CONSTRUCTION PROGRAMME & PRODUCTION CONTROL (CPPC) ONTOLOGY : A REQUIRED INTEGRATION FOR CONSTRUCTION DIGITAL TWIN

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Abstract

With ongoing development of construction digital twins, several works presented in the last couple of years are taking the same approach, solutions, steps, and findings of Building Information Modelling (BIM). This piece of work is questioning if that is enough or we could be misinformed by the BIM's survivorship bias of what information should be collected, integrated, and visualized in construction sites. This research is a part of ongoing research project exploring the application of construction digital twins through production control rooms. In this research, an ontology related to construction programme and production control (CPPC) is proposed. The proposed ontology is shared representation that specify the terms and relations of production control in construction. The development is based on a real case study in the U.K and it is mapped to existing ontologies such as BOT, DiCon and Prov. The developed ontology was evaluated by automatic consistency checking, evaluating the SPARQL queries against the competency questions and representing the outputs to stakeholders of the selected construction project. The results show that the ontology represents the domain knowledge and demonstrates its' efficiency to enhance the production control of construction sites.

Introduction

The construction sector is known for the fragmentation of specializations, which has resulted in inefficiencies, uncertainties, and wasteful resources (Murtagh et al., 2020). The main reason behind that is the project stakeholders are focusing only on their individual tasks and data and neglecting the interdependencies of the tasks and data of the entire project (Hwang et al., 2020). Also sometimes the root causes of the waste generated and/or the delay of projects are related to relatively minor factors which could easily have been overcome if the managers are aware of (Povetkin and Isaac, 2020). Therefore, several project delivery approaches have been formed with the aim of improving the performance and reducing the waste in construction project. These approaches, includes Integrated Project Delivery (IPD) and Virtual Design and Construction (VDC), Digital Twins (DT) were armed with several technologies such as such as Building Information Modelling (BIM), Geographic Information System (GIS), 4D, and real-time data sources such as cameras, mobile and sensors (Hwang et al., 2020). These techniques and technologies have been adapted in several construction management systems and environments to better control, visualize, and interact with construction data. However, integrating and visualizing all the information from the different technologies and systems has become a new challenge to overcome to effectively develop construction digital twins (Isaac and Navon, 2014; Sacks et al., 2020).

In Knowledge Engineering, researchers see ontology as a computational model that enables automated reasoning and it is formal and sharable (Borst, 1999). With the aim of managing and integrating the retrieved information from the different tools and systems adopted in the construction industry, many efforts and work have been taking place to bring the ontology concept to the construction sector (Pauwels et al., 2017). The reason behind that is these success stories of ontologies and linked data implementation in domains such as biology, medical records, cultural heritage, accounting, and social media (Schmachtenberg et al., 2014). Several recent work in the construction sector proposed ontological solutions to overcome some challenges such as jobsite sensing and monitoring (Ren and Zhang, 2021), advanced work packaging (Farghaly and Soman, 2021), interdependent infrastructure decision support (Dao et al., 2021), health and safety in construction sites (Farghaly et al., 2022), drill-and-blast tunnelling projects (Sharafat et al., 2021). Armed with existing ontological solutions in the AEC sector, this work proposes an ontological solution for better integration and collaboration between the interdependent construction control systems. The proposed ontology concentrates on controlling production of all the deliverables/submittals during construction such as preconstruction submittals, quality documentations and attempts to proceed for handover stage. The proposed solution aims to address four critical challenges in production control of these production control deliverables: 1) collecting and integrating data from different systems, 2) improving the semantic interoperability of multiple-source data, 3) obtaining knowledge from the integration of the data, and 4) providing an environment supporting resilient decision making in construction sites.

The remainder of this paper is as follows: Firstly, it explores construction digital twins based on existing literature and questions if BIM's survivorship bias has affected our definitions to construction digital twins Secondly, it discusses the objectives of the research and the main project which this work is a part of it. Consequently, three sections illustrate the development, the domain-specific concepts and the implementation of the proposed construction programme and production control (CPPC) ontology. Finally, a section provides the conclusions and future directions respectively.

