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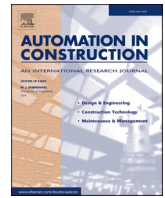
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cSite ontology for production control of construction sites

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A B S T R A C T

In the realm of construction production control, effective communication across operational levels and the rapid influx of diverse data are essential. Yet, integrating this data faces challenges due to disparate systems and a lack of common terminology, resulting in data silos and hindered interoperability. An ontology-based solution emerges as promising for enhancing interoperability. This research paper introduces the development, implementation, and assessment of the cSite ontology, encompasses several crucial facets necessary for efficient production control such as location, activities, and documents. To evaluate its practicality, a real-case study was conducted, wherein the ontology was employed to answer competency questions through SPARQL queries. Furthermore, interactive dashboards, situated within the construction control rooms, were developed to present the information visually. This paper underscores the transformative potential of integrated and visualised production information in construction projects. Additionally, it illuminates how the cSite ontology can facilitate the development and implementation of construction digital twins.

1. Introduction

The construction sector is known for the fragmentation of specialisations, which has resulted in inefficiencies, uncertainties, and wasteful resources [1]. A dominant reason for this fragmentation in the construction information landscape is due to the prevailing practice of project stakeholders focussing on their individual tasks and data while neglecting the interdependencies of the activities and data of the entire project [2]. These activities and data include information and processes for procurement and resource supply chain, the scheduling of deliveries, the coordination and sequencing of labour activities, and monitoring of high impact activities with time-based dependencies such as crane lifts, structural steelwork, and the pouring and curing of concrete. These activities are also impacted by external factors that cannot be controlled, such as local traffic around the site and weather conditions, which contribute to uncertainties and requiring the attention of project managers [3]. Often, there are relatively minor factors which results in these wastes and delays which can be avoided if the projects managers are presented with the right information at the right time [4].

To address the above, several project delivery approaches have been researched and developed with the aim of improving the performance and reducing the waste in construction project. However, they require integrating and visualising all the information from the different technologies and systems. These approaches, includes Integrated Project Delivery (IPD), Virtual Design and Construction (VDC) and Digital Twins (DT), were armed with several technologies such as such as Building Information Modelling (BIM), Geographic Information System (GIS), 4D simulation, and real-time data sources such as cameras, mobile and sensors [2,5]. These techniques and technologies have been adapted in several construction management systems and environments to better control, visualise, and interact with construction data [6]. However, integrating and visualising all the information from the different technologies and systems has become a new challenge to overcome [7].

In Knowledge Engineering, researchers see ontology as a shared formal representation of concepts and relationships as a computational model that enables automated reasoning [8]. Given the success of using ontologies and linked data implementation in domains such as biology, medical records, cultural heritage, accounting, and social media [9], recent decade has seen considerable research bring the ontology concept to the construction sector [10]. With the aim of managing and integrating the retrieved information from the different tools and systems adopted in the construction industry, researchers have proposed ontological solutions to overcome some challenges in construction projects such as jobsite sensing and monitoring [11], interdependent

infrastructure decision support [12], drill-and-blast tunnelling projects [13]. Although there are several efforts towards ontology development towards specialised tasks, there are not any ontologies dedicated production control in construction which requires data of high variety and velocity and originate from heterogeneous sources to be integrated. Building upon existing ontological solutions in the AEC sector, this work addresses the following question: "How can an ontology integrate construction data across disciplines to enhance production control through comprehensive analytics?". The remainder of this paper is as follows: Section 2 reviews the literature in production control and the implementation of ontological solutions in the construction sector. Section 3 discusses the objectives of the research, and the ontology development framework. Sections 4–6 critically assess key phases in the ontology engineering methodology. Section 4 examines pre-development activities, notably gathering case-studies datasets and end user perspectives that grounded the ontology design. Section 5 analyses the iterative development process, highlighting the techniques and tools leveraged to ensure comprehensive coverage aligned to existing ontologies and user needs. Finally, Section 6 evaluates post-development outcomes, underscoring how the resulting ontology addressed core challenges related to fragmented data and stakeholders. Finally, Section 7 and Section 8 provide the discussion and conclusions respectively.

2. Literature review

This literature review section serves as an analytical foundation for our research by focusing on innovative developments in production control mechanisms within the construction industry. Importantly, the review identifies existing ontology-based solutions as the primary inspiration and guiding framework for our ensuing research and solution development.

2.1. Production control in construction

Production control is crucial in construction sites to ensure that projects are completed on time and within budget. It involves coordinating resources, materials, and labour to ensure that work progresses as planned and any issues are addressed promptly [14]. Production control is critical in construction project management, ensuring projects are completed on time, within budget, and with high-quality standards. By implementing effective production control measures, construction companies can improve efficiency, reduce costs, and enhance their reputation for delivering quality projects [15]. As construction projects increase in complexity, manually processing data for informed decisions can lead to schedule delays, cost overruns, rework, and heightened emissions. In the present day, implementing information management systems and techniques is crucial for effective production control at construction sites. A sturdy digital communication and collaboration system can effectively tackle production control challenges, such as uncertainties from external factors, insufficient coordination among subcontractors, and misalignment between the main contractor and subcontractors' schedules. Since the early 2000s, numerous efforts have been made in the field of ICT to enhance production control at construction sites. The Last Planner System (LBS) for production control was introduced in 2000 by [16]. The LPS has four primary functions. The first function is "pull planning", which determines the necessary activities to achieve the targets. The second function is "make ready planning", which ensures that any constraints hindering the execution of the required activities are eliminated. The third function is weekly planning, which involves making a set of promises among responsible individuals to ensure task completion. The fourth function is tracking, which compares the actual work completed (did) to the work committed to (will) during daily meetings. [17] presented a roadmap for a digital construction site utilising mobile ICT. This roadmap emphasised integrated site knowledge, context-based decision tools, and collaborative virtual teams as crucial elements for successful implementation. Since then,

numerous studies and implementations have focused on enhancing the production control process through the utilisation of technology such as BIM [14,18,19], GIS [20,21], Real-time location and tracking systems [22], Blockchain [23], Internet of Things [24] and AR and VR [25].

