Conceptual Modeling of Lifecycle Digital Twin Architecture for Bridges: A Data Structure Approach

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Abstract

The concept of Digital Twin (DT) has emerged in recent years to facilitate the use of Building Information Modeling during the entire projects' lifecycle. In the DT concept, cyber-physical system theory is utilized to collect condition data about an existing asset and then integrate this data into the digital model. The major limitation though is that the current scope of DT is limited to the operation and maintenance phase. Nevertheless, the DT concept can be extended to the entire lifecycle of the asset if the relevant sensory and non-sensory data are incorporated into the digital model in an automated and systematic way. However, in the current literature, there is no clear insight about such a holistic and life-cycle DT concept for infrastructure projects. Especially, there is very little understanding about how various sensory and non-sensory data from construction and operation phases can be seamlessly integrated into the 3D BIM models. Therefore, this research aims to develop a conceptual model for the architecture of Lifecycle DT (LDT) focusing on bridges. To this end, an ontological modeling approach is adopted. The proposed ontology is validated through a workshop session where domain experts assessed the results with respect to some competency questions. The outcome of the session indicated that the proposed ontology scored sufficiently in all the criteria and succeeded in satisfying the information needs of the LDT. Overall, the proposed model offers an insight into a lifecycle modeling practice as well as automated data incorporation, enabling a smooth transition towards an upgraded modeling practice.

Keywords –
Digital twin; Lifecycle digital twin; Bridge information modelling; Ontological modelling

1 Introduction

Integrating the lifecycle information of a construction project in a centralized/federated model has received much attention lately [1]. Building Information Modeling (BIM) attempts to store and represent all the relevant information of a project's lifecycle in an object-oriented 3D model. However, time-consuming and error-prone manual work is required for the generation, maintenance, and upkeep of the information in BIM [2, 3]. This problem can be potentially addressed by automating information acquisition and integration [3~7].

Digital Twin (DT) is an upcoming concept, which can address the need for automatic acquisition and integration of information. DT is a multi-physics model, fed with meaningful data about the asset and the environment around it [8]. The concept of DT was first introduced in 2012 for the verification and validation of aerospace vehicle models As far as the construction industry is concerned, DT can be described as an extension of BIM, with the addendum of the dynamic and reactive aspect emerging from the use and integration of sensors, IoT architecture, and cyber-physical systems [10~11]. Such technologies make the physical asset smart and enable it to communicate with its digital counterpart about its health and condition. In other words, DT intend to fuse as-designed and as-is physical representations [3]. In this sense, DT is a system consisting of a physical twin, a digital twin, and a communication interface that connects the two [9]. Among the characteristics of DT, the real-time reflection of the physical space to the virtual one has been expressed as a distinguishing factor for the concept.

Nevertheless, current applications of DT is mostly limited to Operation and Maintenance (O&M) activities [12]. From literature, it is already known that design information/decision has significant impact on the performance and the maintenance of a project [12~15]. That is why it is important to take a life-cycle approach towards the development of DT models. To integrate the entire lifecycle information, the digital and physical counterparts should evolve in parallel from the design phase until the final demolition, creating what can be labelled as a Lifecycle Digital Twin (LDT). BIM can be potentially used as a platform for developing LDT, but this requires the expansion of its scope to real-time and automated data acquisition. Because of this, the BIM should be developed in view of the requirements of the LDT. All the necessary lifecycle information and the respective sensors should be predefined, and the expected data pieces should be allocated to the relevant model components. This way, a LDT-ready BIM model, which is created in the design phase, can function as a LDT once the physical counterpart and the communication channels with the model are in place. In other words, future BIM models should be prepared from the design phase already in view of a full-scale LDT model.

Currently, there is a lack of a comprehensive approach towards building a LDT-read BIM model that can be used for different purposes across the lifecycle of an asset. To address this problem, this research aims to offer a conceptual model for the architecture of the LDT, focusing on bridges. This model outlines requirements for the transformation of conventional BIM models to DT-ready models.