Point of Departure

The NASA mission operations control room is a well-known example of a large-scale collaborative data display, with multiple streams of real-time data available to engineers. Inspired by this example, a team of industry partners and universities in the UK are developing and piloting a production control room on the construction site. The overall project proposes to build a scalable and repeatable 'plug-and-play' construction management and reporting platform that will be tested on three significant projects in the UK. To unfold the research, aim and objectives, we have identified four main themes to achieve an effective repeatable production control room, namely end-user requirements, visualization, integration, and insights (Farghaly et al., 2021). We then used these themes to identify the best research approaches and methods should be implemented to achieve the research aim. The work presented in this paper is related to the data integration part of the data integration part and concentrates only on the ontology for production and programme control (PPC) deliverables.

Construction Digital Twins

One of the early papers related to construction digital twins has been built on integration of the applications of BIM in construction stage and the abilities of Digital Twins (Boje et al., 2020). They proposed 3-tier generation evolution of the construction digital twin: monitoring platforms, intelligent semantic platforms and agent driven soci-technical platforms. Despite the merit of the paper, it is based on that BIM is a digital twin sub-component. This assumption is not wrong; however, it is not completely true. Most of the work presented in the last couple of years related to digital twin in built environment, and especially digital twin in construction stage, is taking the same approach, solutions, steps, and findings BIM. This made the author question if that is the right approach or could be misinformed by the BIM's survivorship bias. Digital Twin is based on developing a digital replica of a real-world asset in the built environment context. While this looks close to simulation attained by BIM, Digital Twin provides much more than BIM. The main difference between BIM and Digital Twin is that Digital Twin requires a high-fidelity representation of its physical asset's operational dynamics, which most of the building information models lack. This formulated several questions such as why we are utilizing BIM for CDT? Is CDT applied in the same applications of BIM? Are the challenges the same in BIM and CDT? Should we have a 3D model to say it is CDT? These questions were discussed with the end-users (construction project managers, planners, project directors) during the initial stage of the research project. Table 1 summarizes the output of the discussions and the author mapped it to existing literature related to DT and its layers and maturity (Jiang et al., 2022; Kritzinger et al., 2018) . This part work was done to understand what the application of the production control room is and how it is linked to the

Table 1: The maturity stages and levels of CDT

Stages	Digital Model	Integration between DM and PM	Levels	Physical Model	Name
Stage 0	As designed Model	N. A	Level 0	Not existed yet	Digital Model
Stage 1	As designed Model	DM feeds in the construction of the PM.	Level 0	Under construction	Digital Model
Stage 1	As built model	PM feeds (manually input) in the development of As-built DM.	Level 1	Under construction or existing.	Digital Model
Stage 1	As built model	PM and DM are compared using semi-automatic approaches.	Level 2	Under construction or existing.	Digital Model
Stage 2	DM represents the progress in construction sites	DM represents the planned schedule and high-level of the actual schedule (manually input).	Level 1	Under construction or existing.	Digital Shadow
Stage 2	DM represents the progress in construction sites	DM represents the planned and actual based on the week look ahead not only the baseline. The integration is partially automatic.	Level 2	Under construction or existing.	Digital Mirror
Stage 3	DM controls and predicts the progress in construction sites	DM is fully integrated with other datasets such as resources, submittals, and external constraints. That where collaborative digital twins are integrated and aligned.	Level 3	Under construction or existing	Digital Twin

initiative of construction digital twins. Unlike previous studies in this area, which propose migration to an all-in-one solution, this research proposes integrating existing tools and workflows to provide data-driven production control. The paper demonstrated how data from multiple sources should be integrated to create a construction digital mirror and how this information should be accessed through a control room for data-driven production control.

Literature review

Monitoring is field in the AEC domain where semantic web technologies have a significant impact. Linking datasets across multiple domains such as sensors, building information and project management and making logical inferences is critical for monitoring. For example, Pradhan et al. (2011) presented a data fusion ontology to support tasks such as i) data source identification, 2) data fusion plan generation and 3) synchronisation of spatial and temporal data sources. For a data source, this ontology can describe the level of detail and reference systems for the data items. Similarly, Marroquin et al. (2018) developed an ontology to fuse building's contextual information with data extracted from a smart camera network. Another potential use of ontology for monitoring is to integrate dynamic data with static building data. For example, Arslan et al. (2019) developed a framework to link the Driver, Needs, Action, and Systems (DNAS) ontology to integrate the dynamic data with a building model to understand occupant behaviour. DNAS ontology was linked to STriDE model which keeps track of building entities and different relations among them. Another application of ontologies for monitoring is to create a formal representation expert's casual judgment of construction project changes. Shahinmoghaddam et al. (2018) used three ontologies: (i) Project Profile Ontology (PPO), (ii) Context Sensing Ontology (CSO), and (iii) Change Causality Ontology (CCO) to describe this. PPO describes the context-invariant characteristics and general features associated to a typical construction project whereas CSO layer represents the "contextual-sensitivity" for the causality behind project change events. The CCO is used to describe a contextualised explanation of a fuzzy cognitive mapping used to imitate the intuitive casual judgement of an expert responding to a contextual setting. Although there are specific ontologies for different purposes related to monitoring, most of these ontologies are not linked to other ontologies limiting its capabilities for inferencing. Ren and Zhang (2021) developed a new construction procedural and data collection (CPDC) ontology. The ontology links between planned and executed procedures that are collected from the construction documents and the sensing tools used in the construction jobsites respectively.

