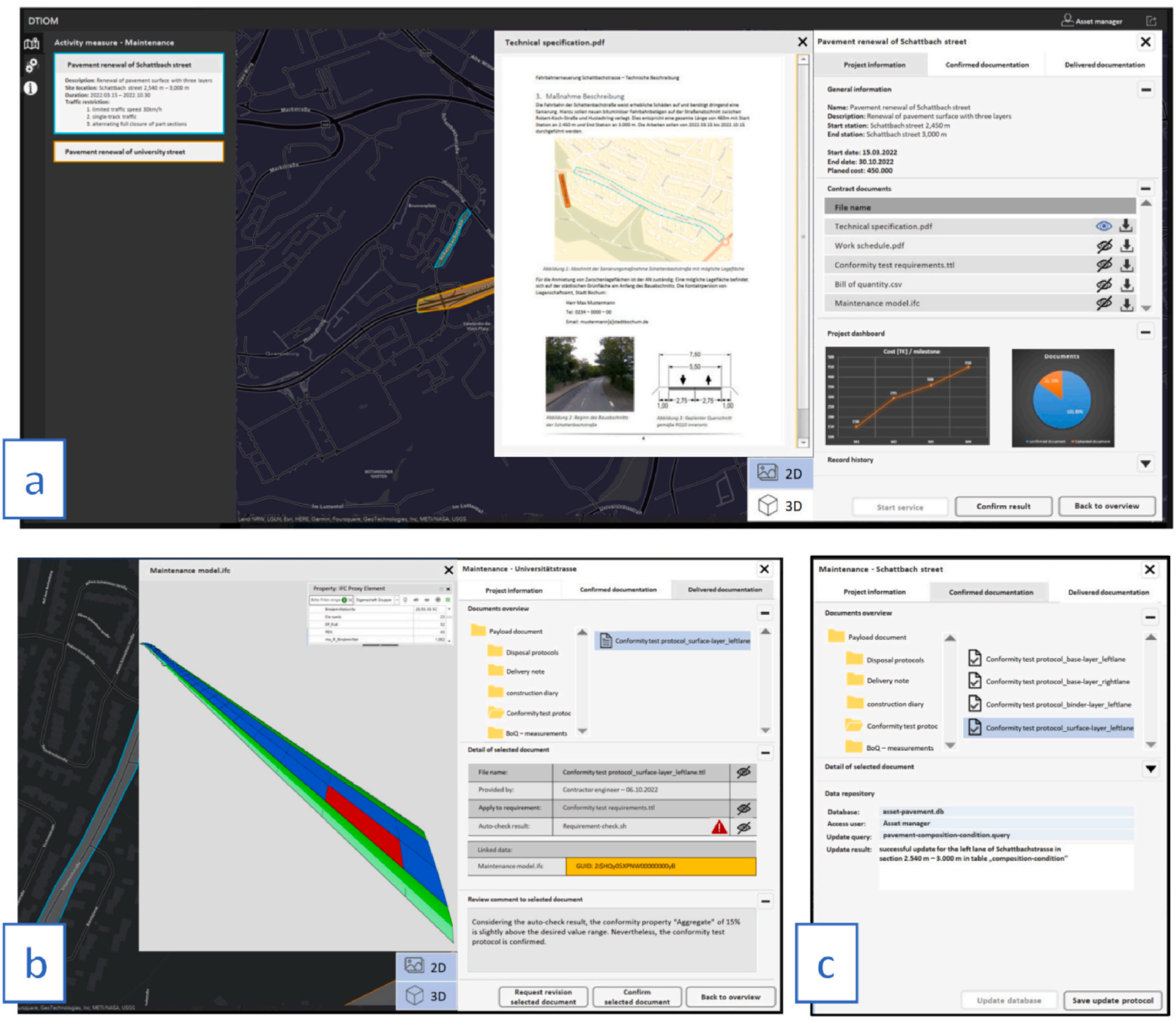

Fig. 8. Pavement maintenance measure (a) user interface for project information with contractual documents and project dashboard; (b) content of delivered documentation by the contractor; (c) confirmed documentation with update options into the designated database.

delivered document or confirm it as shown in Fig. 8 – b.

