Platology: A Digital Twin Ontology Suite for the Complete Lifecycle of Infrastructure

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Abstract. The construction industry will have to present compelling solutions to achieve the UN societal development goals (SDG). A digital twin has the potential to revolutionize the design, construction, and performance of civil infrastructure assets across the environment. This paper proposes an ontology mapping the physical objects with required attributes aiming to augment built infrastructure development throughout their complete lifecycle in the context of cyber-physical synchronicity of the digital twin paradigm. This research is conducted within the framework of the H2020 project ASHVIN, aiming to develop a real-time Digital Twin for the Design, Construction, and Operation phase of the infrastructure. The proposed "Platology" ontology suite will encompass physical assets and processes of an infrastructure's lifecycle and the possibility for accurate version, configuration, and state management to form a bidirectional communication path between the physical and the virtual.

1. Introduction

The European Union (EU) is embarking on a unique stage of history with significant challenges at its helm such as climate change, rapidly expanding urban areas, deteriorating infrastructure, and a significant need to reduce carbon emissions to which buildings and construction contribute around 40%. The Architecture, Engineering, Construction (AEC) industry being one of the largest consumers of natural resources and generators of waste in addition to being one of the least digitalized sectors has a significant role to play (Kovacic et al., 2020). In order to cope with the above-mentioned challenges, the commitment to the digital transformation of the European construction industry is not only ineluctable but critical in delivering sustainable solutions and meeting the objectives of the European Green Deal (European Construction Sector Observatory, 2021).

Digital solutions are widely used across the construction industry focusing on automating processes across different phases of the infrastructure's lifecycle. Although these systems yield considerable improvements, they largely remain detached from one another. Digital Twins (DTs) offer coherent solutions by integrating many technologies and methodologies to create an effective living system (Boje et al., 2020). In this research study the definition set out for a digital twin is that it is "a digital replica of a building or infrastructure system together with possibilities to accurately simulate its multi-physics behavior (think of structural, energy, etc.) with additional possibilities to represent all important processes through its development lifecycle."

A digital twin (DT) for built infrastructure, as a means to link digital models and simulations with real-world data, opens new possibilities for improving productivity, resource efficiency, and safety. The physical and digital elements of a construction DT involve heterogeneous data formats & different information capturing methods thus resulting in an undefined conceptual framework. The need for holistic thinking is advocated by (Sacks et al., 2020) to incorporate new processes and technologies for a construction DT, which can be attained through the logical approach of ontology and knowledge representation thereby also establishing a

https://doi.org/10.7146/aul.455.c219

conceptual framework. An ontology defines a common vocabulary for a domain with a formal representation of concepts and relations, from the construction DT perspective these can be basic information and technology elements, the relation between them, and their individual and collective functions. Therefore, this paper introduces a systemization of core concepts for the development of an ontology for a digital twin of an infrastructure project through its lifecycle in the form of an ontology suite called "Platology". The paper begins with the introduction and motivation, followed by the review of existing literature related to knowledge representation of digital twins and relevant ontologies. Section 3 summarizes the methodology adopted for ontology specification. Followed by Section 4 presenting Platology. Lastly, the discussion and conclusions are epitomized in Sections 5 and 6.

2. Literature Review

This section contemplates previous research on digital twin knowledge representation and relevant ontology works to give a background and reference for the development of Platology.

2.1 Knowledge Representation for Digital Twins

Digital Twin is a term that was coined in 2003 at the University of Michigan's Executive Course on Product Lifecycle Management (Grieves, 2014). Although at that time the concept was not mature enough due to technological limitations, it has resurfaced in recent years and has become more mature and definitive as the world becomes more interconnected. Despite the fact that the concept of DT was introduced by Grieves in 2003, it was revisited by the National Aeronautics and Space Administration (NASA) in 2012 defining it as "integrated multi-physics, multi-scale, probabilistic, simulation of a system that mirrors the life of its twin promptly using historical data, real-time sensor data, and available physical models". This is still the most used definition of a digital twin in academic publications (Glaessgen and Stargel, 2012).

