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OPEN LETTER

Ontologies in digital twin: Methodology, lessons learned and practical approach

[version 1; peer review: 3 approved with reservations, 1 not approved]

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Abstract

This article is a result of joint workshop which took place during Sustainable Places 2022 conference in Niece, France, and was co-organized by the Building Digital Twin Association (BDTA) and six EU-funded projects that have developed a construction-phase digital-twin data model, and their ontological representation, which is capable of capturing all data requirements for the digital representation of building and/or infrastructure construction sites. Four of the EU-funded projects participating in the event contribute to this Open Letter which aims to highlight the relevance of ontology in the digital twin environment, and the approach by the different EU-funded projects. All four LC-008-EEB funded projects contributing to this article (BIMprove, COGITO, ASHVIN and BIM2TWIN), agreed on joining forces for raising awareness around Digital Building Twins and its impact in the construction industry. Their primary aim is to share knowledge, experiences and research outcomes with other stakeholders and communities around the EU and beyond, via online communication like webinars, newsletters, social media channels and scientific or technical articles. This initiative aims at delivering the wide range of digital tools for the construction sector needed on the European market and to raise awareness about the benefits coming from their use.

Keywords

ontology, digital twin, construction, digitalization

Open Peer Review

Approval Status ? ? ✗ ?

	1	2	3	4
version 1 22 Jun 2023	? view	? view	✗ view	? view

1. **Xiao Li**, The University of Hong Kong, Hong Kong, Hong Kong
2. **Edlira Kalemi Vakaj**, Birmingham City University, Birmingham, UK
3. **Mohamad Kassem**, Newcastle University, Newcastle upon Tyne, UK
4. **Claudio Mirarchi**, Politecnico di Milano, Milan, Italy

Any reports and responses or comments on the article can be found at the end of the article.



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This article is included in the Digital Twins collection.



This article is included in the Sustainable Places 2022 collection.

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Author roles: Mikołajczyk A: Project Administration, Writing – Review & Editing; **García-Castro R**: Writing – Original Draft Preparation; **Tomar R**: Writing – Original Draft Preparation; **Khan R**: Writing – Original Draft Preparation; **Teclaw W**: Writing – Original Draft Preparation; **Fies B**: Writing – Original Draft Preparation; **Schlenger J**: Writing – Original Draft Preparation

Competing interests: No competing interests were disclosed.

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Abstract

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Keywords

ontology, digital twin, construction, digitalization

Open Peer Review

Approval Status *AWAITING PEER REVIEW*

Any reports and responses or comments on the article can be found at the end of the article.

This article is included in the Civil Engineering gateway.



This article is included in the Electrical, Electronic and Information Engineering gateway.



This article is included in the Horizon 2020 gateway.



This article is included in the Digital Twins collection.

Corresponding author: Agnieszka Mikołajczyk (a.mikolajczyk@asmresearch.pl)

Author roles: Mikołajczyk A: Project Administration, Writing – Review & Editing; **García-Castro R**: Writing – Original Draft Preparation; **Tomar R**: Writing – Original Draft Preparation; **Khan R**: Writing – Original Draft Preparation; **Teclaw W**: Writing – Original Draft Preparation; **Fies B**: Writing – Original Draft Preparation; **Schlenger J**: Writing – Original Draft Preparation

Competing interests: No competing interests were disclosed.

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Introduction

Digital twin is a technology that has been present and developed for years. The digital twin allows testing of the hardware and software installed in a given space, which allows primarily to optimize costs. According to Deloitte, the global market using digital twins will grow by up to 38% by 2023. These forecasts have their source in the observations of the market of new technologies in 2020. It was then that the digital twin became one of the most important trends.

Ontologies provide the basis for the digital twin solutions as they encompass a set of domain-specific models and relationships between entities for designing, creating, and parsing a digital twin graph; thus, many benefits can be recognized by the construction industry actors, especially in terms of business management. Ontologies enables easier data interoperability, they help to systematize software components, they reduce investments in system developments, and they provide the outcomes of lessons learned during the development process to avoid making the same mistakes. Thanks to ontologies, elaborated models and described relationships construction manager is able to plan works on site in advance, using the process as a good practice and avoiding unexpected failure.