The remainder of the paper is structured as follows. Firstly the scope of the study and the methodology are briefly explained. Next, each step of the methodology is further elaborated. More specifically, the current modelling practices are explained and a data map of the current data structure is presented. Then, the information requirements are presented followed by proposed enriched ontology, which integrates the information requirement. A case study that explains how the proposed ontology can be of use is presented in the next section. This is followed by the validation of the results. Finally, a reflection upon the findings of the research is presented in the discussion and conclusions section

2 Research scope and methodology

To identify the missing elements for a smooth transition towards the DT concept, it is important to have a clear picture of the current modeling practices. To address that need, the first step of the research was an exploration of existing BIM models of bridges. A Dutch contractor was studied as a context. More specifically, Revit files of different bridges were investigated to extract the data scheme, i.e., how the bridge model is decomposed into different objects, what are the properties of the different objects and how they are stored. In the next step, a set of interviews with domain experts from disciplines covering the entire lifecycle were carried out to identify the information that the different disciplines desire to extract from a LDT. These information needs were then expressed as specific properties that LDT-ready model needs to incorporate. Some of the missing properties can be easily allocated to the existing elements, while some may require the introduction of new entities. The addition of new entities in the current data structure led to an enriched bridge LDT ontology. This ontology was further validated at the final step of the research via the assistance of human domain expertise. More specifically, domain experts from disciplines covering the entire lifecycle, were asked to assess and rate the proposed ontology with respect to its correctness, completeness, conciseness and extensibility by answering a set of competency questions.

3 Requirements Analysis

In the following section, the different steps of the methodology are explained.

3.1 Current Modelling Practices

Figure 1 presents the high-level ontology that represents the dominant approach toward bridge information models. This model emerged from the exploration of several bridge BIM models. It was observed that these models consist of two main parts, the topographic view, and the bridge model itself. The latter consists of a set of digital entities representing the bridge objects, e.g., piles, pile caps, piers, headstock, girder, abutments, wing walls, etc. All these elements are characterized by a shared set of parameters like the area, volume, and year of construction. Apart from the geometric properties, all the objects of the model are characterized by a unique identifier code. This code is composed of a set of digits that are determined based on the location and decomposition of the objects. For example, a pile is characterized by 6 digits, where the first two digits indicate whether the pile is located in the western or eastern half of the bridge, the second two digits indicate that the pile is part of the foundation, and the last two digits designate the specific pile from the pile bundle that the foundation consists of. This naming approach aims to create an unambiguous naming policy for the elements across the different disciplines and is a prerequisite for applying filtering processes and logic rules, which enable the management of metadata in an automated way.

3.2 Information Requirements

During the interviews, the domain experts were asked about what information they would like to be able to extract from the LDT in order to assist their tasks. A set of example information requirements that emerged from the interviews are presented in Table 1.

Each information requirement was further linked to a target class, i.e., the ontology entity that should host that specific information. Some of the target classes already exist in the current ontology, while some new classes had to be introduced to allow a meaningful distribution of information. For example, the required information of the end of the lifespan (No2) refers to all the construction instances that already exist in the current ontology. On the other hand, the required information of the location of the equipment (No10) demands the introduction of the equipment class, as well as a class for a technology that traces and registers the location of the equipment. Among others, some of the newly introduced target classes are the processes, equipment, the agent and process model, as well as some information collecting technologies like the laser scanners and Radio Frequency Identification (RFID) tags. The content of the new classes as well as the way they are incorporated to enrich the current ontology are further explained in the next section.