DTs are essentially nourished by bidirectional interaction between the physical and virtual spheres and therefore establish new possibilities. Data management is decisive for the development and maintenance of any information system, DT being one such concept requires data management to address challenges such as data variety, data mining, and DT dynamics between the virtual and physical spaces (Singh et al., 2021). Ontologies as the basis for the application of semantic web and linked data technologies are a well-established approach for leveraging data and information sources (Zhong et al., 2015). An ontology supports the development of formalized knowledge representation and is essentially an explicit representation of concepts, terminologies, and relationships existing in a particular domain (Gruber, 1995). Ontologies formalize complex engineering knowledge allowing humans and computers to understand and exploit domain knowledge. Furthermore, with knowledge mapping and logic as its basis, it can assist the automation of routine engineering tasks alongside providing computational solutions to complex tasks (Hartmann and Trappey, 2020).

2.2 Knowledge Representation for a Construction Digital Twin

The formulation of workflow for a construction-centred DT system is fragmented and is built upon fundamentals of computing in construction, construction monitoring technologies, and lean construction (Sacks et al., 2020). Recent studies have explored data-driven representations and ontological dimensions of DTs for construction. Sacks et al., (2020) introduced a conceptual evaluation on the characterization of information systems for digital twin construction (DTC) along 4 dimensions explicitly: physical-virtual, product-process, intent-status, data information-knowledge decisions. As a result, by basic classification of information entities into virtual or physical, product or processes, and intended or realized aspects, they establish the required ontological dimensions of digital twins for construction. On the other hand, (Fjeld, 2020) proposed a six-level framework Digital Twin Maturity Index (DTMI) based on the degree of automation and degree of integration between the physical and virtual starting with a Static Twin (Level 100) to an Intelligent Twin at Level 500 with each level possessing the features of lower maturity levels. The contemplated incremental and data-driven approach envisions a process of learning and simulation of several scenarios to become a fully autonomous twin. Further building upon work by Fjeld, (Mêda et al., 2021) advocated the use of digital data templates (DDT) and digital building logbooks (DBL) within the framework of incremental DTC to establish maturity levels that streamline the digital transformation of construction for a circular economy.

2.3 Ontologies for an Infrastructure's Lifecycle

Within the AEC industry, the use of semantic web technologies in the form of ontology development has increased over the years (Pauwels et al., 2018). Ontological studies have focussed on mapping knowledge discretely during the design, construction, and operational phase of an infrastructure's lifecycle. At the initial design phase, Niknam and Karshenas (2017) present a BIM design ontology (BIMDO) approach to conceptualizing the design properties of building elements with further integration with cost-estimation and scheduling knowledge bases to create a resource use profile during the design and planning phase of an infrastructure's lifecycle. In addition, some ontologies have conceptualized the construction stage of an infrastructure's lifecycle. A recent research study by (Zheng et al., 2021) adduces an ontology set of digital construction ontologies (DiCon) formalizing and integrating construction workflow domain information with data from heterogeneous sources and information systems for an organised representation of multi-context data within the digital construction context. Research by Gregor and Tibaut (2020) proposes an ontology-based method for information creation for the digital twin of buildings with its core built on the existing Building Topology Ontology (BOT). Intending to minimize human assistance and processing of raw point cloud data, the authors introduce a BOT-driven approach to translate point cloud data to ontology data (individuals and their object and data properties), which can be further formatted to establish the automated scan-to-BIM aspect for a digital twin. In addition, a study by Liu et al. (2021) introduces the Building Concrete Monitoring (BCOM) ontology mapping the information schema for monitoring of concrete work, concrete curing, and testing of concrete properties. Furthermore, the use of an information container holding information about concrete works and linking it to the IFC-based building model enables possibilities for information flow between the construction and operation phase for the further development of digital twin and asset management.

In the operational phase of the infrastructure, the use of an ontology to model the environment adds richness for intelligent exploitation. (Zhong et al., 2018) developed an ontology-based framework for integration of building information from BIM, building environment monitoring through sensors, and regulatory information based on building regulation and design requirements to automate compliance checking during the monitoring phase of the building's lifecycle. Researchers (Ait-Lamallam et al., 2021) detail an ontological approach IFCInfra4OM for the standardisation of road infrastructure BIM during the operation and maintenance phase of highways through the integration of monitored data into the 3D model to establish a highway information model to manage project data during the operational phase of the highway infrastructure.