The confirmed documents are upgraded into the confirmed documentation so that the client can integrate the document into the foreseen database from the individually hosted data repository with the responded access by executing the matched query (Fig. 8 – c). The SoDT-IOM use case enables participants to deliver information of a maintenance measure digitally and promptly. Using the predefined requirements within the service container, the client can check the information machine-supported, and automatically update data into the designated database.

6.2. Bridge monitoring

The corrosion of prepressing steel is a critical issue for structure safety, as corroded tendons can lead to unforeseen structural failures, such disasters must be avoided. However, the condition of prepressing steel is mostly difficult to recognize through conventional inspection methods due to the tendons embedded or hidden in the concrete structure elements. Therefore, the use of sensors for the measurement of tendon electronic resistance can improve the assessment about continual corrosion development on the tendon monitored (Budelmann et al., 2014).

The sensor-based monitoring system of tendon corrosion detection in this use case applies to a motorway bridge which is reinforced with 8 tendons extended during the last maintenance measure. At the same time, the sensors are installed for each tendon, which measures once per month and sends the data to the intended database. To overcome the heterogeneous database, the proposed monitoring service of SoDT-IOM bundles the bridge and the sensor data for facilitating the visualization of relevant information and supporting further decision-making. In the first step, the monitoring asset "motorway bridge" is selected through the user interface, and relevant asset data from the bridge database is then integrated into the service information container shown in Fig. 9 – a, which considers the task "E2. Import information of selected entity into container" in Fig. 7 – a. The sensor system using IoT devices is also added into the service, and the assessment algorithm is set to analyze the measured data. The service conditions, such as the admitted range of values, and the action settings for exceeding the range are shown in