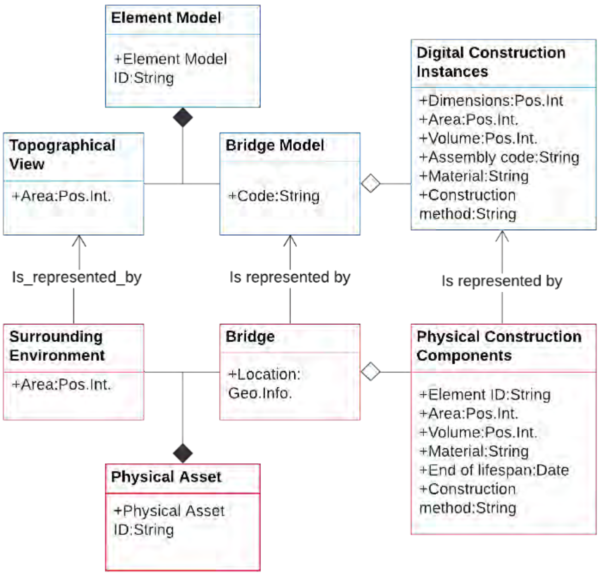

Figure 1. Current ontology

3.3 Proposed Ontology

The new information pieces and respective required classes that emerged from the requirements analysis are used to developed the proposed ontology for a DT-ready bridge information model. The proposed ontology consists of three main sections: the physical asset, the digital model, and the lifecycle, which is the main addition compared to the current ontology. The physical asset has a lifecycle that is proposed to be represented in the digital model, which in turn communicates bilaterally with the physical asset, as the concept of DT implies. This relationship between the three main sections is depicted in the higher-level proposed ontology shown in Figure 2.

Figure 3 presents a more detailed representation of the proposed bridge LDT. More specifically, the lifecycle section includes new aspects such as the resources, processes, and involved risks. The resources class includes the subclasses of equipment and material used in the construction activities, as well as the software and human agents, which may be designers, engineers or workers. The processes refer to different kinds of construction-related activities like designing, concrete pouring, drilling and transferring.

Table 1. Information Requirements Taxonomy

No	Information Requirement	Target Class
1	To select and filter the elements in the model to highlight those satisfying a requirement	Construction Instances, Processes
2	End of lifespan for each element separately	Construction Instances
3	Environmental Impact Value in the model for each element	Construction Instances
4	Access Material Passport (MP) of each element	Construction Instances
5	Executed quality checks and potential non-conformances with the model	Construction Instances, Processes, LiDAR for as-built scanning
6	Duration and cost of the execution for the different work sets and objects separately	Construction Instances, Processes, Process Model
7	Usage loads bearing the deck	Deck, Weight-In-Motion sensors
8	Deviation between planned maintenance schedule and implemented maintenance record	Construction Instances, Processes
9	Concentration of dangerous substances in the air during drilling activities	Drilling, Surrounding Environment, Real-time respirable dust monitoring devices
10	Trace the location of equipment	Equipment, RFID for asset tracking
11	Duration and cost of rented equipment	Equipment, RFID for asset tracking
12	Deviation between actual and designed environmental variables	Construction Instances, Surrounding Environment, Hygrometer. Thermometer
14	Proximity between workers and identified danger (steep slope, height, moving vehicle, dangerous materials)	Crew, Surrounding Environment, Materials, Agent Model, RFID for people and asset tracking,
15	Proximity between moving vehicles and areas with unstable or humid ground.	Moving Vehicles, Surrounding Environment, Agent Model, RFID for asset tracking, Terrestrial laser scanner