When effectively implemented and integrated, these technologies have the potential to enhance production control in construction sites. They can improve coordination, communication, efficiency, and decision-making throughout the project lifecycle. However, integrating these technologies and their systems can be challenging and requires achieving both semantic and syntactic interoperability [18,26]. To address this challenge, the construction sector emphasises the use of existing open formats like IFC (Industry Foundation Classes), and the implementation of ontological solutions based on these open formats. By utilising open formats and ontological solutions, the industry aims to achieve seamless integration and interoperability among different technologies and systems [27]. In the upcoming section, we will discuss the existing research and developments related to ontological solutions in the field of production control within construction sites.

2.2. Ontology in construction production control

Ontologies play a crucial role as semantic facilitators for effective communication among diverse stakeholders in the construction sector [10]. By providing a collaborative representation, ontologies enable seamless interoperability between various applications. This advantage has contributed to their widespread adoption in areas such as construction safety [28,29], digital construction workflow [30], energy and mass flow [31], asset management [32], sustainability [33], and modular construction [34], where achieving semantic interoperability is paramount.

The well-known ontologies in the sector can be taxonomically divided into three primary categories: top-level ontologies, small domain-specific ontologies, and large domain-specific ontologies. Top-level ontologies, exemplified by the Basic Formal Ontology (BFO) [35] and the PROV Ontology [36], provide foundational frameworks but are fraught with challenges in terms of their adaptability to construction planning and monitoring. Their generalist orientation necessitates substantial customisation and supplementation to align with the specific objectives of construction research. Similarly, small domain-specific ontologies like the Building Topology Ontology (BOT) [37] offer solutions for narrow facets of construction. It solely focuses on the topological aspects of building components. While similar ontologies are useful within their limited scope, they often require mapping or extension to serve the holistic needs of a construction project. Large domain-specific ontologies, such as Industry Foundation Classes expressed in Web Ontology Language (IFC-OWL) [38], promise semantic interoperability but come with their own set of challenges. Their complex schemas demand specialised knowledge for navigation and proper utilisation. Furthermore, they impose an evaluation overhead to ascertain their appropriateness for specific planning and monitoring tasks. DiCon [30] is a shared representation of construction knowledge, focusing on essential higher-level concepts within the digitalized construction context. It comprises six modules: Entities, Processes, Information, Agents, Variables, and Contexts. However, DiCon does not provide detailed classification hierarchies of domain entities and may require extensions for specific use cases.

Within construction production control, existing work on ontologies can be categorised into two aspects: construction planning and construction monitoring.

● The ontologies for construction planning requires merging data from various sources to enhancing decision-making procedures. However, review of construction planning ontologies reveals fragmented perspectives operating in disciplinary silos. For example, Process Specification Language (PSL) represents fundamental of production concepts while ignoring social dynamics aspects of production

control [39]. In another case, constraint ontologies take a reductionist view focusing narrowly on constraints without considering broader enabling conditions that allow progress [40]. While IC-PRO-Onto comprehensively details processes, it lacks product dependencies crucial for inferring progress [41]. Similarly, ontologies that are developed for isolated planning aspects also exhibit similar narrow focus. The 4DCollab ontology incorporates limited concepts for collaboration without integrating other aspects such as resources and documents [42]. Plan definition ontologies overlook downstream impacts on interconnected processes [43]. Look-ahead scheduling ontologies operate in isolation rather than linking across project dimensions [44].

● Several ontologies have been developed for monitoring construction sites and integrating heterogeneous data to enable richer analysis. For example, [45] introduced a data fusion ontology to facilitate tasks like identifying data sources, generating fusion plans, and synchronizing spatial and temporal data from diverse systems. In another study, [46] developed an ontology specifically for fusing contextual building data with video data extracted from camera networks monitoring the site. Also, [47] presented a framework linking the Driver, Needs, Action, and Systems (DNAS) ontology with building information models to understand occupant behaviour through dynamic and static data integration. Furthermore, [48] employed multiple ontologies like the Change Causality Ontology (CCO) to formally represent experts' causal judgments regarding changes in construction projects. While these ontologies are useful for specific monitoring purposes, many focus on narrow datasets and tasks without broader linkage between ontologies. This can limit inferencing abilities by preventing insights across different project aspects. However, [11] helped address this by developing the Construction Procedural and Data Collection (CPDC) ontology to establish connections between planned and actual procedures collected from diverse construction documents and sensor systems. While there has been work towards a digital twin data schema incorporating lean construction and digital twin concepts such as BIM2TWIN core ontology [1] which has cross use case concepts, they miss the main concept of documents which are relevant in a production control environment.

In the existing body of literature, ontologies for construction planning and monitoring have gaps and limitations, lacking a unified solution that fully meets the needs of construction planning and monitoring. Either the ontologies are at an abstract level requiring extensions and customisation or it is at a single task level without connections to abstract ontologies or other disciplines. Also, there are a large portion of the work in this field remains unpublished or not readily linked/mapped to well-known ontologies [49]. This highlights the importance of a more integrated and adaptable approach.

2.3. Synthesis

The literature reveals a fragmented landscape lacking a unified ontology for construction production control, necessitating greater consolidation. While numerous ontologies address discrete problems like planning, monitoring, and collaboration, interoperability issues persist. Most ontologies operate in isolation, focused on narrow objectives. This segregation hinders a holistic view of the construction process and limits the inference capabilities needed for decision support. This fragmentation also reflects disciplinary silos and proprietary interests impeding standardization. Dominant groups shape ontologies towards their specific needs, while most research remains unpublished and disconnected from widely adopted ontologies. Synthesizing across these works exposes the opportunity for a unifying ontology that consolidates isolated efforts, enriches semantics, bridges planning and monitoring, and incorporates diverse perspectives. This research begins addressing that gap through an integrative ontology co-developed with end users.

This proposed ontology does not exist in isolation as it also connects to and carefully incorporated insights from established higher level ontologies such as BOT [37] and DiCON [30], which are aligned with other ontologies like BFO, IFC-OWL, and PROV.