CPPC Development

For developing a domain or upper ontology, it is essential to follow a set of defined and ordered steps. After the analysis of various methods, techniques and processes for ontology development such as Uschold and Gruninger (1996) approach, METHONTOLOGY (Fernández-López et al., 1997), SKEM (Noy and McGuinness, 2001), and NeOn (Suárez-Figueroa et al., 2012). The Uschold and Gruninger (1996) approach has been adapted in this research as a guidance for the process of the ontological solution development. The approach consists of five main steps: identification of the purpose and scope, building the ontology, integrating with existing ontologies, evaluating the ontology, and finally documenting the ontology for further use. The first step concentrates on the purpose and scope of the ontology. As this step plays a significant role in the ontology development and its quality. As such, answering competency questions of the overall requirements of the research is critical aspect. The questions and their associated – presented in Table 2 - answers driven the ontology scope and purpose.

Table 2: CPPC Ontology competency questions.

Question
1. What is the progress of each subcontractor for each deliverable?
2. Where is each subcontractor working on a specific date?
3. How many of the planned dates of activities have changed and the reason behind each change?

The preliminary development of the ontology based on the answered question in step one included step 2 and step 3. This started with identifying the available existing ontologies related which can be extended, mapped, or reused. The author in this research has utilized existing published ontologies as much as possible rather than developing new classes such as BOT (Rasmussen et al., 2019) and DiCON (Zheng et al., 2021). The development ontology consists of a glossary of essential terms based on the collected requirements from the end-users. Once the classes were identified, three main kinds of properties were utilized in the ontology development: object properties, data properties and annotation properties. Step 4 includes the evaluation of the developed ontology. This step consists of several aspects such as verification, validation, and implementation. The last step is the documentation, and it is under-progress.

CPPC Domain-Specific Concepts

The CPPC model consisted of a main class named "information content entity" and divided based on the classification proposed in dice ontology. For production control, there are two main information content entity to take into consideration: the week plan and the production submittal. In this research, we have concentrated on the production submittal. It is divided into three subclasses: preconstruction submittal, construction submittal, postconstruction submittal. The preconstruction hosts submittals related to drawings, technical submittals, schedules, and models, while construction hosts the submittals related to quality signoffs, quality hold-points and quality benchmark schedules. Finally, the post-construction submittal hosts the submittals related to handover stage such as: installation sign-off, commissioning completed and handover documentations. Several data properties and object properties were added to the information content entity class. The data properties are mainly related to the date of submission, while the object properties are identifying and clustering the submittals such as discipline, workflow utilized for the approval of the submittal, format, and submittal type.

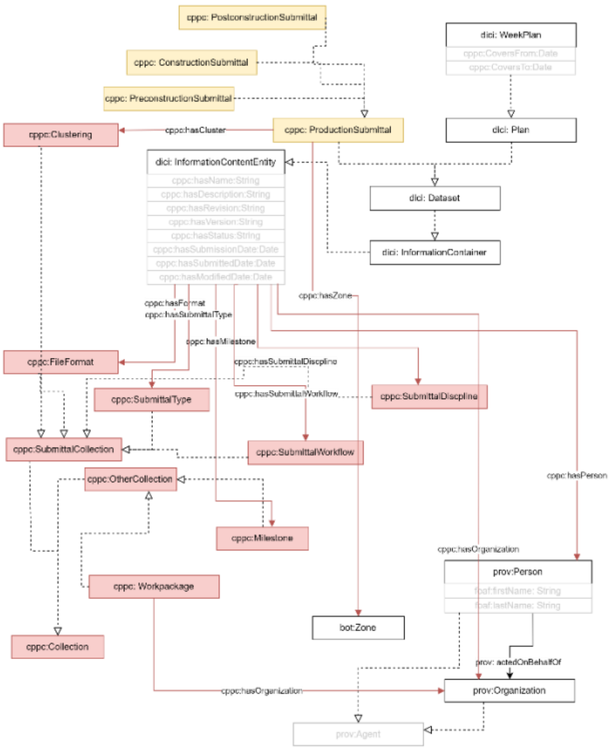

Figure 1: CPPC Ontology classes and relationships.