Digitalisation for lean construction is a steppingstone to achieve the industrialisation of the construction sector, although buildings and infrastructures' construction phase has so far been overlooked by the Digital Twin community. Going beyond "static" Building Information Modelling (BIM) is required by leveraging technologies like IoT, Cloud Computing and Artificial Intelligence. However, lack of commonly agreed standards and low interoperability among collected data reveal a major drawback to the enterprises' digital transformation, even for large construction enterprises with full access to state of the art digital, reality capture tools. Construction projects require collaboration between many parties and it comes as no surprise that often different, non-transparent platforms for digital data handling are used.

Four EU-funded projects BIMprove, COGITO, ASHVIN and BIM2TWIN (described in detail below) have developed a construction-phase digital-twin data model, and their ontological representation, which is capable of capturing all data requirements for the digital representation of building and/or infrastructure construction sites. The cooperation between the 4 EU-funded projects, includes organizing joint workshops every year to highlight each aspect of digital twin solutions provided by each project. The series of joint workshops is a part of Sustainable Places conference since 2021, and will be continued in 2023.

The aim of this Open Letter is to present the approach to ontologies in digital twin environment by different EU-funded projects which provides solutions in this area for the European construction industry.

The objectives of the article are:

- to present the ontology concept of each innovative project,
- to raise awareness around the digital twin environment in the context of construction sector,
- to highlight the benefits of the ontology concepts for the construction projects.

COGITO

The COnstruction phase diGItal Twin mOdel (COGITO) project aims to establish a Digital Construction 4.0 toolbox, which will be available for the tools users, that integrates: reality capture technology to collect data capturing the actual state of operations from construction sites; Building Information Models (BIMs) initially containing design and planning information and subsequently augmented with as-built data; and innovative integrated data management and software solutions to optimise site operations.

The COGITO Digital Construction 4.0 Toolbox will effectively deliver a "Digital Twin" of construction operations and employ it for improving performance in terms of safety, quality, schedule and cost. The reality capture tools will include digital cameras, laser scanning, and resource tracking sensors.

An important contribution of the project is in developing methods to ensure interoperability among the different components constituting the digital twin ecosystem. This includes the development of the COGITO ontology network that will integrate all data/information in a model that can be meaningfully queried by the software tools.

The COGITO ontology network has been developed following the Linked Open Terms (LOT) methodology [Poveda-Villalón *et al.*, 2022], which includes four activities: 1) ontology requirements specification, 2) ontology implementation, 3) ontology publication, and 3) ontology maintenance. The COGITO ontology portal (available here) contains the latest version of the ontologies and all related artefacts for ontology development.

The COGITO ontology network consists of seven modules corresponding to the facility (the construction itself and the construction project), the construction process, the construction resources, the IoT devices used to locate resources, the quality information managed by the project, the safety information related to the facility, and the entities managed by the digital twin platform (digital twins and information resources).

Figure 1 provides a graphical overview of the COGITO ontology network showing the main concepts defined in each module.