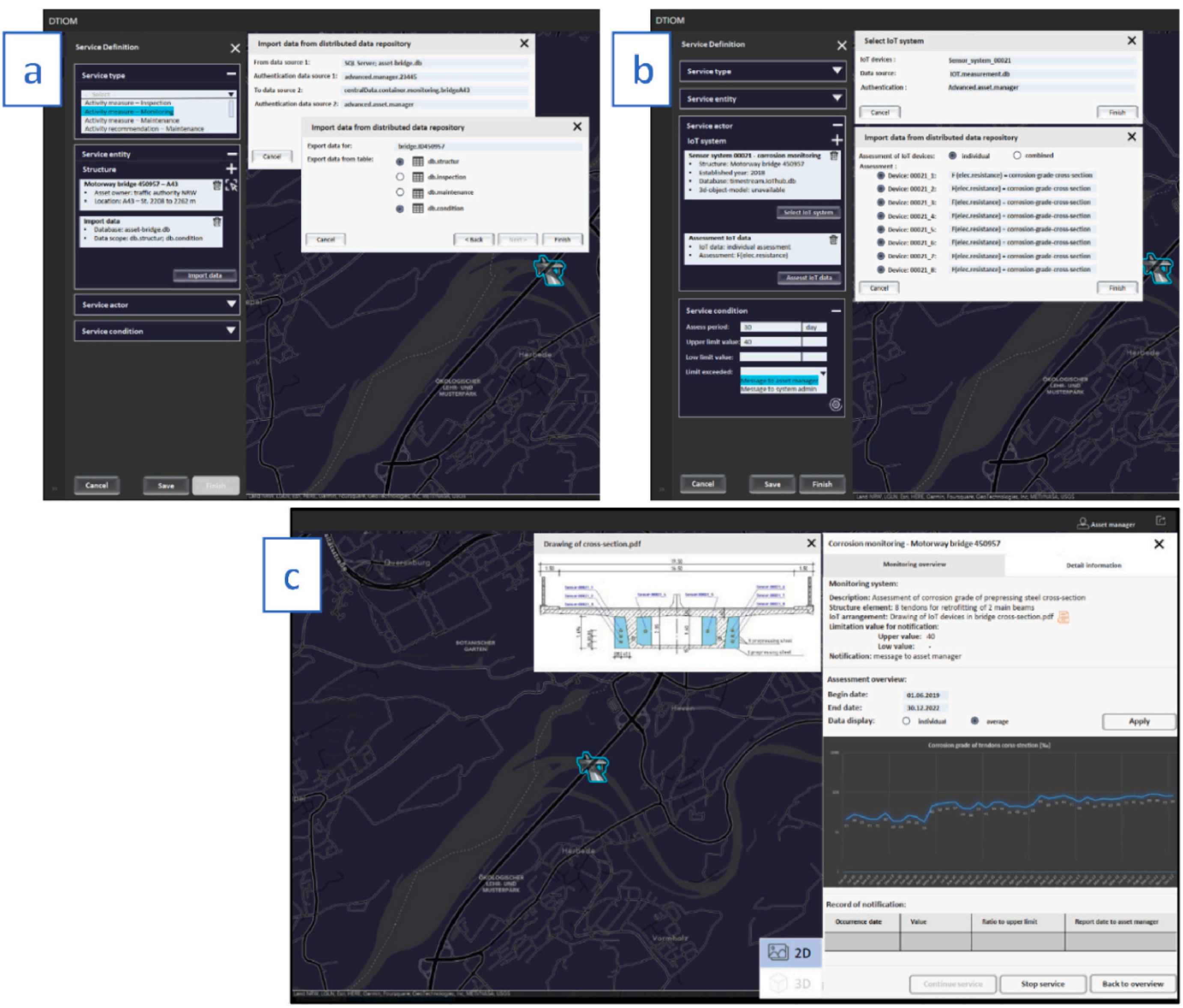

Fig. 9. Monitoring of tendon corrosion development on a motorway bridge (a) establishing monitoring service with selection of bridge and integration of bridge data; (b) adding sensor system into the monitoring service and determining the service condition; (c) observation of the information captured by the monitoring service.

Fig. 9 – b. Once the service setting is finished, the monitoring service runs in real-time considering the predefined condition. The service information shown in Fig. 9 – c, e g., description of the detected elements and properties, 2D-drawing of the sensor arrangement due to missing 3D bridge model, etc., and an assessment diagram of the measured data, can provide information from a general view to the detail.

The SoDT-IOM with this use case enables participants to establish individual digital twin services to bundle, process and visualize heterogeneous information from different sources. By integrating IoT devices into asset information and assessing the measurement data considering the service setting, the client can slightly monitor the current state and the development, and be automatically notified in real-time when the valid range is exceeded.

In this research, the two use cases demonstrated revolve around addressing the challenges of managing and maintaining digital assets mirrored to physical assets in a timely manner through SoDT-IOM. While the primary focus of the proposed framework is on integrating various data sources such as IoT devices and existing AMSs, this limits the ability to directly create new information models during design, construction, or major maintenance activities. This limitation highlights the need to differentiate the role of SoDT-IOM as a service-oriented digital twin for real-time asset performance assessment and advanced data management, rather than a solution for modeling new digital assets.

Notably, it is also important to recognize that while the platform excels in data integration, it may fall short in facilitating seamless communication and collaboration among stakeholders in the operations of infrastructure projects. Therefore, facing the limitations of person-to-person collaboration, future work could explore opportunities to extend such functionality to enhance communication and investigate the need for the utility of SoDT-IOM for project management and execution.

7. Evaluation

7.1. Framework evaluation

The functionality and efficacy of the proposed SoDT-IOM framework were evaluated through a structured interview with a group of industrial experts (see Table 4). The SoDT-IOM concept was first introduced, and its components were described, followed by the demonstration of two use cases. A structured interview with the experts ensued around four key topics: the advantages, disadvantages, willingness to use, and further improvements of the proposed SoDT-IOM. The experts' responses are collected to assess the concept in view of data integration and IOM service support.