Platology envisions to conceptualize the entire lifecycle of infrastructure digital twin, but in this research study, the construction phase is given greater emphasis.

3. Methodology

The name Platology draws inspiration from the ancient Greek philosopher Plato who in his work explained an ontological dualism in which there are two worlds, essentially depicting a DT which is a bridge between real and virtual worlds. In his work, Plato introduces the Theory of Forms which consists of two worlds. The Sensible World consists of individual realities and existence in the realm of material and space things thus representing the real world. Whereas the Intelligible World is the world of eternal and invisible realities called Ideas (or “Forms”) hence characterizing a virtual world (Burt, 1889). Therefore, the ontology presented in this paper introduces Plato’s ontological dualism as a concept underlying DT by illustrating the applicability of the ontology through a knowledge domain aimed at mapping the real physical assets involved in the construction lifecycle and their bi-directional communication with their virtual replicas. Platology is the basis for the ASHVIN platform which represents an open-source real-time DT platform integrating IoT, image technologies, a set of tools, and demonstrated procedures aimed at productivity, cost, and safety for the European construction industry. Figure 1 represents the envisioned data mapping for the ASHVIN digital twin platform. Platology provides a knowledge base for the development of the ASHVIN platform and its DT toolbox. The deliverable D7.1 within the ASHVIN project (Łukaszewska, 2021) gives an extensive insight into the implementation of the ASHVIN platform and tools to be validated on the real-life demonstration projects.

This section presents the methodology adopted to develop Platology. The ontology development is based on the guidelines described by the METHONTOLOGY approach (Fernández-López et al., 1997) which stresses on the processes of knowledge acquisition, conceptualization, implementation, and evaluation.

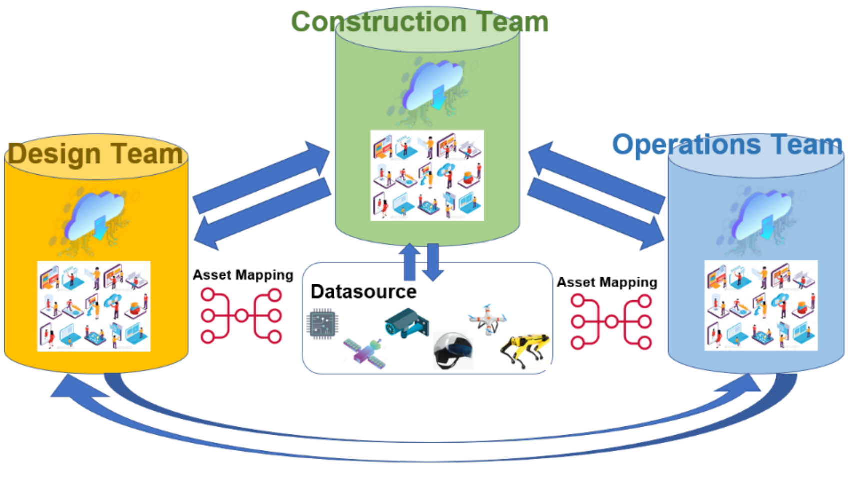

Figure 1: Envisioned data flow for ASHVIN platform.

3.1 Ontology specification

The objective of ontology specification is to give explicit information about the aim and scope of the targeted ontologies and ascertain the intended end-users and requirements of the ontology. This can be established through a list of questions called competency questions that the knowledge base based on the particular ontology should be able to address (Grüninger and

Fox, 1995). Thus, this section presents the specification of Platology using natural language and a set of competency questions (CQs).

What is the purpose? The purpose of Platology is to formalize concepts related to connectivity and information creation between the physical and virtual for an infrastructure DT during its entire lifecycle to enable collaboration among different disciplines through an iterative and coordinated exchange of information.

What is the scope? Platology will cover concepts and relations related to the representation of physical world objects on the construction site during its lifecycle & the IoT enabled sensors and their communication to facilitate a state-of-the-art DT platform. It will further provide a basis for the development of specific toolkits quantified in the research project.