3. Research objectives and point of departure

This research aims to address the research question *"How can an ontology integrate construction data across disciplines to improve production control through holistic analytics?"*. To answer the research question, we propose an ontology-based solution centred on enabling the creation of an immersive control room designed to enhance decision-making processes in construction sites. The key innovation is the development of the cSite ontology that maps and relates the schemas of existing data sources into a unified structure. This allows data extracted from various platforms to be combined and queried as an integrated whole. The objectives of this research are tripartite, corresponding to the following three distinct but interrelated sections: 1) To ascertain the specific needs of end users for effective production control, pinpoint the requisite data points, and evaluate pre-existing ontologies that could facilitate meeting these criteria; 2) To architect an ontology optimised for the effective control of construction site production; and 3) To empirically validate the proposed ontology through application in a real-world case study, ensuring its alignment with the initially established requirements.

To achieve these objectives, the cSite ontology was developed using a hybrid approach that combined inductive, synthetic, and collaborative techniques (Table 1). This allowed the researchers to leverage specific use cases, align with existing ontologies and dashboards, and incorporate end-user perspectives [50]. The inductive process analysed real-world datasets to extract an initial ontological framework. The synthetic phase integrated this with established ontologies to enable interoperability and adoption. Finally, collaborative workshops refined the ontology based on feedback from construction experts. The significance of this approach is threefold. First, grounding the ontology in actual project data ensured its relevance to real-world needs and existing interoperability challenges. Second, integrating existing ontologies provided a common language for interacting with external systems. Third, engaging end-users throughout development helped minimise blind spots, validate the ontology's structure and evaluate the outputs against the requirements. The hybrid technique underscores the importance of human-centred design in developing ontologies for complex domains like construction production control. This helps

Table 1
Process development of the user-centric ontology.

Phase	Approach	Activities
Ontology Pre-development	Inductive	Observe and analyse specific use cases of construction data platforms and datasets
	Synthetic	Identify relevant existing ontologies in the domain
	Synthetic	Integrate and align key concepts from these ontologies
Ontology Development	Inductive	Extract ontological characterization from specific use cases
	Synthetic	Incorporate alignments with existing ontologies
	Inductive	Apply developed ontology to integrate use case construction data
	Synthetic	Enable immersive analytics and visualisations
	Collaborative	Gather feedback on draft ontology structure and outputs
Ontology Post-development	Collaborative	Conduct workshops with construction experts/end-users
	Collaborative	Refine ontology based on user perspectives and needs
	Collaborative	Iterate on ontology design through collaborative workshops
	Collaborative	Explore integrated data for insights

ensure the ontology can support integration, query, and analysis of heterogeneous data sources to reveal new insights.

It is important to mention that the research presented in this paper is a part of a broader research programme. The research programme proposes to build a scalable and repeatable 'plug-and-play' construction management and reporting platform that will be tested on four significant projects in the UK. The four construction projects were selected by the main contractor partner for the research programme. The selection criteria were for non-residential buildings with complex construction work packages and the involvement of a considerable number of subcontractors. The execution of the solution encompassed numerous tasks, each of which both influenced and was influenced by the ontology development process (Fig. 1). While more validation is still needed regarding scalability and extensibility, this research represents a key step towards repeatable, plug-and-play integration of construction data. The analytical approach of mapping heterogeneous schemas into a unifying ontology paves the way for more holistic understanding of project performance across interacting systems. This has broad applicability for decision support and process improvement in the construction domain. The next three sections will dig into the specifics of each phase involved in the development of the ontology.

4. CSite ontology pre-development

This section discusses the tasks related to ontology pre-development. To ground the ontology development in real-world data, our team conducted extensive field studies across several construction sites. We shadowed and interviewed stakeholders like project managers, engineers, and BIM managers to understand their workflows and data pain points. Through on-site observation and attending the lookahead meetings, we documented the various platforms and datasets used, including project management systems, design and construction documents, sensor data, and equipment logs. We analysed the terminology, taxonomies, formats, and schemas used to structure data in these disparate systems. The data were delivered in different platforms and the data was not semantically mature to integrate them, for example: the name convention of the building level was different in different platforms. Consequently, semantic enrichment and enhancement have taken place first. These insights from the datasets and the interviews informed the ontology requirements. We performed a review to identify existing published ontologies with potential relevance to construction data integration. For each ontology, we examined its structure, formalism, classes, properties, and limitations. Upon examination, it was discerned that the Basic Formal Ontology (BFO) offers a foundational framework with wide applicability, albeit with limitations in construction-specific contexts. During our preliminary consultation, end users found BFO's
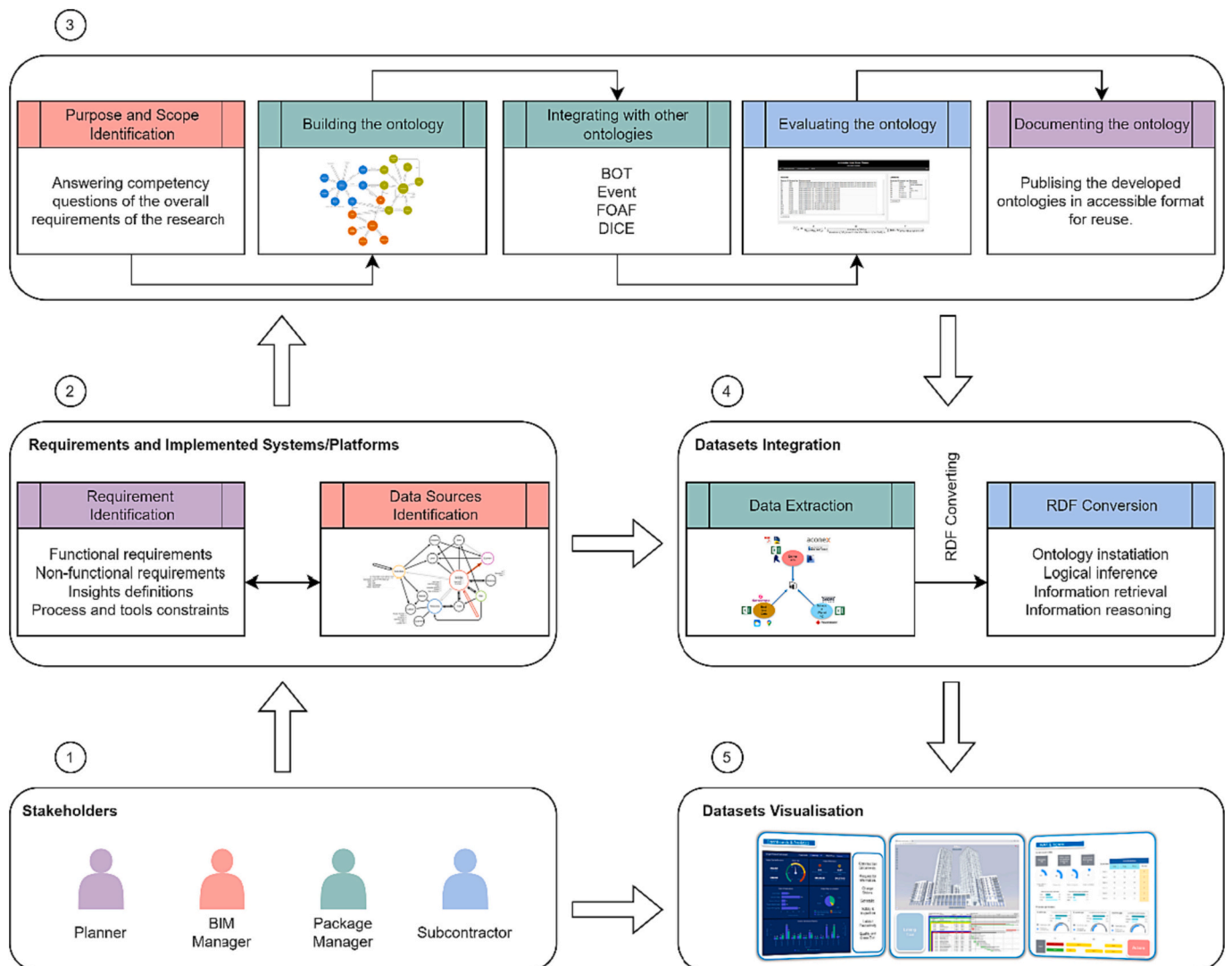