ASHVIN

The aim of the ASsistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance

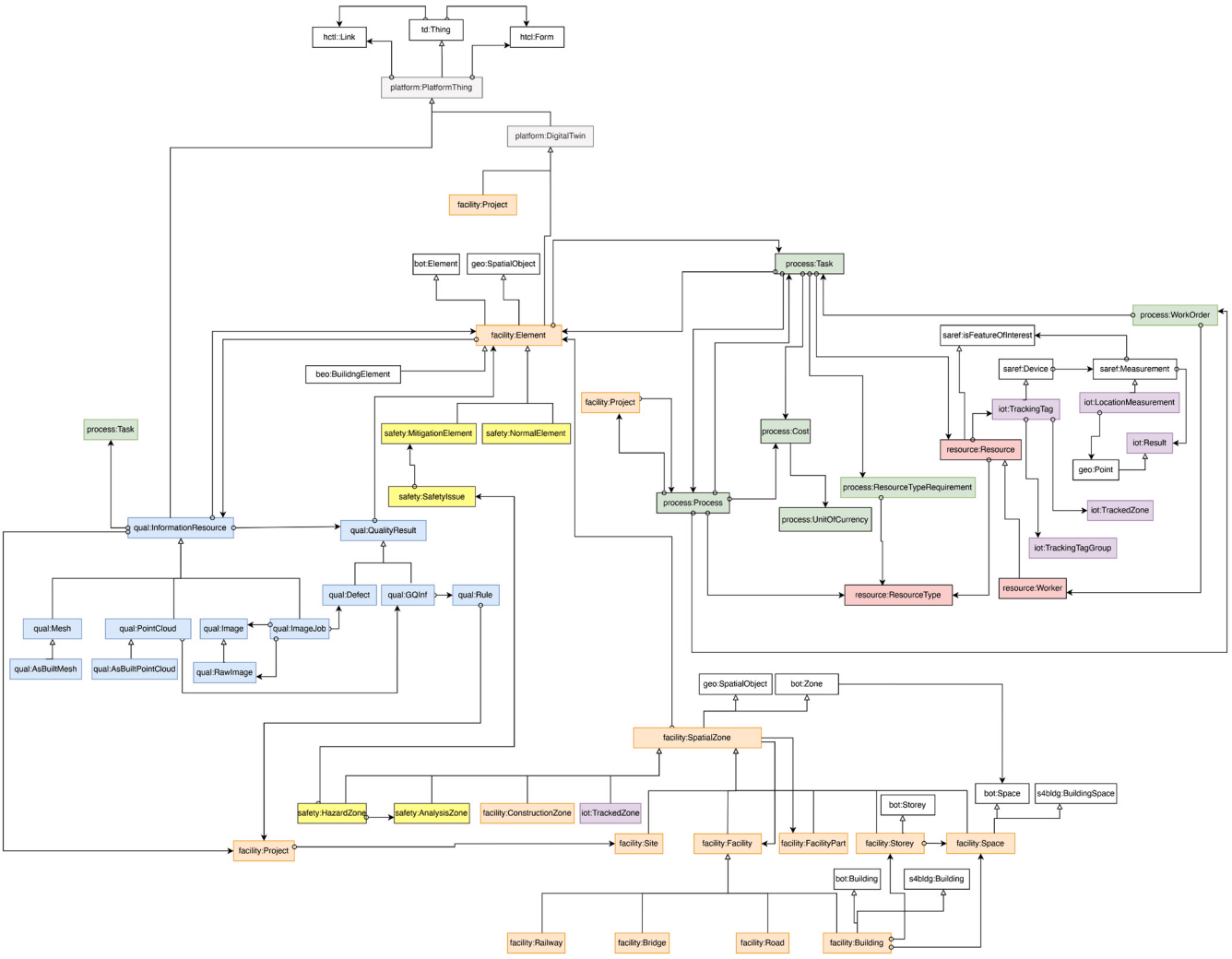

Figure 1. Overview of the COGITO (The COnstruction phase diGItal Twin mOdel) ontology network.

using a Digital Twin (ASHVIN) project is the digitalization of the construction industry to improve designated key performance indicators (KPIs): productivity, resource efficiency, and safety through the application of digital twin technology. To this end processes were developed for coherent information integration within and through the design/engineering, construction, and maintenance of civil infrastructure projects. The Ashvin DT platform implements the main functionality that allows collecting IoT-related data from construction site processes and convert this data into meaningful information that can be consumed by different tools. Accordingly, an ontology was developed (not yet available) to map the physical entities with the necessary attributes to their virtual entities in the context of cyber-physical synchronicity of the construction digital twin model.

The ontology systemizes the core concepts for the development of the digital twin of an infrastructure project lifecycle through an ontology suite called "Platology". It primarily comprises of DesDT, ConDT, and OpDT ontologies for the design, construction, and operation phases correspondingly for a digital twin of civil infrastructure and is purposed to be applicable across different ASHVIN demo-sites projects (see Figure 2).