Who are the end-users? The envisioned end-users include those directly using the ontology such as digital twin tech providers, IoT developers, and digital solution providers in the construction industry, alongside European standardization bodies. The indirect users could be those primarily involved in the construction industry such as construction managers, construction workers, architects & designers.

3.2 Knowledge Acquirement and Conceptualization

Knowledge acquisition is needful to determine relevant concepts for the ontology and its domain for developing a class hierarchy and setting class properties. Identification of relevant terms is guided by the specification and competency questions presented in the previous section. The acquirement of knowledge is based on literature review, case studies for digital twins in AEC, and brainstorming with project partners.

For knowledge regarding DTs in construction (Mêda et al., 2021; Sacks et al., 2020) provide implicit knowledge for ontology development. For construction monitoring aspect of the ontology (Boje et al., 2020; Mêda et al., 2021) have been used to develop the classes and sub-classes of Platology. To make the digital twin models of buildings and infrastructure machine-readable, only geometric data is not fully sufficient, instead semantic data consideration is very important as has been shown also as a part in Figure 4. To properly describe and structure this specific information, multiple data modelling concepts are currently being applied. Platology considers the most important data modelling notations and concepts (Borrmann et al., 2015).

4. Platology

Platology encompasses the systemization of physical and digital assets for an infrastructure digital twin through its entire lifecycle (Design, Construction & Operation). The conceptualization is done through a phase-wise approach through the complete lifecycle for the DT of an infrastructure. As illustrated in Figure 2 each *InfrastructureDigitalTwin* during its lifecycle has a *DesignPhase*, *ConstructionPhase*, and *OperationPhase*. Developing an ontology to represent each of these phases could result in a complex, large, and probably unpractical approach. Therefore, the Platology ontology suite mainly consists of three ontologies DesDT, ConDT, and OpDT ontologies for the design, construction, and operation stages respectively for a digital twin of civil infrastructure. For this research study, the construction phase is focused upon to develop the ontological model for the construction phase DT and to limit the scope of demonstration in this paper.

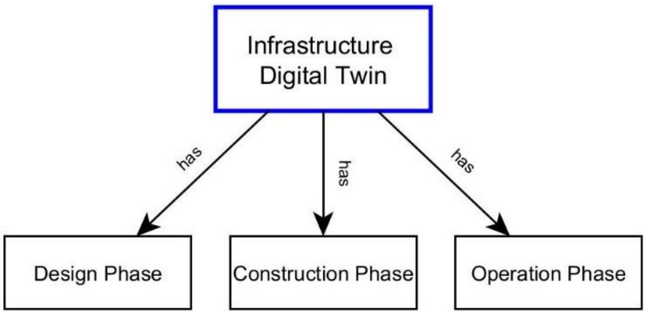

Figure 2: Platology suite with phase-wise lifecycle representation.

4.1 ConDT Ontology

The main classes of construction digital twin ontology (ConDT) comprise of general concepts which are common for a construction DT. The concepts illustrated in Figure 3 capture the domain knowledge of the digital twin of infrastructure during the construction phase. The *PhysicalStructure*, *Processes*, and *DigitalModel* are part of a construction DT and make up the core. Also, the construction DT generates *Outcomes* that can be categorized as the benefits generated due to the implementation of DT during the construction phase. Similarly, the digital twin has *DataResources* which fuel the DT during the construction phase of an infrastructure's lifecycle.

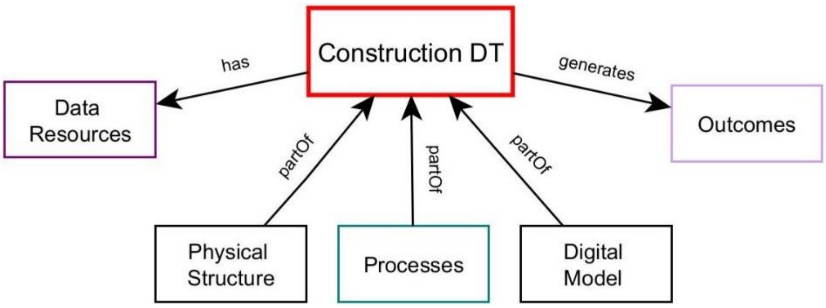

Figure 3: ConDT ontology and its sub-classes.