For the evaluation, the responses from each expert are sorted by the four key topics at first. Then, the key statements of responses to each topic are retrieved and listed into two categories: data integration and IOM service support. In the context of assessment, data integration is identified as a key feature that should be addressed with SoDT-IOM functionality. IOM service support, on the other hand, is referred to as another key feature of the SoDT-IOM that requires even more communication and interaction between stakeholders beyond digital systems. The evaluation result is determined with the experts' answers of advantages and use intention pro, and disadvantages and use intention-contra related to the data integration and service support. As a result, the key statements are classified according to the four categories and listed in Table 7.

The resulting advantages of data integration show that the proposed improvement of data management (e.g., precise, timely, linked heterogeneous data) using SoDT-IOM is recognized by experts. To conclude, SoDT-IOM can provide relevant, integrated data in a timely and accurate manner. With improved data management, experts have the opportunity to gain better service support for IOM. In particular, SoDT-IOM can provide a better overview of IOM activities and decision-making, as well as improve collaboration during an activity.

Table 7
Result of SoDT-IOM evaluation.

	Advantages & Use Intention	Disadvantages & Use Intention
Data Integration	Digitalization Timely update Precise data Linked heterogeneous data	Data security In-depth data processing
IOM Service Support	Better overview of IOM activities Supporting decision-making Improving collaboration	Cost impact Difficulty of automation Activity complexity Effort of system adoption

However, experts also mentioned two obvious disadvantages in data integration: data security considering using and aggregating data from different stakeholders, and in-depth data processing for complex analysis, which are also challenging for multi-domain data management. For IOM service support with SoDT-IOM, there are disadvantages mentioned in 4 aspects: cost, automation, complexity and system adoption. Installation and maintenance of IoT devices can improve process automation, but it is always associated with additional costs. Even with the support of IoT devices, a fully automatic process is still difficult to achieve given the complexity of IOM activities. Furthermore, the adoption of a new system often leads to more efforts for employees, as traditional work methods run in parallel for a period of time until the application of the new system has proven itself.

The experts also provided suggestions to improve the presented SoDT-IOM, which are listed in the following in data management and IOM aspects:

Data integration: considering in-depth data processing required using specific tools, a standardized mechanism for data transfer between different digital tools should be considered. To provide more services in different domains, more domain data should be integrated and linked in the SoDT-IOM.

IOM service support**:** in addition to the extension of domain services by linking the related data, the integration of communication with third parties (e.g., residents) is also mentioned as a feature to enable advanced collaboration. As another extension of SoDT-IOM, the integration of novel technologies, such as immersive devices, can provide additional services (e.g., training).

7.2. Methodology evaluation

DSR is concerned with problem-solving and with the knowledge developed for constructing the artifact. Therefore, methodological evaluation is essential to ensure the knowledge development process. The evaluation of this research's process for rigor and relevance was conducted following the guidelines by Hevner and Chatterjee (2010). Table 8 shows the DSR methodology evaluation results.

7.3. Discussion

Designed as a framework of the service-oriented digital twin, SoDT-IOM provides an overall solution to enable essential management functions for multiple infrastructure assets, which is not fully considered in current research. Service orientation is the core concept that condenses practical problems and provides solutions. Guided and evaluated by this principle, SoDT-IOM is designed as a type of digital twin framework that generates value through data integration and utilization. It integrates functional modules, including data integration, data flow, periodic maintenance, emergency maintenance etc. According to current literature and industrial demand, data integration is a key technical challenge. Therefore, technical solutions and implementation processes for data integration are proposed, such as the centralized data repository, individually-hosted data repository, and mapping approach for the linkage mechanism. Furthermore, technical contributions are

Table 8
DSR methodology evaluation.