Fig. 1. Framework of CSite Implementation in Construction Production Control Rooms.

multifarious classes challenging to comprehend. Conversely, the Digital Construction Ontology (DICON) offers a specialised framework that excels in construction production control but may fall short in encompassing a broader scope. DICON, however, provides instructive insights into ontology development via both top-down and bottom-up methodologies, drawing from existing datasets. The Building Topology Ontology (BOT), focused on typology, has been adapted for the location ontology discussed in Section 5.2, with added classes and relationships to fulfil research aims. In sum, the optimal employment of these ontologies involves a nuanced, complementary integration tailored to specific case requirements, thereby leveraging their individual strengths whilst mitigating their limitations. This catalogue of existing ontology concepts and relationships provided a solid foundation for our integration. With priority ontologies selected, we developed methods to integrate them into a unified schema which is discussed in the following section.

5. CSite ontology development

5.1. Development process

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 approach [51], METHONTOLOGY [52], SKEM [53], and NeOn [54]. The Uschold and Gruninger [51] 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.

First step is the identification of the purpose and the 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 corresponding answers, which drive the scope and purpose of the ontology, are depicted in Table 2. Meanwhile, the competency questions along with their related classes and properties are set forth in Table 3. The second step includes the preliminary development of the ontology based on the answered question in step one. This started with identifying the available existing ontologies related which can be extended, mapped, or reused. The authors in this research they have utilised the existing published ontologies as much as possible rather than developing new classes. The development ontology consists of a glossary of essential terms based on the collected requirements from the end-users [53]. Once the classes were identified, three main kinds of properties were utilised in the ontology development: object properties, data properties and annotation properties. All the classes and relationships are annotated with the own prefix *cSite,* and the "hashtag" strategy was chosen to avoid redirection issues associated with the "slash" format. To describe a detailed model of the construction production control entities, the main four modules are explained in detail separately and aligned existing ontologies and then the relationships between the different modules are discussed in the following section. Step 4 includes the evaluation of the developed ontology. This step consists of several aspects such as verification, validation, and implementation. For verification, Protégé includes several built-in reasoners to evaluate an ontology model. In this research, the most used reasoners were utilised which are "Pellet" and "Hermit" [55]. The computations were done with no errors, showing the consistency and coherence of the developed ontology. Other verifications were done using DL queries. Examples of the DL queries and their results are shown in Section 6. Finally, Step 5 includes the publishing of the developed ontology. Researchers can find the ontology file in the following link. The various parts of the ontology are explained in the following subsection.

Table 2
Questions and their corresponding answers, which drive the scope and purpose of the ontology.

Question	Corresponding answer
Why the development of cSite ontology?	provide an integrated dataset for visualisation in the construction production control rooms.
What domain the ontology would cover?	the ontology should cover four main aspects which are the construction activities and associated constraints especially 3WLA information, the location of activities, the resources related to the production activities such as material, equipment, and labour and finally the documents' submission and their status.
Who is going to use the outputs of the data integration?	the main contractor project manager, planner, and BIM manager and the datasets will be utilised during the planning meetings with the subcontractors.
What is the source of information?	mainly several sources already implemented in the case study such as: 3D Models (Autodesk Revit), 4D Models (Synchro), Schedule baseline (Microsoft Project), 3-week look-ahead (Excel), labours and deliveries (datascope), health and safety (yellow jacket) and documents (Aconex for preconstruction documents and BIM360 field for construction documents).
How the ontology will be developed?	OWL is the selected language, protégé is the editing tool for its open code, free access, and simplicity and finally, SWRL is selected as the reasoning rules of ontology as it allows adding and modifying rule restraints flexibly.
Why was OWL chosen for conceptualisation instead of using SQL?	Several key factors influenced the choice to use OWL over SQL databases. These include OWL's capability for semantic expressiveness, which allows for the representation of complex relationships and hierarchies, as well as its flexibility in accommodating dynamic changes in knowledge. The overarching goal "future research" of the project—to map various ongoing and archived projects to enhance understanding of subcontractor productivity—aligns well with these OWL capabilities.
What are the expected requirements and insights from that integration?	Based on the end-users' requirements, there are seven competency questions were formulated and the queries are designed based on them (Table 3).