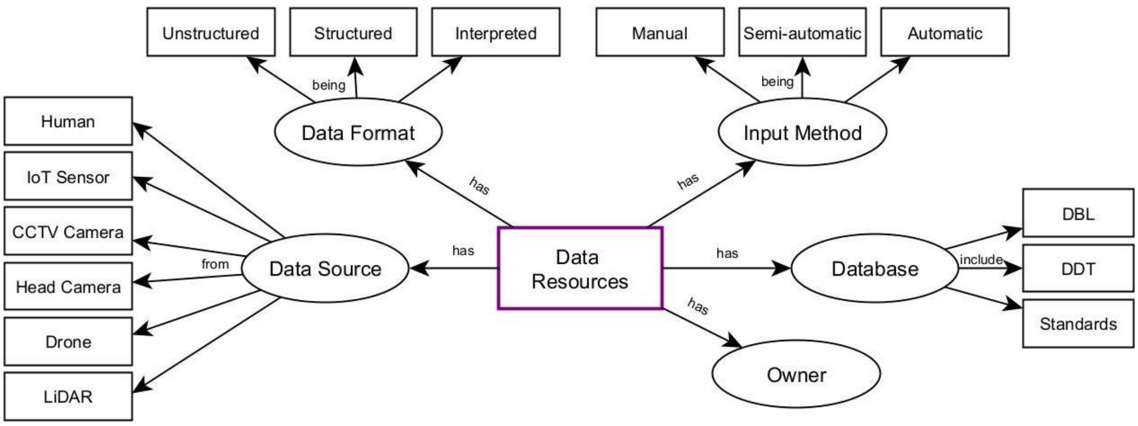

Figure 4: *DataResources* class and knowledge block for different dimensions.

As shown in Figure 4, the *DataResources* class has five main concepts named *DataSource*, *DataFormat*, *InputMethod*, *Database*, and *Owner*. This ontology integrates the dimension of data resources from the ontological framework proposed by Barth et al. (2020) and also incorporates the possible dimensions related to data for a construction DT. The sub-classes *DataFormat* and *InputMethod* show the type of data format and the automation level of data collection. Additionally, the data resources can include a *Database* that can consist of relevant standards, historical data, digital building logbooks (DBL), and digital data templates that can augment data-driven construction for the deployment of digital twins (Mêda et al., 2021).

The *Processes* class essentially represents the processes required to define the workflow for construction centered on digital twins and form the link between the physical structure and the digital model of a construction DT. Figure 5 depicts the relevant processes such as *ConfigurationManagement* to maintain consistency among requirements, design, configured items & associated construction, *ConstructionSimulation* for simulation of construction sequence & activities and *LeanPlanning* to support lean project planning.

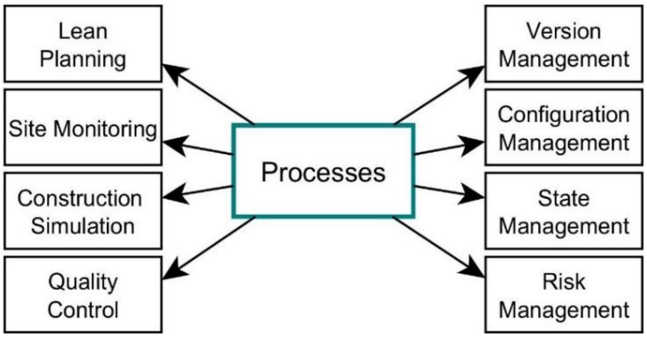

Figure 5: Processes representation for a construction DT.