Guidelines	Evaluation results
Design as an artifact	The critical artifact is the SoDT-IOM framework with key components for multi-domain data integration and IOM service support.
Problem relevance	The heterogeneous data are the practical reality for recording the IOM activities, which includes a wide range of data formats from damage photos to point clouds or BIM models. Meanwhile, the asset authorities established individual digital systems to cover the major demands of IOM. A mechanism for multi-domain data integration is required and a design for multi-party involved IOM service is needed.
Design evaluation	The utility and efficacy of the SoDT-IOM framework were rigorously demonstrated via use cases with real project context. Moreover, this study involved an evaluation conducting structured interviews with industrial experts.
Research contributions	The clear contributions of this research include the design artifact: the novel framework and its components and mechanisms design, the demonstration with use cases, and the methodology of their design and development. Moreover, this study provided implications for future research on DT for infrastructure.
Research rigor	Under the guidance of DSR paradigm, using advanced DT applications, the mature data integration method (e.g., Linked-data), two-stage industrial interviews for the system design and evaluation, and continuous development ensure research rigor.
Design as a search process	This study navigated through data management methods for IOM to capture what is inefficient. Further, a thorough analysis of the system functionality was conducted based on industrial practices.
Communication of research	We communicated with both the technical and managerial participants. Communication results formed implications for DT practices for infrastructure and contributed to the continuous development of the SoDT-IOM framework.

integrated within a management perspective in this research.

To achieve data integration, a hybrid data repository structure is introduced based on the conceptual standard of BIM (ISO 19650-1, 2018) (shown in Fig. 10). This provides the foundation for efficient, centralized data processing during IOM service support, and considers the asset manager's need for authorized access and controlled management of information from disparate data sources. The data management service in the DT design provides an overall flow of data processing based on CDE. This includes the tasks of integrating and updating information from various domains for current and further IOM service support. During IOM service support, the information of asset inventory is linked with further information to provide a comprehensive service information model within the standard information containers. This service information model can be accessed by relevant stakeholders and provide adequate information promptly considering automated processes through the digital twin service in SoDT-IOM.

In particular, a mapping approach is proposed as a basis for data integration between various data sources. This mapping approach enables the provision of comprehensive and meaningful information to support IOM activities. Combined with the proposed workflow of data processing, data quality and consistency between the center and individually hosted data repositories can be ensured. However, future studies are required to fully develop the mapping approach and implement and validate the introduced data processing workflow. From the management perspective, federated, consistent and qualified data obtained through SoDT-IOM provides effective support for reliable decision-making.

To aim the improvement of IOM, the service-oriented concept design of DT shows its benefits at the point of process automation of the IOM activities, besides the improved automation for data integration and processing. In the SoDT-IOM, the services are classified and summarized by considering the IOM activity types and the influence of novel technologies. The classification of the services is based on interview outcomes with industry experts, ensuring that the services meet the practical needs of IOM. In addition, the module design of the digital twin service incorporates a process loop for each service type, defining the essential functionalities associated with these loops. This module design provides a generic framework for customizing IOM service support by using various IoT devices at different automation levels. By considering a range of IOM activities with classified process loops, SoDT-IOM reduces the need to develop stand-alone digital solutions based solely on BIM models, when new IoT devices are introduced, a specific asset is required, or an individual service is identified. In contrast to previous digital twin research in infrastructure, which predominantly concentrated on monitoring the structural condition of a single asset, SoDT-IOM provides a generic framework capable of delivering multiple assets-related activity services, spanning from conventional inspection and maintenance tasks to real-time monitoring.

Summarizing the entire design process shown in this paper, the following aspects are important for the future extension of SoDT-IOM and the design and implementation of a new digital twin solution, which can be extended to asset lifecycle management:

1. Design requirement from the management aspect: The service-oriented design should consider that one IOM activity mainly involves various stakeholders. These include various professional areas (e.g., financing planning, engineer planning, work planning, etc.). The requirements must then be extended in consideration with individual agreements, engineering experience, resources at disposal, etc. to achieve more collaboration and automation for asset lifecycle management.
2. Design requirement from the technology aspect: For advanced data analyzing and processing, specific tools are still required through specific experts (e.g., for calculating structure capabilities or modeling structure geometry). To streamline the data integration and sharing between specific tools and the general asset management system, the digital implementation of both sides should use