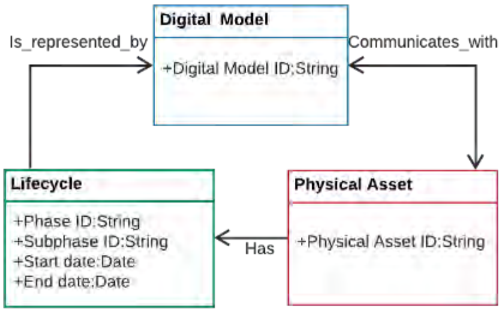

Figure 2. Higher-Level Proposed Ontology

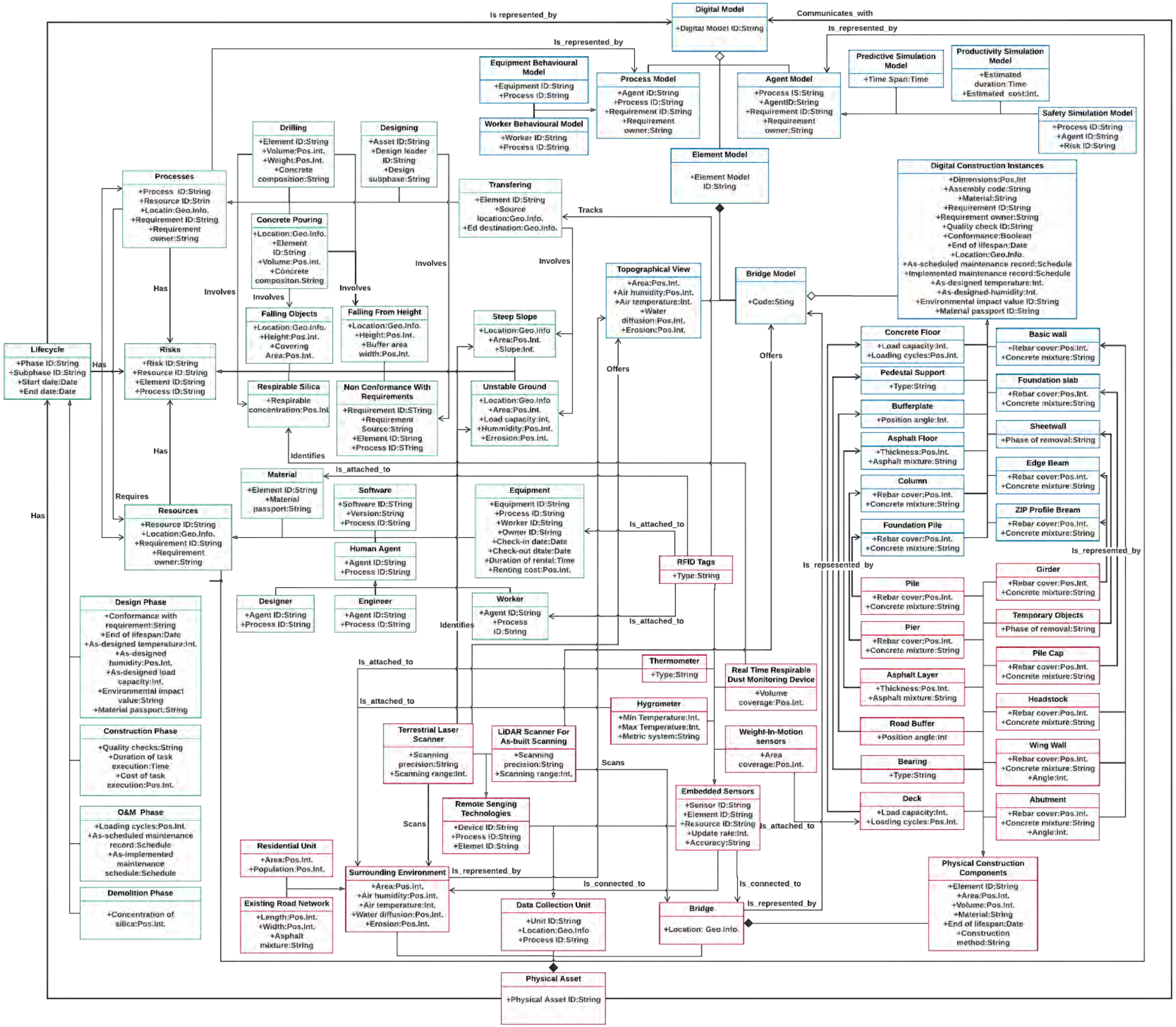

Figure 3. Proposed Enriched Ontology for the LDT

Furthermore, the risks concern potential accidents like falling from height of from steep slopes, breathing dangerous substances but also design related risks like insufficiency to meet the client's requirements. Finally, regarding the relationships between these classes, the different processes require resources while the also involving risks.