5.2. CSite ontology

In this section we describe the main concepts of the CSite ontology.

5.2.1. Location
The first model is of Location module is presented in Fig. 2, in which the classes and properties are organised with respect to the essential categories of BOT. Several data properties were added to the Space class – for example, RevitID and ifcIdentifier. Additionally, in this Location module, a class called SpaceType was included to cover the description of the location and more information related to the location and who and why the designers and contractors have added it. In our study, this was crucial as they were several spaces were added to represent the construction areas rather than using the identified spaces by designers in the 3D models. Also, a class call Project was added under the collection class to identify these zones are related to which project. The reason behind that was the research includes a HQ control room which will present information related to several projects at the same time.

5.2.2. Resources
The second model is of Resource module in Fig. 3, in which the

Table 3
Existing ontologies suitable for reuse in the aec sector.

Question No.	Competency Question	Related ontology classes and properties
Question 1	What are the deliverables per floor/storey in each week plan?	Week Plan, Activity, Room, Storey
Question 2	What is the number of deliverables completed per floor/storey in the last six weeks?	Week Plan, Room, Storey, Activity, Status Completed
Question 3	Who is the least performing subcontractor in the last 6 weeks in a specific storey?	Storey, Room, Activity, status completed, organization
Question 4	Which level/storey has the least productivity in the last 6 weeks?	Storey, Room, Activity, status completed
Question 5	What is the completion rate for each week for each subcontractor in the last 6 weeks?	Week Plan, Activity, status completed, organization
Question 6	What is the organization responsible of the most of not completed activities in the last 6 weeks? What are their main reasons of non-completion?	Week Plan, Activity, status completed, organization, reason of non-completion
Question 7	Which level/storey has the highest number of replanned activities in the last 6 weeks by whom, why and most affected organization?	Week Plan, Room, Storey, Activity, planned version, organization, planned version, organization

classes and properties are organised with respect to the essential categories of PROV and BFO. An upper class called Resource was added to host both the Agent and Object subclasses. The Agent class had two new object properties to link the organization and the person to the project where they participate in and to the work package, they deliver. Furthermore, the Person class had two data properties to capture the attendance of the workers, engineers and managers in the construction

sites and their working duration every day. Meanwhile, the Object class covers all the different objects which can be on-site. It consists of three subclasses: building object, equipment, and material batch. The building object represent all the object/elements will be built, fabricated, and assembled in the construction site, equipment represents tools utilised to achieve the construction activities such as crane and finally material batch represents the delivers related to material which are used to build the building objects. In the next sub-section, the activity ontology is discussed, including the delivery activity which would manage all the material batches arriving to the construction sites.

5.2.3. Construction activities

The third model is related to Process module is presented in Fig. 4 to help in describing the construction process and activities. The process class consists of activity which consists of four main subclasses naming: engineering activity, construction activity, procurement activity and quality activity. The engineering activity subclass hosts all the activities related to the preconstruction stage and usually their output is a document such as drawings, technical submittals, and request for information (RFIs). These outputs are usually stored in one document control management system. The construction activity subclass hosts all the activities conducted on site and usually updated in the 3 week lookahead. These activities are usually lacking integration between the different subcontractors and most of the time are not mapped to the baseline programme. The procurement activity subclass is related to the deliveries arriving on the construction site and their time and for which subcontractors and milestones. In the projects selected for this research, an access control was utilised to plan and control the deliveries on sites. Finally, quality activity subclass is related to the quality signoffs, quality hold points and milestones identified for the construction and engineering activities. The quality activities do not only check the progress
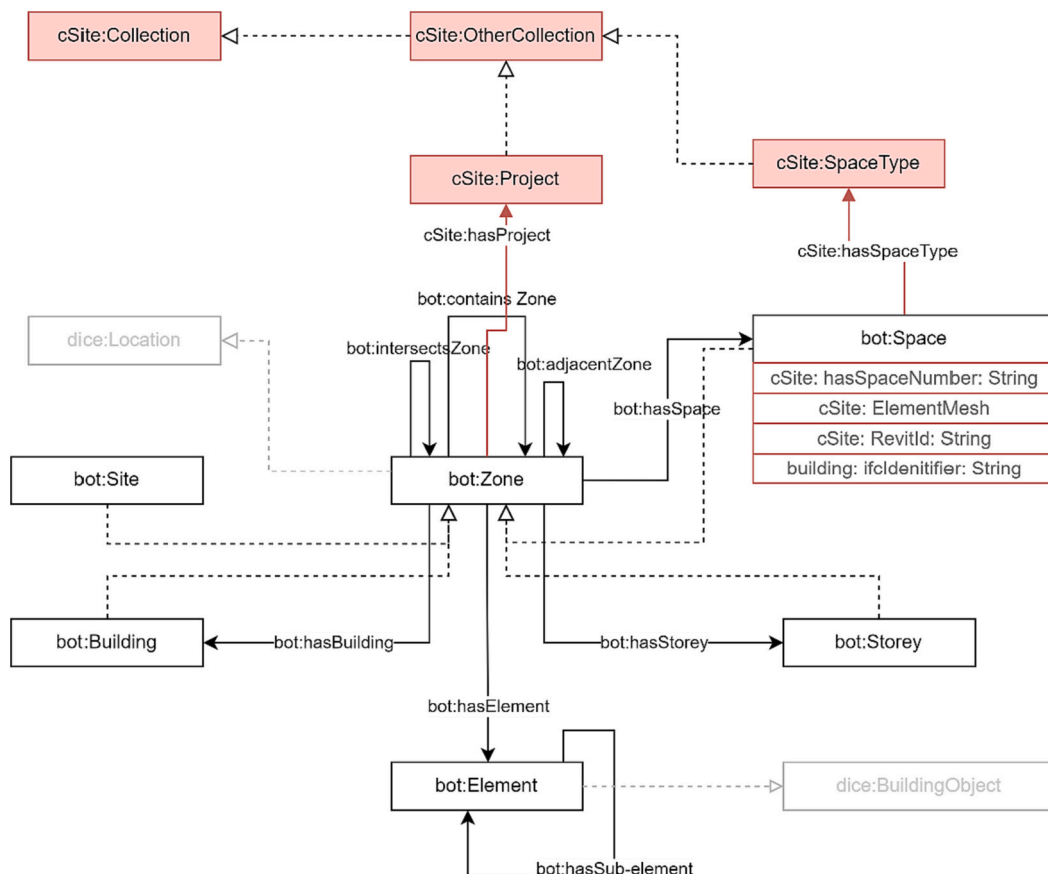