Figure 2 illustrates the fundamental classes i.e., BuiltEnvironment, Processes, and DigitalAsset of a construction phase DT. The class Outcomes represent the predicted advantages due to the implementation and DataResources which fuels the application of DTs during construction.

To summarize, Platology conceptualizes information, physical and virtual parameters of construction to support the development of the ASHVIN DT platform and contribute to a common understanding of facets of construction digital twins. The aim for Platology is to evolve with further development

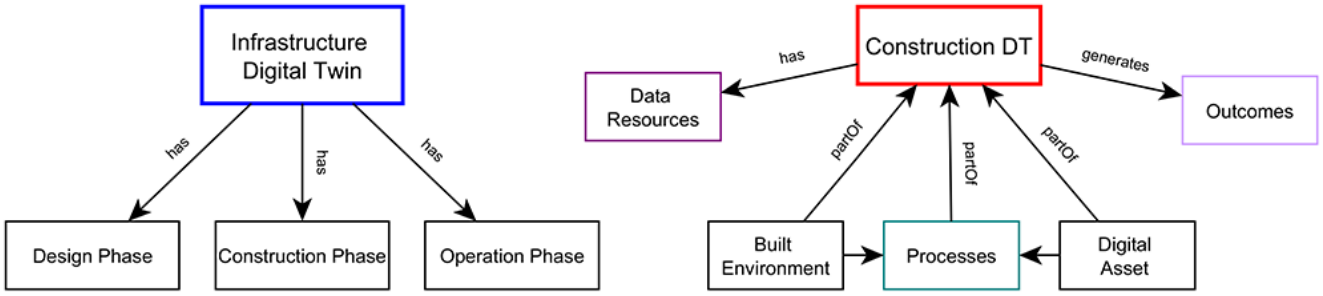

Figure 2. Platology and ConDT ontology overview. DT, digital twin.

of digital twins in terms of applicability and as real-life application cases emerge in the near future.

BIMprove

The concept of the origins of the digital twins was proposed by Michael Grieves in the early 2000s (Grieves, 2014). In the following years, researchers and industry professionals developed multiple tools and technologies which are now used as core concepts for DT development. One crucial technology is knowledge graphs allowing for machine and human interpretability of stored data in the form of a graph (Boje *et al.*, 2020). In the BIMprove project, such an approach has been used to semantically link risk with images, risk type and risk zone, as presented in Figure 3.

The first benefit of implementing an ontological approach to risk representation is the ability to merge data from different sources and express them in a machine and human-interpretable forms. The key concept of digital twin requires the information's bi-directional flow. During the BIMProve project, researchers demonstrated the usage of UAVs (Unmanned Aerial Vehicle), UGVs (Unmanned Ground Vehicle) to capture the data in the form of sets of 2D images, point clouds and thermal images. Then processing the data through ROVAS (Risk Object Visual Analysis System) is human and machine-readable. This feature allowed us to demonstrate the practical implementation of systems providing fall-from-height and fire safety prevention (Edvardsen, 2022). Discovered risks associated with a danger zone were sent to all workers in certain areas, warning them about occurring hazards.

Moreover, the well-structured and organized stored graph database allows researchers to better plan, execute and predict hazards during erecting of a construction object, making the construction site cleaner, safer and more organized.

BIM2TWIN: Optimal construction management and production control

The BIM2TWIN project aims at building a Digital Building Twin (DBT) platform for construction management that provides full situational awareness and an extensible set of construction management applications.

This platform relies on several ontologies (they are organized into three layers: data, information, and knowledge -– Ackoff, 1989) that provide the requested semantics to contextualize various types of data related to the construction phase. While data can be understood as raw data coming from the construction site, information and knowledge are created by dedicated digital twin services that process and analyse data to extract information and thus generate knowledge.