CPPC Implementation

Once classes and relationships were developed classes were mapped to existing ontologies for integration, instances were added from a pilot study, For the instances added, several sources already implemented in the selected case study such as: 3D Models (Autodesk Revit), 4D Models (Synchro), Schedule baseline (Microsoft Project), 3 week look-ahead (Excel), labors and deliveries (datascope), health and safety (yellow jacket) and documents (Aconex for preconstruction documents and BIM360 field for construction documents). For this research, the PPC datasets and its associated datasets were only the added ones to the CPPC ontology. Therefore, the instances included only the datasets from Aconex (Preconstruction submittals), BIM 360 filed (Quality construction submittals), Facility Grid (Handover submittals) and finally BIM 360 Glue (3D models). Both reasoners "Pallet" and "Hermit" were utilized to test the consistency and coherence. The results have shown no errors and for further verification, DL queries were created and executed after the reasoner classifications. An example of the DL queries and its corresponding result is shown Figure 2. The query executes to find all the quality submittals for a specific subcontractor which should have been submitted in specific week and they are not submitted yet.

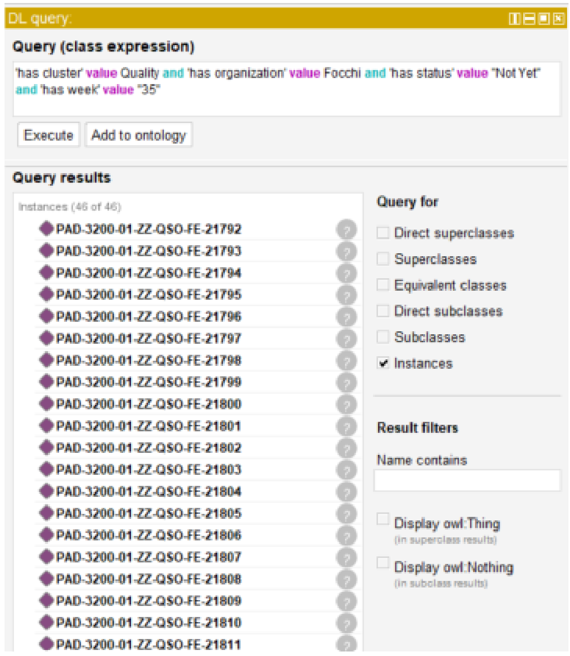

Figure 2: Example of DL queries for verification of CPPC ontology.

Consequently, several SPARQL queries were developed and executed for the ontology evaluation respectively. The SPARQL queries were designed to answer the three competency questions mentioned earlier. Figure 3 illustrates an overall abstract of the developed ontology, while Figure 4 illustrated the dashboard presented to the end-users based on the integration occurred using the proposed ontology. The dashboard provided several capabilities to the end-users for monitoring and controlling their construction sites. It includes the ability to answer the competency questions where all submittals related to a specific location for a specific date can be filtered to avoid any activity location conflict, Also, the progress of each subcontractor for a specific interval of time can be easily identified across all the deliverables rather than one aspect only. Finally, the dashboard can represent the number of versions of planned and actual of submittals and the reasons behind the variation for lesson learnt and overcome that challenge in the next submittals.