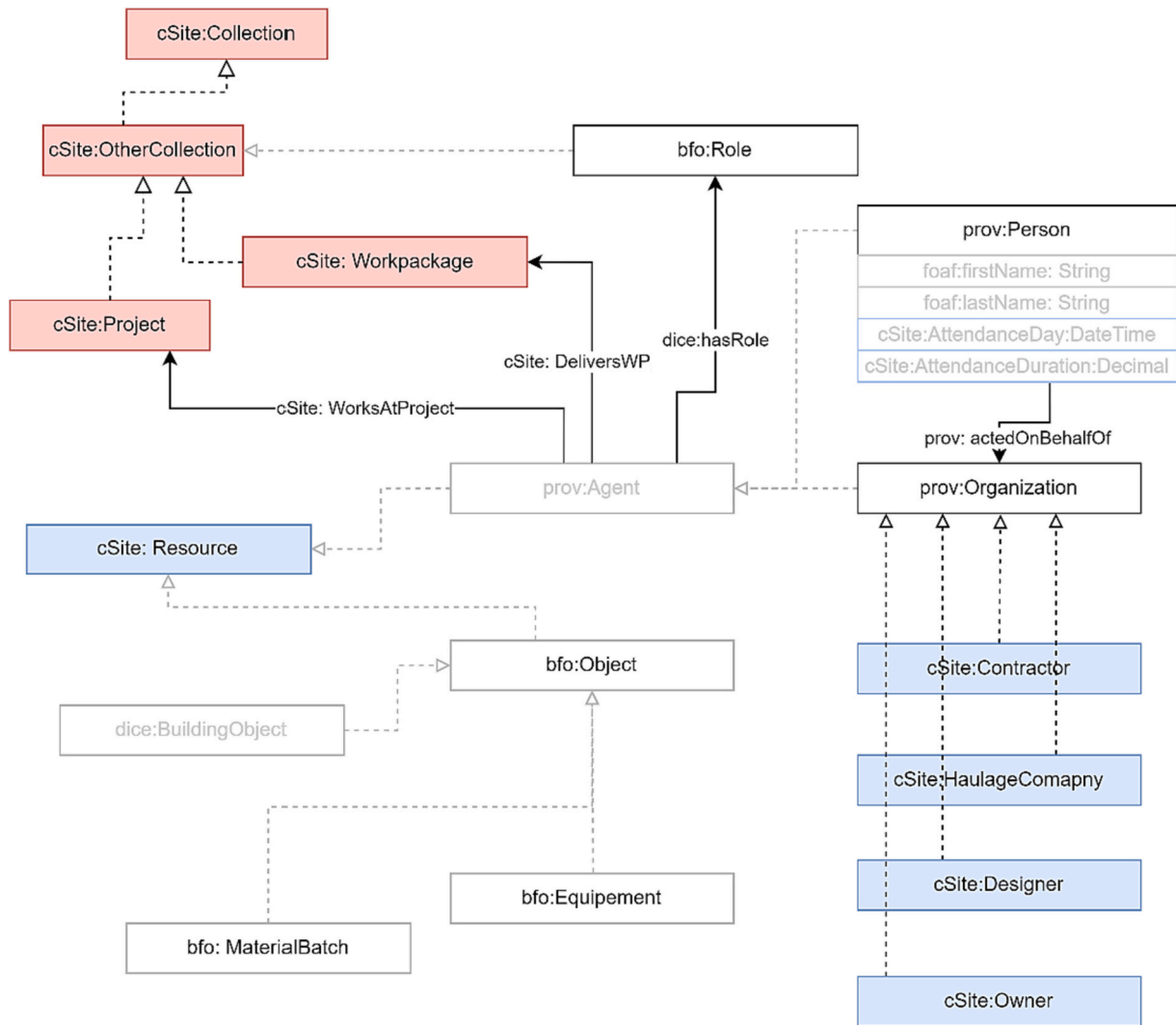**Fig. 2.** Location concepts and properties.

Fig. 3. Resource concepts and relationships.

against time but also the quality of the tasks performed. Several object properties and data properties were identified to control these activities. It is important to mention that these properties were identified to cover all the requirements by the end-users of the production control room. For example, the activity was not only mapped to milestones, but they were mapped to location, work package, stakeholder responsible to perform the activity, and to the documents required to perform the activity. These two different information content entities are discussed in the detail in the next sub-section.

5.2.4. Documents

The fourth model is related to documents and named "information content entity" and divided based on the classification proposed in dice ontology (Fig. 5). 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 related to the date of submission, while the object properties are identifying and clustering the submittals such as discipline, workflow utilised for the approval of the submittal, format, and submittal type.