Regarding the digital model section, an agent and process model were added alongside the element model. While the element model represents physical components of the bridge, the agent and process models offer an insight in the behavior of the asset. An example of the behavior of an excavator is shown in the agent model in Figure 4 [16]. Process models, on the other hand, represent the sequence of activities that take place in different lifecycle operations, e.g., excavation, as shown in Figure 5 [17]. The combination of agent and process models allows to develop various types of simulation models that can support the asset management by predicting the asset behaviors, assessing safety, and estimating the productivity of different operations.

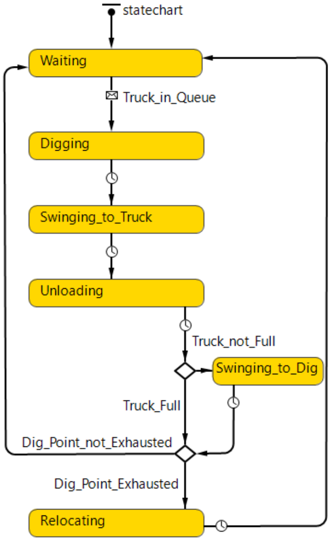

Figure 4. Example of an agent model (adapted from [16])

As far as the physical asset section is concerned, a set of collecting units is added, which collects data about the physical asset and feeds that data to the digital model. The data collecting units may either be (1) embedded sensors like thermometers and hygrometers attached to the bridge, RFID tags attached to the resources, and weight sensors embedded in the deck, or (2) contactless sensors like LiDAR scanners, which register the as-built condition, or terrestrial scanners, which offer a detailed depiction of the ground surface.

The incorporation of the new classes in the LDT ontology led to a large set of new relationships, which connect different interrelated entities. An exhaustive description of all the relationships and linking possibilities is beyond the scope of this paper, however the following two examples aim to offer an insight about the information linking potential of the proposed ontology:

Example 1: During the construction phase, the transportation process takes place. The resource used in this process is a vehicle. This process involves the risk of the vehicle approaching a steep slope on the construction site. The location of the steep slope is acquired via the assistance of a terrestrial laser scanner and is registered in the topographic view of the element model. Furthermore, the location of the of the moving vehicle can be traced via the assistance of RFID tags. This information is registered to a safety simulation model. The simulation model and the topographic view are interlinked parts of the digital model, and this way the proximity of the moving vehicle to the steep slope can be calculated.

Example 2: The design phase involves designer agents. A risk associated with this process is failing to meet the client's requirements. Additionally, the designing process is assisted by the use of terrestrial scanners that offer a representation of the ground surface of the surrounding environment. Finally, once the asset is built, a LiDAR scanner for as-built scanning can identify non-conformances between the as-designed and as-built situation.

Overall, the proposed ontological model addresses the current limitations in multiple ways. Firstly, the combination of different model types, namely agent, process and element models, offers a multiscale modeling practice and a holistic modeling approach. Such a global modeling perception is in favor of managing and incorporating diverse lifecycle data generated through the lifespan of a construction project. Furthermore, the definition and inclusion of the different properties, as well as the information flow channels, increases the DT-readiness of the element model. Moreover, the new emerged relationships assist the combination and extraction of a big variety of information as explained in the examples. With the assistance of some algorithms and the application of logic rules, it is possible to deeply mine data and identify patterns, apply correlation analyses, and identify emergent and latent phenomena. These applications serve as a basis for machine learning and artificial intelligence, which are concepts closely related to the DT.

3.4 Hypothetical Validation

To further explain how the proposed ontology can assist the extraction of information, a hypothetical validation is developed based on a scenario extracted from the required information in Table 1.