These sub-ontologies rely on existing ontologies as much as possible. The B2T data ontology (not yet publicly available) is used to catalogue the available raw data with their storage locations, reusing SOSA (Ontology for Sensors, Observations, Samples, and Actuators) and SSN (Semantic Sensor Network Ontology) to describe different types of sensors and their measurement results (Haller *et al.*, 2018). The B2T core ontology is used for the information layer, mainly concerning the construction processes and their preconditions, working zones, resources, and, finally, the building structure, which relies on the BOT ontology (Rasmussen *et al.*, 2020). Special attention has been put on modelling construction processes on several granularity levels inspired by the Takt planning concepts. Another unique feature of the B2T core ontology is explicitly modelling the project intent and status, allowing direct comparison. Finally, the B2T KPI ontology defines construction related KPIs, like cycle time and equipment utilization rate, using and extending Quantities, Units, Dimensions and Types - QUDT (Ray *et al.*, 2011). Currently, all B2T ontologies are undergoing an intense testing phase and will be made public once they have reached a stable state.

With these data structures, a close link between project intent, construction schedule, and other planning documents and the information captured on the construction site is achieved.

Recommendations and next steps

All 4 EU-funded projects are developing, testing and improving their solutions at different stages. It is recommended to

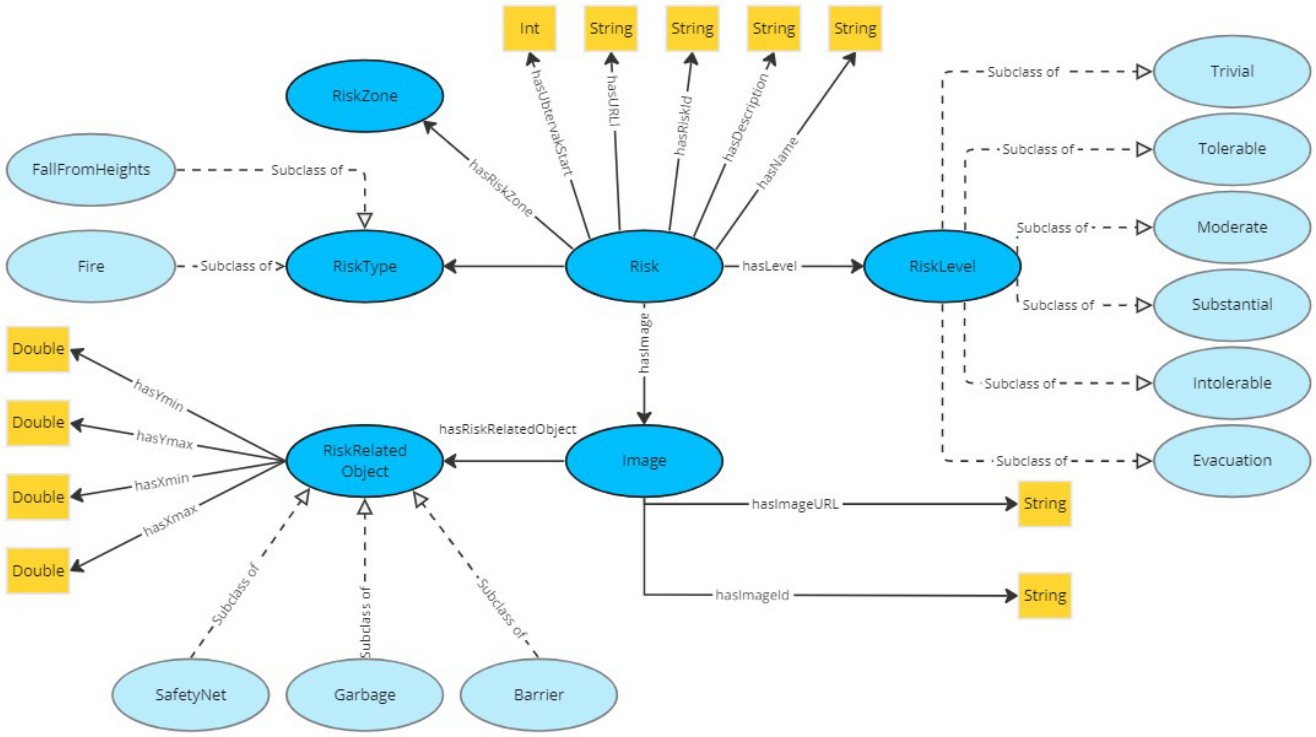

Figure 3. Risk ontology. Reproduced with permission from Purhonen, Aihkisalo and Niskanen (2022).

follow the results within the projects duration, taking part in webinars, workshops, and gain knowledge about all projects directly from the main sources of information.