5.2.5. Overall ontology

The overall ontology consists of a class called "collection", as presented in the previous sub-sections, it hosts all the classes required to define, arrange, and integrate the different datasets coming from different data sources. It consists of two sub-classes grouping the classes based on their use such as: information related and others. Table 4 summarised the different classes of the cSite and the existing ontologies utilised. For cSite, both reasoners "Pallet" and "Hermit" were utilised to test the consistency and coherence. The results obtained from the development of classes and relationships in the ontology demonstrated no errors. To further validate the ontology and ensure its effectiveness, a series of queries were formulated and executed in the subsequent section. The SPARQL rules were created to evaluate and assess the ontology's performance. These steps were undertaken to enhance the reliability and robustness of the ontology, ensuring its suitability for the intended purpose.
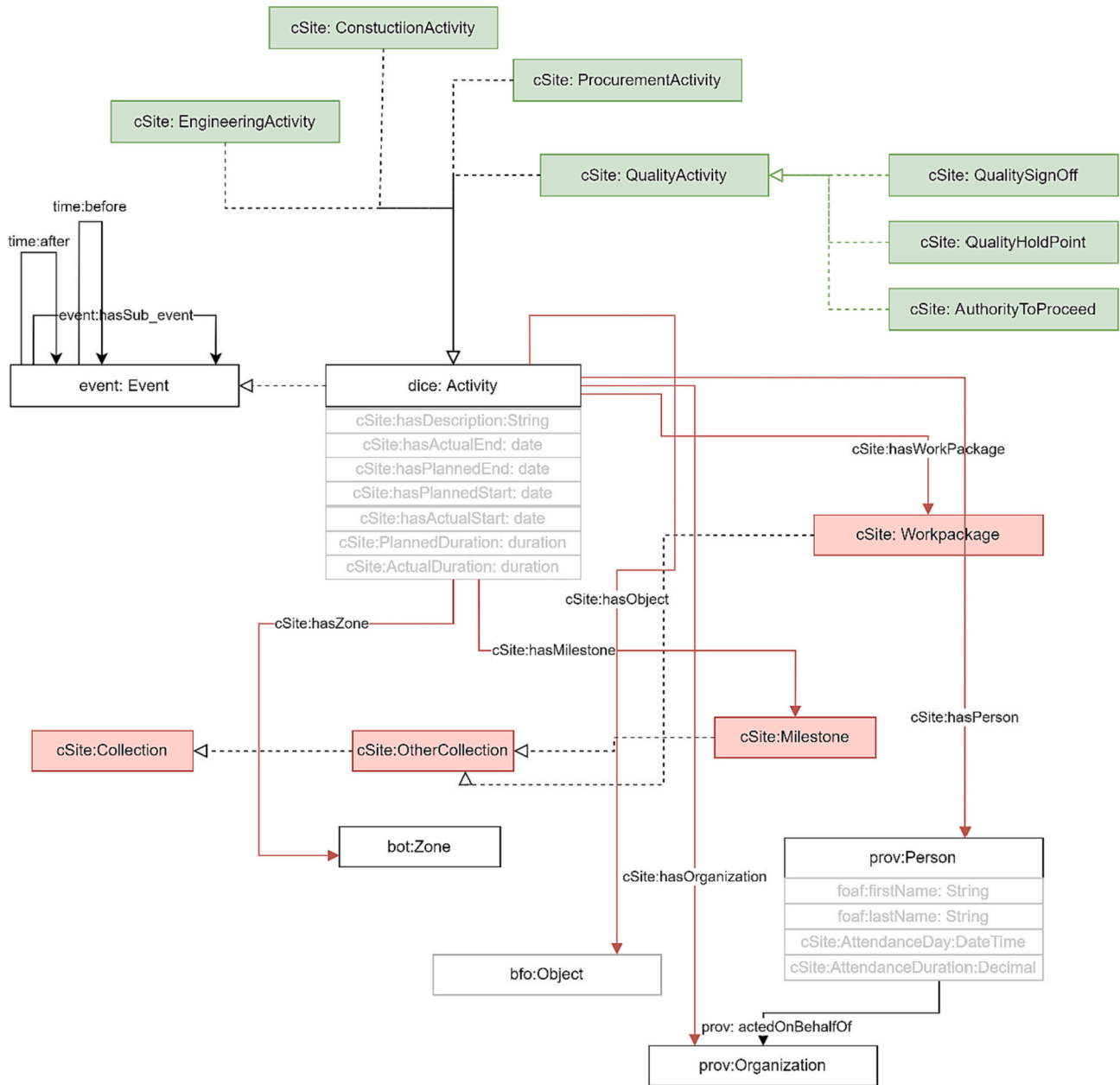
Fig. 4. Process concepts and relationships.

6. CSite post-development

This section discusses the post development activities which includes verification and validation.

6.1. CSite verification

In order to implement and verify the ontology, data from a pilot project was incorporated to align with the cSite schema. To assess its effectiveness, seven queries corresponding to the seven competency questions listed in Table 2 were executed on the datasets. These queries assist project managers in planning and monitoring activities on the site, thereby facilitating production control. In this research, we utilised both RDF (Resource Description Framework) for data integration within the ontological solution and CSV (Comma-Separated Values) format for tabular integration. Since a significant portion of the datasets were exported as CSV, the transformation process into RDF format proved to be a straightforward step. The datasets were gathered from various

sources within the data lake of the main contractor, with input from the 20 subcontractors involved in the project. To ensure consistency in the vocabulary used across the data, multiple meetings were conducted with the information manager. These meetings aimed to establish similar and/or mapped vocabulary across the different data sources, while also enhancing subcontractors' understanding of the value of such integration. As the verification was held during the active phase of the construction project, the information manager and the planner manager were independently monitoring relevant data using their own spreadsheets. Although these spreadsheets answered the first three competency questions, they were not exhaustive. When the outputs from our queries were compared with their data, the managers confirmed the accuracy and credibility of our results.