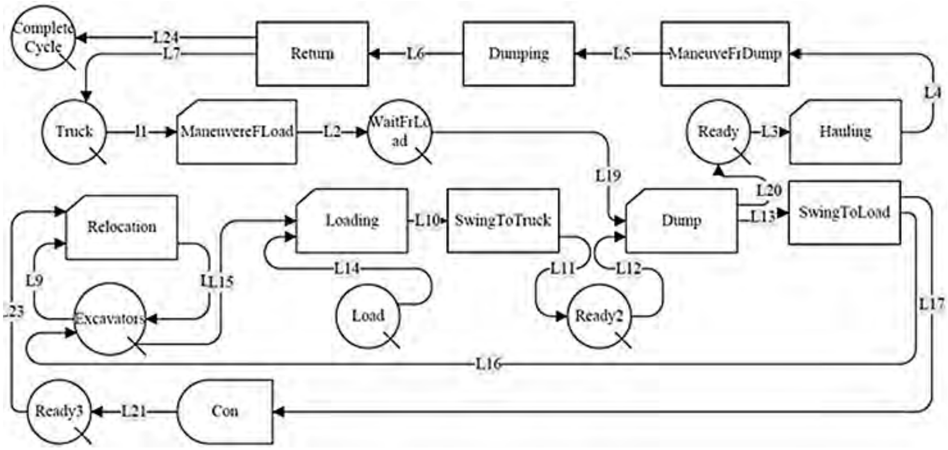

Figure 5. Example of a process model (adapted from [17])

It is required to extract the deviation between the programmed and implemented maintenance tasks. According to the proposed ontology, the as-planned maintenance frequency and the implemented maintenance record are properties assigned to all the construction instances. Therefore, it is possible to use a query to highlight the elements of the model that require more frequent than scheduled maintenance.

Similarly, it has been asked to extract the deviation between the designed temperature and humidity capacity of the elements and the actual ambient conditions. The as-designed values are included in all the different construction instances, and the actual ambient conditions are being retrieved via the use of embedded hygrometers and thermometers, and stored in the topographic view of the model. Therefore, it is possible to filter and isolate the elements that present a deviation between the as-designed and implemented ambient conditions.

Finally, it is possible to combine the aforementioned information and identify potential correlations between the climate change and the maintenance demand of the asset. This insight allows optimizing the maintenance schedule of the reference project, but also considering more resilient construction practices for new generations of the project. It can be hence observed that the proposed ontology combines different information to offer a deep insight and it can even provoke the genesis of new knowledge.

3.5 Validation

The proposed ontology was validated through a workshop session where the ontology was presented to a group of six domain experts from different phases of the entire lifecycle of a bridge. More specifically, the participants were a systems engineer, a designer, a site engineer, a maintenance engineer, a safety and a sustainability specialists. The participants were asked to assess the proposed ontology with regard to a set of predefined criteria by answering a set of competency questions. The evaluation criteria used to assess the ontology were correctness, completeness, conciseness, and adaptability [18~19]. The criterion of correctness indicates whether the ontology correctly represents the real-world concept of the lifecycle of a bridge. Completeness measures whether the domain of interest is appropriately covered, while conciseness indicates that an ontology does not include unnecessary concepts or redundancies. The last criterion, adaptability or extendibility, designates whether an ontology is easily adaptable in the case of adding new definitions and new knowledge to existing ones.

The results of the session, which are presented in Table 2, showed that the proposed ontology scored well in all criteria. An improvement recommendation about the correctness of the proposed ontology concerns the introduction of tiers in classifying the elements, meaning libraries, objects and instances. Regarding the completeness, it was proposed to add the pre-design phase in the lifecycle to incorporate tendering processes and involved risks as well. Additionally, it was proposed to keep the ontology at a higher level of abstraction, and further develop it at a project level. This way the ontology can be adapted for several infrastructure assets apart from bridges. Lastly, it was suggested to align the object breakdown structure to the national standards to improve the adaptability potential of the ontology. Overall, the proposed ontology is considered to adequately cover the lifecycle information needs of a LDT of a bridge.