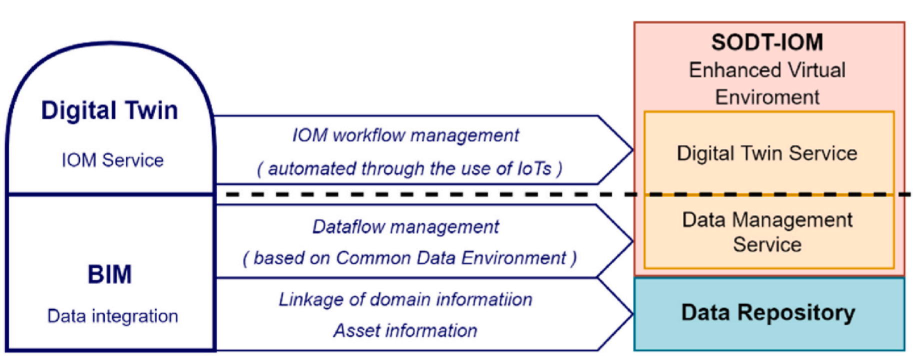

Fig. 10. Summary of Leveraging BIM to Digital Twin: associated activities, methods, and the system components.

standardized protocol and open data formats, for example, introduced by ISO 19650-4 (ISO 19650-4, 2022) for data transmission.

3. Implementation from the research-practice transformation aspect: The limited budgets and intensive workloads are well-known reasons for the delayed adoption of novel digital technologies in AECO. The introduction and implementation of new technologies often require more skilled workers and funding, which is often lacking in practice. In addition, the capacity and resources of organizations vary greatly from the municipal to the national level. To improve the acceptance and maturity of new digital solutions, a prototypical realization based on concept design is important to demonstrate the solution advantages and to identify further improvements based on real needs from AECO practice.

8. Conclusion

In this paper, a digital twin framework for infrastructure operation and maintenance, i.e., SoDT-IOM is iteratively developed based on the theoretical analysis and industrial requirements. Current methods and technologies, such as BIM, Linked Building Date, and CDE are adopted for realizing the key mechanism of data integration and IOM service design. Especially considering the specificity of the infrastructure, a theoretical mapping method is proposed as a basis for data integration. Two use cases from the common IOM practical activities are illustrated for the functionality evaluation. Meanwhile, the research process is evaluated following the DSR paradigm. This study leads to two important contributions that are considered in the proposed framework:

Data interoperability, work collaboration and process automation can be improved by integrating novel technologies (e.g., semantic web) and devices (e.g., Internet of Things - IoT) based on BIM. Especially, data management should be organized using BIM standards and Semantic Web technology given the heterogeneous data stored in distributed data sources. Data precision is one essential point that can be achieved through a clear definition of information requirements and the responsibility for information delivery. The timely data updates can be realized through the automatic data management service of SoDT-IOM.

The digital twin is recognized by experts mostly as a method for process automation. The proposed SoDT-IOM improves the process automation both for the data management using CDE, and for the IOM activities by integrating new technique devices. Even the SoDT-IOM is evaluated as useful to improve the digitalization and automation for data management and IOM service, several challenges (e.g., limited budgets) in the AECO industry show the real difficulties that hinder the realization of the digital twin in practice.

To investigate and adopt the SoDT in practice, there are two major recommendations concluded for the practitioners: (1) strategically select and define the intended IOM service balancing the capability of existing AMS, the benefits of novel technology, and the resources made available; (2) embrace open data formats by exchanging and processing data with SoDT facing the limitation of the increasing communication demands and advanced data processing with a single solution.

For future work, more efforts should be made to integrate theory with practice regarding DT service for IOM. In addition, further studies should address complete SoDT-IOM and explore real-time forecasting functions. Based on sufficient historical and real-time data, it is possible to apply machine learning and deep learning techniques to forecast maintenance problems and achieve proactive infrastructure operation and maintenance.

CRediT authorship contribution statement

Liu Liu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ningshuang Zeng:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yan Liu:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Writing – original draft. **Daguang Han:** Conceptualization, Writing – review & editing. **Markus König:** Conceptualization, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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