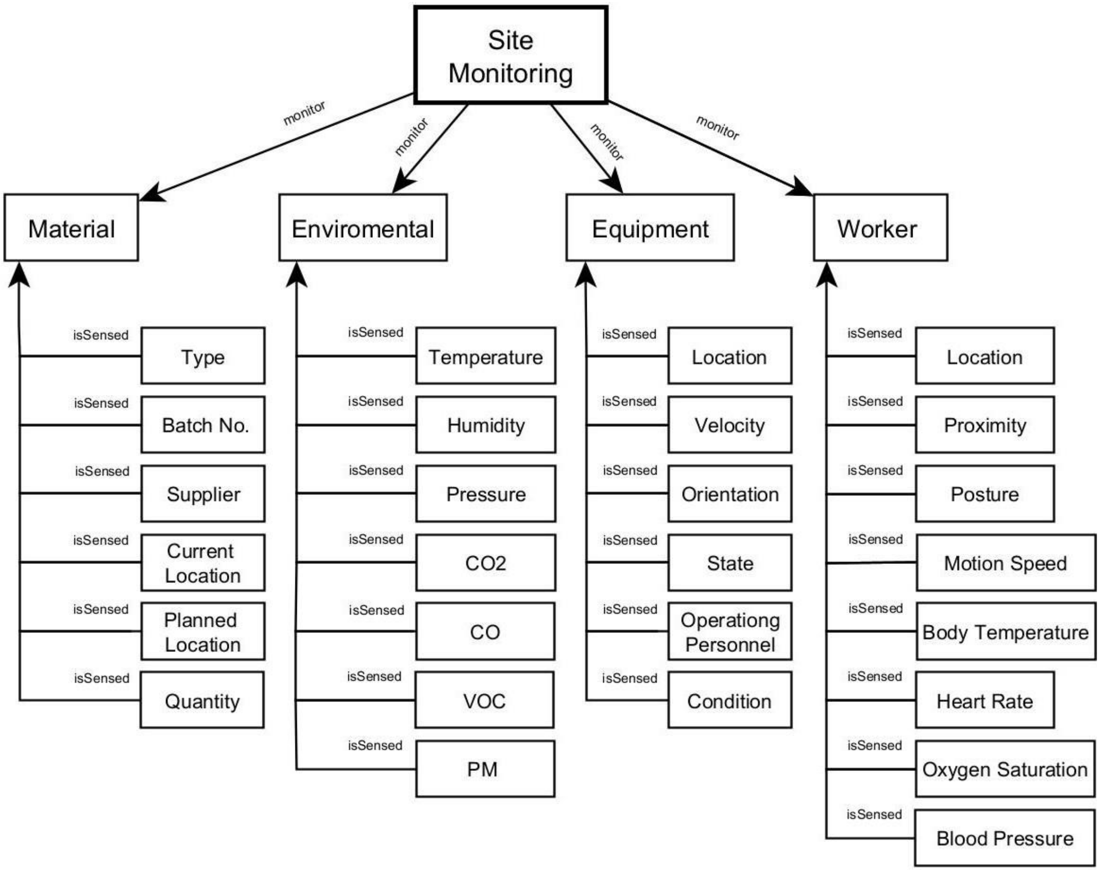

Figure 6: Site monitoring conceptualization.

To support a DT, a sensored construction site is necessary to monitor construction material, environment, equipment or machines, and workers (Calvetti et al., 2020). Figure 6 conceptualizes the dimensions of the process *SiteMonitoring* for various aspects that are monitored such as *Material*, *Environmental*, *Equipment*, and *Worker*. Each dimension has parameters that can be sensed to enable data collection and analysis. Monitoring of equipment through parameters such as *Location*, *State*, and *Condition* facilitates better allocation of resources and optimization of equipment usage.

Figure 7 illustrates the outcomes generated through DT application enabling productive, resource efficient, and safe construction. Each outcome (*Productivity*, *ResourceEfficiency*, *Safety*, and *Cost*) has performance indicators (PI) identified for planning and controlling construction activities. Each sub-class of *Outcomes* has PI which contributes to its implementation. The PI were identified to support the implementation during construction works on ASHVIN demonstration projects and ASHVIN tools.