Conclusions

In the open letter, details about the ontology concepts in each EU-funded project are announced, explaining the benefits of ontologies in developed digital twin solutions. First of all, it ensures better planned, safer and well-organized construction site. Secondly data structures provide a clear path from the construction project intent, through the documents, schedules, and information captured on the construction site. Thirdly, a systemization of core concepts for the development of the digital twin of an infrastructure project lifecycle is presented in the form of an ontology.

Data availability

No data are associated with this article.

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Reference Source

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Publisher Full Text

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Publisher Full Text

Open Peer Review

Current Peer Review Status: ? ? ✗ ?

Version 1

Reviewer Report 14 August 2024

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?

Claudio Mirarchi
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Lombardy, Italy

The article, as an open letter, presents the results developed in four EU-funded projects considering in detail the development and use of ontologies around the Digital Twin concept.

The reviewer agrees with the importance of exploring, developing and use ontologies in the construction sector and with the central role that dissemination and knowledge sharing have in this context.
The ontology concept is nowadays one of the central one in the research and industrial development. To support the reader in understanding the context of application, the introduction should provide information about the existing approaches and limitations in the data exchange for digital twin considering e.g. existing standard data schema like IFC, the use of common data environments and platforms.

Following the same criteria, and considering the three objectives stated in the introduction, it would be valuable including a discussion section where the results of the four projects are discussed and generalized to understand their relations and their benefits in a transversal way, that is on the construction sector in general.

Is the rationale for the Open Letter provided in sufficient detail? (Please consider whether existing challenges in the field are outlined clearly and whether the purpose of the letter is explained)
Yes

Does the article adequately reference differing views and opinions?
Partly

Are all factual statements correct, and are statements and arguments made adequately supported by citations?

Partly

Is the Open Letter written in accessible language? (Please consider whether all subject-specific terms, concepts and abbreviations are explained)
Yes

Where applicable, are recommendations and next steps explained clearly for others to follow? (Please consider whether others in the research community would be able to implement guidelines or recommendations and/or constructively engage in the debate)
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My research area is related to the knowledge management (KM) in construction sector considering especially the digital aspects that can support KM. In detail my research is focused on the exploration of information systems for the KM in construction.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 27 March 2024

https://doi.org/10.21956/openreseurope.16513.r33195

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Mohamad Kassem
School of Engineering, Newcastle University, Newcastle upon Tyne, England, UK

The report looks more like minutes and description of existing funded projects rather than an open letter.
There are no challenges and recommendations provided but an individual description of the four projects on the topic of DT for construction phase and in particular their enabling ontologies.
For example, there is not across-analysis of data types or approaches from across the four projects which can be done only if deeper knowledge sharing and learning between the projects takes place .
There are no actionable findings (recommendations) from the meetings that took place during Sustainable Places 2022 conference.
Some other specific comments:
It is clear that the focus of the projects is on digital twin for construction phase. But it is not clear why lean construction come up so early in the introduction which should be simply introducing the rationale about the need for an ontology. It is not a priority to add Lean to the introduction when everything else (ontology, interoperability, etc.) need to be introduced and addressed.

The aim expressed in the abstract ("Their primary aim is to share knowledge, experiences and research outcomes with other stakeholders and communities around the EU and beyond, via online communication like webinars, newsletters, social media channels and scientific or technical articles") is not a suitable aim for this open letter but it rather the aim of the conference that took place.
Finally, it looks like it is too early for the projects to issue an open letter. What is presented here are just general summaries of existing info from project funded, not derived from an actual knowledge sharing/exchange..