4 Discussion

Regarding the scientific contribution of this study, the proposed ontology incorporates and allocates sensory data to the elements of the BIM model, addressing the issue of seamless integration of the automated/sensory data into lifecycle information models. Furthermore, it proposes a lifecycle implementation framework for the DT, introducing a holistic approach, which is missing from the existing fragmented application efforts. Moreover, the research provides an insight into how to transit towards DT-ready bridge information models by indicating how sensory data, different databases and simulation models can increase the automation potential of the BIM models.

Table 2. Validation scores and potential improvements

Criterion	**Score (1~5)**	**Potential Improvement**
Correctness	3.8	Structure of the classification of libraries, objects and instances
Completeness	4	Inclusion of pre-design phase
Conciseness	4.2	-
Adaptability/ extensibility	3.25	Keep ontology at a higher level of abstraction Align with national standards about OBS

The outcome of the study indicates that the DT is not necessarily only about sophisticated technological application, but also systematic data structure. The actual value of the DT concept is in the incorporation and linkage of various data and its continuous flow across the lifecycle.

Regarding the strengths of the research, the participation of actual domain experts in the development of the ontology adds to the implementability potential of the proposed ontology. The data pieces, which were used to enrich the current ontology, were derived from actual practitioners and reflect the real modeling needs. Additionally, apart from input, domain expertise was also used for validation. Another strong point of the proposed ontology is that it is conducted at a relatively high level of abstraction, allowing its easy adoption for other types of infrastructure assets without significant changes. On the other hand, a limitation of the research is that it is not an exhaustive study of neither all the lifecycle aspects that the DT model, nor all the potential data collection variety that can assist such a model. The proposed ontology serves rather as a high-level data framework for a bridge's DT modeling practice.

As far as the application of the ontology is concerned, there are some prerequisites that need to be met. From a technical point of view, the different platforms, databases, and data collecting technologies should be interoperable to apply the recommended data structure. Interoperability, in this sense, does not only refer to the data format but also the data granularity. In other words, the decomposition of objects, worksets and the naming policy should be aligned across different disciplines. Regarding the working routines, they will also need to undergo some changes. New collaborations, roles and tasks will emerge, and people should be persuaded to embrace them in view of a greater lifecycle picture. Closer collaborations and more intense interdisciplinary communication are needed to communicate the information needs and find the best path for the information to flow. Finally, people should be adequately informed about the added value of the DT readiness practice to embrace enthusiasm about and avoid resistance regarding new working routines.

5 Conclusion

To summarize, this research aimed to bring the current state of art one step closer to the application of DT by identifying the requirements a BIM model should meet to allow a gradual transition towards LDT. To address the research objective, an ontological model was developed to map the distribution of various data pieces among elements of the model. This ontology describes what is the additional information that need to be included in the BIM model, what are the needed data collection technologies, how are the sensor measurements distributed in the model and what are the relationships between the different entities. The proposed data structure indicates how the models should be created in consideration of the LDT offering a smooth transition for the application of the concept. Overall, the results of the research indicate that the proposed ontology has great potentials to support a variety of activities throughout the entire lifecycle of a bridge.

References

[1] "White paper: National digital twin | Bits & Pieces." https://global.royalhaskoningdhv.com/digital/resources/publications/national-digital-twin (accessed Feb. 14, 2022).

[2] T. Borangiu, D. Trentesaux, P. Leitão, A. G. Boggino, and V. Botti, "Studies in Computational Intelligence 853 Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future." [Online]. Available: http://www.springer.com/series/7092

[3] V. Stojanovic, M. Trapp, R. Richter, B. Hagedorn, and J. Dollner5, "Semantic Enrichment of Indoor Point Clouds An Overview of Progress towards Digital Twinning."