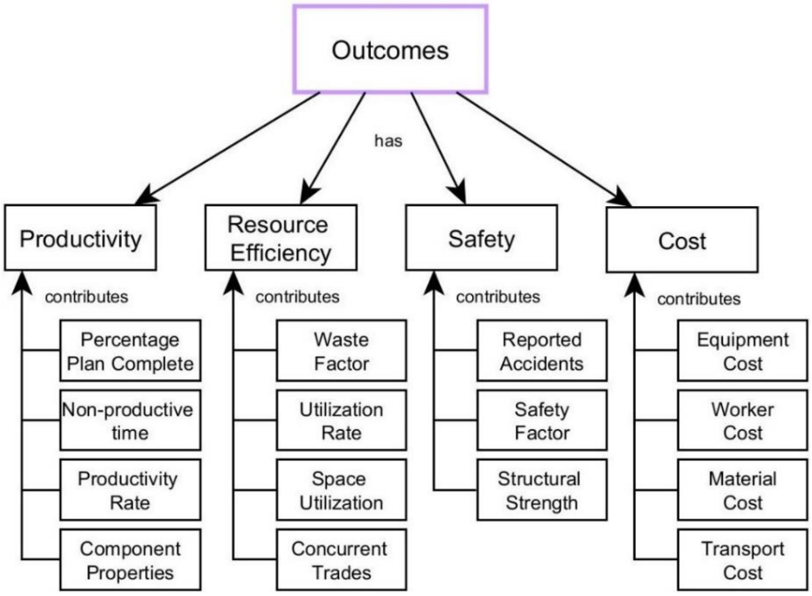

Figure 7: DT-related outcomes for the construction phase.

5. Discussion

The proposed Platology aims to conceptualize knowledge and concepts related to DT of civil infrastructure through their entire lifecycle. In this research paper, the construction phase is given emphasis, and attributes concerning DT of a construction site are defined in the form of an ontology ConDT. The knowledge systemization of the design and operation phases alongside information exchange between these phases based on the incorporation of interoperability task within ASHVIN planned under future research will enrich the ontological model to enable a semantic real-time DT platform for civil infrastructures. Future research work shall include validation of Platology and ConDT to verify its competency against the problems identified. The knowledge base Platology is tailored to be applicable across demos-sites within the research project ASHVIN. With further instantiation for a few selected demos-sites (Table 1), the knowledge base will enrich its potential. Future activities also include implementing Platology using OWL/RDF to develop a machine-readable model.

Moreover, ConDT ontology doesn't conceptualize details regarding the physical process of the construction site, ontologies such as Building Topology Ontology (BOT) defining core concepts of a building can be used to connect with ConDT ontology and will be part of future work. Also, the processes forming the link between the digital and physical part of a DT can be explored more in detail, with only the *SiteMonitoring* process conceptualized in this study. The proposed approach will evolve, as the development of the DT in terms of applicability is still at the outset and research along with real cases in the particular area are just emerging. Thus, the addition of new dimensions or refining the definition outlined in this paper is highly plausible.

Table 1: Real-world infrastructure projects under the ASHVIN consortium.

Infrastructure project	Lifecycle (Phase)	Location
Kineum office building	Construction	Gothenburg, Sweden
Logistic hall	Construction	Rinteln, Germany
Highspeed railway bridges	Monitoring	Spain

6. Conclusion

This paper advocates and outlines an approach for the conceptualization of knowledge for digital twins of civil infrastructure projects through their entire lifecycle. The linkage between objects existing in the physical world (construction (sub-) products, the environment, construction machinery) and their virtual replicas and simulations for a DT is vital. The knowledge systemization of this aspect has not been widely explored. Hence the motivation for the proposed ontology is to contribute towards a common understanding of the dimensions of the construction digital twins. The proposed ontology and framework support researchers and professionals in structuring and positioning their construction DT activities with their manifold benefits and communicating with internal and external stakeholders. Furthermore, the ConDT ontology provides a conceptual view of information, physical and virtual parameters of construction that can aid in the formulation of a real-time digital twin platform for construction.

Acknowledgements

This research project is funded under the European Union’s program Horizon 2020 research and innovation programme under grant agreement no 958161.

References

Ait-Lamallam, S., Sebari, I., Yaagoubi, R., Doukari, O., 2021. IFCInfra4OM: An ontology to integrate operation and maintenance information in highway information modelling. ISPRS International Journal of Geo-Information 10.