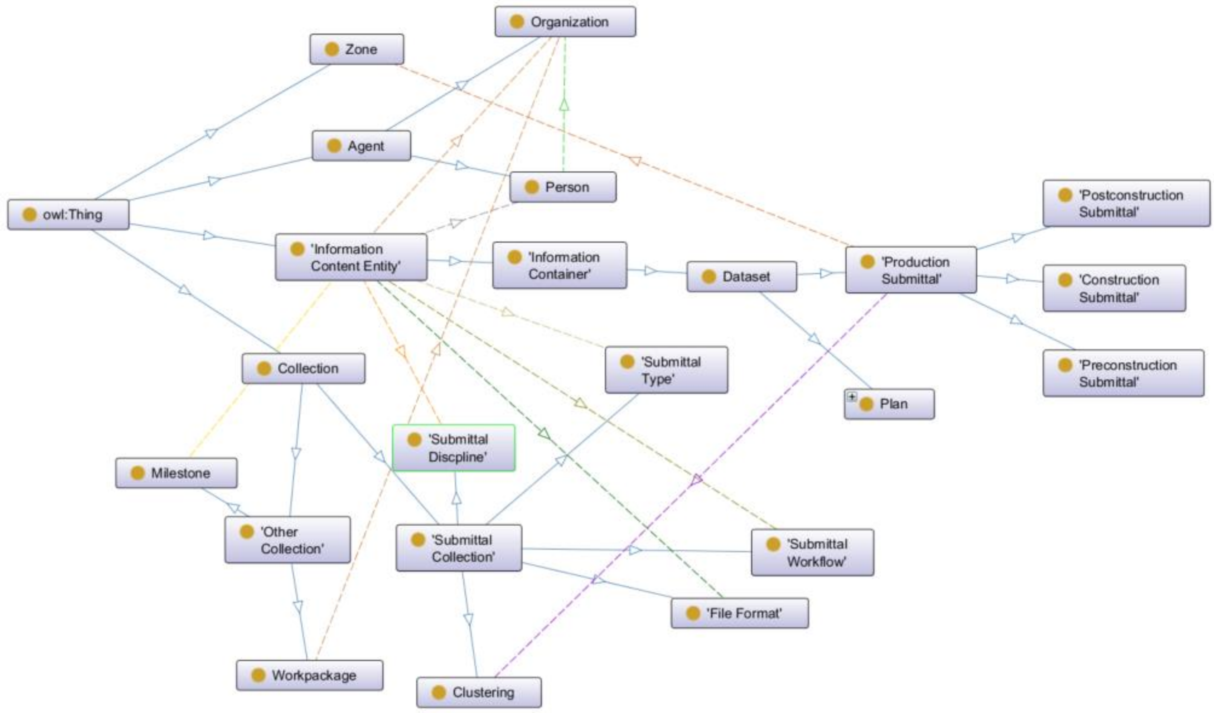

Figure 3: Screenshot from protege for CPPC Ontology.

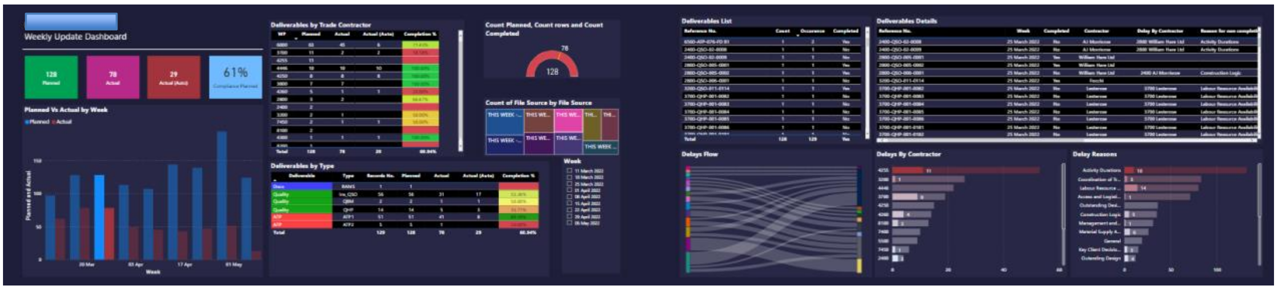

Figure 4: Screenshot from one of the dashboards based on the CPPC ontology.

Conclusions

Driven by the advancement in the industry 4.0 technologies and techniques, the built environment sector is shifting rapidly towards a smart building ecosystem not only during operation but also during construction. Nowadays, it is common that the owners of buildings require the existing of construction digital twins. As construction digital twins are deliverables, several competency questions need to answer which is "what are the requirements needed, and outputs and outcomes expected from CDT as a deliverable?". It could be there is no need for 3D models to answer that question, however, during this research it has shown that an integration between data resources is always required.

Research has shown that the design and management of datasets integration for an effective construction production control are complex and the main reason behind that is the different breakdown structure of the datasets and the presence of data in silos. To support the development of construction digital twins, this research concentrates on overcoming the challenge of datasets integration for an effective production control. Within the scope of this study, we focused on the development of an ontology – called CPPC – that covers the main aspects and domains for construction production control of submittals and deliverables.

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