[4] Ü. Işıkdağ, "Enhanced Building Information Models Using IoT Services and Integration Patterns."

[5] J. P. 1959- Wulfsberg, *1. interdisziplinäre Konferenz zur Zukunft der Wertschöpfung Konferenzband*.

[6] B. Becerik-Gerber, F. Jazizadeh, N. Li, and G. Calis, “Application Areas and Data Requirements for BIM-Enabled Facilities Management,” *Journal of Construction Engineering and Management*, vol. 138, no. 3, pp. 431–442, Mar. 2012, doi: 10.1061/(asce)co.1943-7862.0000433.

[7] J. Chen, T. Bulbul, J. E. Taylor, and G. Olgun, “A Case Study of Embedding Real Time Infrastructure Sensor Data to BIM.”

[8] E. H. Glaessgen and D. S. Stargel, “The digital twin paradigm for future NASA and U.S. Air force vehicles,” 2012. doi: 10.2514/6.2012-1818.

[9] S. Haag and R. Anderl, “Digital twin – Proof of concept,” *Manufacturing Letters*, vol. 15, pp. 64–66, Jan. 2018, doi: 10.1016/j.mfglet.2018.02.006.

[10] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, “Digital twin-driven product design, manufacturing and service with big data,” *International Journal of Advanced Manufacturing Technology*, vol. 94, no. 9–12, pp. 3563–3576, Feb. 2018, doi: 10.1007/s00170-017-0233-1.

[11] D.-G. J. Opoku, S. Perera, R. Osei-Kyei, M. Rashidi, T. Famakinwa, and K. Bamdad, “Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review,” *Buildings*, vol. 12, no. 2, p. 113, Jan. 2022, doi: 10.3390/buildings12020113.

[12] D. G. J. Opoku, S. Perera, R. Osei-Kyei, and M. Rashidi, “Digital twin application in the construction industry: A literature review,” *Journal of Building Engineering*, vol. 40. Elsevier Ltd, Aug. 01, 2021. doi: 10.1016/j.jobe.2021.102726.

[13] H. Gervasio, S. Dimova, and A. Pinto, “Benchmarking the life-cycle environmental performance of buildings,” *Sustainability (Switzerland)*, vol. 10, no. 5, May 2018, doi: 10.3390/su10051454.

[14] W. Hu, T. Zhang, X. Deng, Z. Liu, and J. Tan, “Digital twin: a state-of-the-art review of its enabling technologies, applications and challenges,” *Journal of Intelligent Manufacturing and Special Equipment*, vol. 2, no. 1, pp. 1–34, Aug. 2021, doi: 10.1108/jimse-12-2020-010.

[15] F. Jiang, L. Ma, T. Broyd, and K. Chen, “Digital twin and its implementations in the civil engineering sector,” *Automation in Construction*, vol. 130. Elsevier B.V., Oct. 01, 2021. doi: 10.1016/j.autcon.2021.103838.

[16] F. Vahdatikhaki, K. el Ammari, A. K. Langroodi, S. Miller, A. Hammad, and A. Doree, “Beyond data visualization: A context-realistic construction equipment training simulators,” *Automation in Construction*, vol. 106, Oct. 2019, doi: 10.1016/j.autcon.2019.102853.

[17] F. Vahdatikhaki, “TOWARDS SMART EARTHWORK SITES USING LOCATION-BASED GUIDANCE AND MULTI-AGENT SYSTEMS,” 2015.

[18] J. Raad, C. Cruz, and C. A. Cruz, “A Survey on Ontology Evaluation Methods,” 2015, doi: 10.5220/0005591001790186ï.

[19] P. Delir Haghighi, F. Burstein, A. Zaslavsky, and P. Arbon, “Development and evaluation of ontology for intelligent decision support in medical emergency management for mass gatherings,” *Decision Support Systems*, vol. 54, no. 2, pp. 1192–1204, Jan. 2013, doi: 10.1016/j.dss.2012.11.013.