Is the rationale for the Open Letter provided in sufficient detail? (Please consider whether existing challenges in the field are outlined clearly and whether the purpose of the letter is explained)
Partly

Does the article adequately reference differing views and opinions?
No

Are all factual statements correct, and are statements and arguments made adequately supported by citations?
Yes

Is the Open Letter written in accessible language? (Please consider whether all subject-specific terms, concepts and abbreviations are explained)
Yes

Where applicable, are recommendations and next steps explained clearly for others to follow? (Please consider whether others in the research community would be able to implement guidelines or recommendations and/or constructively engage in the debate)
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Digital Construction, BIM and Digital Twin.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 30 August 2023

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Edlira Kalemi Vakaj
Birmingham City University, Birmingham, England, UK

The article elaborates on the importance of Digital Twins (DTs) in the Build Environment domain with a specific emphasis on ontologies as an important step towards scalable and sustainable DTs.

The challenges as well as the opportunity to overcome those challenges are real and the cases elaborated in each of the projects demonstrate this.

The article can still benefit from some improvements:

Abstract:

The main aim of the article does not reflect the title and brings confusion.

Introduction:

The sections can be organized better for example in paragraph three digitalisation (a wider concept) is described, while ontologies (a specific concept) are mentioned in paragraph 2.

Content-wise there is no mention of other initiatives or projects contributing to the same problem. This can serve comparative discussion or re-enforce your results. The ontology approach is quite elaborated already in the AEC space.

Conclusions:

How are the outcomes (ontologies) of these 4 projects integrated into DTs as complementary, or if not is there a plan to work towards that and use the advantages mentioned about ontologies?

Is the rationale for the Open Letter provided in sufficient detail? (Please consider whether existing challenges in the field are outlined clearly and whether the purpose of the letter is explained)
Partly

Does the article adequately reference differing views and opinions?
Yes

Are all factual statements correct, and are statements and arguments made adequately supported by citations?
Yes

Is the Open Letter written in accessible language? (Please consider whether all subject-specific terms, concepts and abbreviations are explained)
Yes

Where applicable, are recommendations and next steps explained clearly for others to

follow? (Please consider whether others in the research community would be able to implement guidelines or recommendations and/or constructively engage in the debate)
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Ontology Engineering

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 22 August 2023

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Xiao Li
Department of Civil Engineering,, The University of Hong Kong, Hong Kong, Hong Kong

This study aims to highlight the relevance of ontology in the digital twin environment, which is capable of capturing all data requirements for the digital representation of building and/or infrastructure construction sites. And the approach taken by the different EU-funded projects.

Overall, the structure of article is clear, and the practice case can represent the effectiveness of the method. However, the images provided in the article make it difficult to extract useful information. Specific suggestions are as follows:

1. Introduction:
    - The discussion about the issues addressed by digital twin models in the introduction is not very detailed. What are the unique advantages of digital twin models that make them suitable for project management and construction, compared with data-driven models?
2. BIMprove:
    - The first sentence in this section repeats the introduction to the concept of DTS. Perhaps it could be incorporated into the introduction section.
    - In the second paragraph, the first advantage of the ontological approach is mentioned, but there is no further mention of other benefits.
3. Conclusions:
    - The author might provide a summary of the unique advantages and future directions of integrating ontology with DTS in this section.
4. Figure:
    - The font size in Figure 1 is too small, making it difficult to read.

Is the rationale for the Open Letter provided in sufficient detail? (Please consider whether existing challenges in the field are outlined clearly and whether the purpose of the letter is explained)
Partly

Does the article adequately reference differing views and opinions?
Yes

Are all factual statements correct, and are statements and arguments made adequately supported by citations?
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Where applicable, are recommendations and next steps explained clearly for others to follow? (Please consider whether others in the research community would be able to implement guidelines or recommendations and/or constructively engage in the debate)
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: contruction informatics and industrialization

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.