Barth, L., Ehrat, M., Fuchs, R., Haarmann, J., 2020. Systematization of Digital Twins: Ontology and Conceptual Frameworkenvironment. In: Proceedings of the 2020 The 3rd International Conference on Information Science and System. ICST, pp. 13–23.

Boje, C., Guerriero, A., Kubicki, S., Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction 114.

Borrmann, A., König, M., Koch, C., Beetz, J., 2015. Chapter 3 Data Modeling. In: Building Information Modeling.

Burt, B.C., 1889. A BRIEF HISTORY OF GREEK PHILOSOPHY. Boston, Ginn & Co.

Calvetti, D., Mêda, P., Gonçalves, M.C., Sousa, H., 2020. Worker 4.0: The future of sensored construction sites. Buildings 10.

European Construction Sector Observatory, 2021. Digitalisation in the construction sector. Brussels.

Fernández-López, M., Gómez-Perez, A., Juristo, N., 1997. METHONTOLOGY: from Ontological Art towards Ontological Engineering. In: Proceedings of the AAAI-97 Spring Symposium. pp. 33–40.

Fjeld, T.M.B., 2020. Digital Twin-Towards a joint understanding within the AEC/FM sector. Norwegian University of Science and Technology, Trondheim.

Glaessgen, E.H., Stargel, D.S., 2012. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles.

Gregor, M., Tibaut, A., 2020. Ontology based information creation approach for digital twins: Early-stage findings. In: Studies in Computational Intelligence. Springer Verlag, pp. 405–413.

Grieves, M., 2014. Digital Twin: Manufacturing Excellence through Virtual Factory Replication. Whitepaper.

Gruber, T.R., 1995. Toward Principles for the Design of Ontologies Used for Knowledge Sharing? International Journal of Human-Computer Studies 43, 907–928.

Grüninger, M., Fox, M.S., 1995. Methodology for the Design and Evaluation of Ontologies. In: Proceedings of the Workshop on Basic Ontological Issues in Knowledge Sharing, ICJAI-95. Montreal.

Hartmann, T., Trappey, A., 2020. Advanced Engineering Informatics - Philosophical and methodological foundations with examples from civil and construction engineering. Developments in the Built Environment 4, 100020.

Kovacic, I., Honic, M., Sreckovic, M., 2020. Digital Platform for Circular Economy in AEC Industry, Engineering Project Organization Journal.

Liu, L., Hagedorn, P., König, M., 2021. An Ontology integrating As-Built Information for Infrastructure Asset management using BIM and Semantic Web. In: 2021 European Conference on Computing in Construction.

Łukaszewska, A., 2021. D7.1 ASHVIN TECHNOLOGY DEMONSTRATION PLAN [WWW Document]. URL https://zenodo.org/record/5542985 (accessed 4.18.22).

Mêda, P., Calvetti, D., Hjelseth, E., Sousa, H., 2021. Incremental digital twin conceptualisations targeting data-driven circular construction. Buildings 11, 554.

Niknam, M., Karshenas, S., 2017. A Shared Ontology Approach to Semantic Representation of BIM Data. Automation in Construction 80.

Pauwels, P., Poveda-Villalón, M., Sicilia, Á., Euzenat, J., 2018. Semantic technologies and interoperability in the built environment. Semantic Web 9, 731–734.

Sacks, R., Brilakis, I., Pikas, E., Xie, H.S., Girolami, M., 2020. Construction with digital twin information systems. Data-Centric Engineering 1, e14.

Singh, S., Shehab, E., Higgins, N., Fowler, K., Reynolds, D., Erkoyuncu, J.A., Gadd, P., 2021. Data management for developing digital twin ontology model. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 235, 2323–2337.

Zheng, Y., Törmä, S., Seppänen, O., 2021. A shared ontology suite for digital construction workflow. Automation in Construction 132.

Zhong, B., Gan, C., Luo, H., Xing, X., 2018. Ontology-based framework for building environmental monitoring and compliance checking under BIM environment. Building and Environment 141, 127–142.

Zhong, B.T., Ding, L.Y., Love, P.E.D., Luo, H.B., 2015. An ontological approach for technical plan definition and verification in construction. Automation in Construction 55, 47–57.