6.1.1. Identifying deliverables per floor

The first query is about tracking the number of deliverables (activities to be delivered). This helps the project managers to understand the plans and remove workspace conflicts. It also helps the clustering of
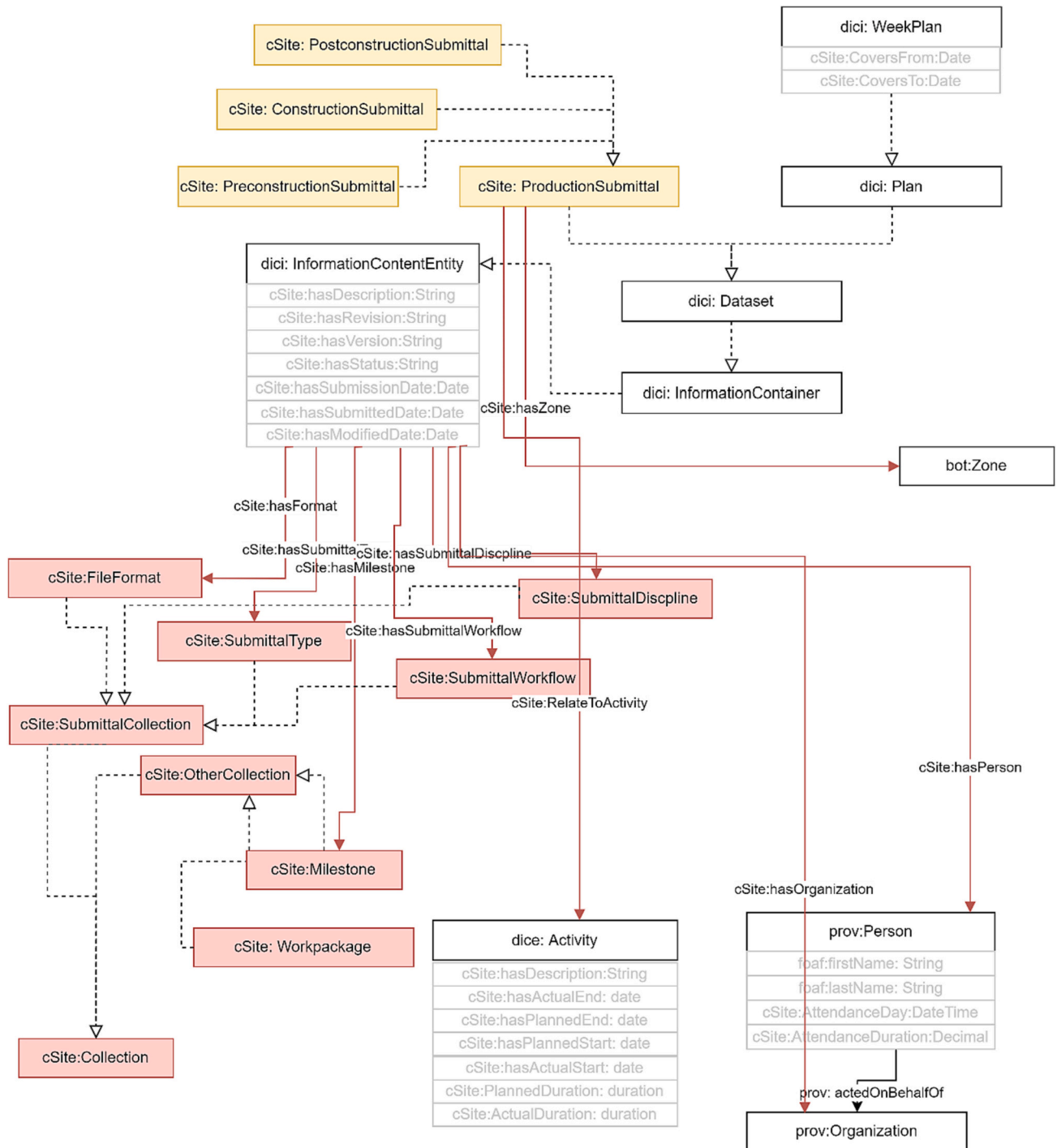
Fig. 5. Document concepts and relationships.

work to be distributed to different package managers. The query is provided in Listing 1. For this, the query first looks at each week's plan and then identify the activities and their location and then groups it by storey. The output after the execution of the query is provided in Table 5.

```
SELECT ?storey ?weekplan (COUNT(?activityversion) AS ?count) WHERE {
 ?activity cSite:hasZone ?space.
 ?space bot:hasStorey ?storey.
 ?activity cSite:hasPlannedVersion ?activityversion.
 ?activityversion cSite:discussedIn ?weekplan.
}
GROUP BY ?storey ?weekplan
```

Listing 1. What are the deliverables per floor/storey in each week plan?

6.1.2. Tracking the deliverables per floor

The second query is about tracking the number of deliverables that has been completed in the last 6 weeks. This helps the project manager to understand the flow of work and plan the further activities. The query for the same is provided in Listing 2. For this, the query first looks for all the activities in the last 6 weeks and infers where the activity occurred and then checks for the completion status. All the completed activities are then grouped by storey. The output of the query is given in the Table 6.

6.1.3. Identifying subcontractor productivities

For effectively managing the workflow and ensure continuous flow of work, it is imperative to know the bottlenecks in the construction. Subcontractor productivity is a major factor contributing to this. Therefore, the third query is identifying the low performing subcontractors in each storey. Listing 3 provides the subcontractor productivity for different floors. For calculating this, the query first looks for all the activities planned for the last six weeks and then identify subcontractor responsible for the same. Then it looks at the completion status for each activity and then groups the results by subcontractor and storey. The output of the listing 3 is given in Table 7.

```
SELECT ?storey ?weekplan (COUNT(?activity) AS ?count) WHERE {
 ?weekplan cSite:CoversFrom ?date.
 ?activityversion cSite:discussedIn ?weekplan.
 ?activity cSite:hasPlannedVersion ?activityversion;
  cSite:hasZone ?space.
 ?space bot:hasStorey ?storey.
 ?activityversion cSite:StatusCompleted ?status.
 BIND((NOW()) - "P0Y6M28DT0M0S"^^xsd:yearMonthDuration AS ?sixweeksago)
 FILTER(?date > ?sixweeksago)
 FILTER(?status = "Yes"^^xsd:string)
}
GROUP BY ?storey ?weekplan
ORDER BY (?storey)
```

Listing 2. What is the number of deliverables completed per floor/storey in the last six weeks?

```
SELECT ?storey ?org ((xsd:float(COUNT(DISTINCT ?activityC))) / (xsd:float(COUNT(DISTINCT ?a
ctivity))) AS ?Completion_Rate) WHERE {
 ?weekplan cSite:CoversFrom ?date.
 ?activitycompversion cSite:discussedIn ?weekplan.
 ?activityC cSite:hasPlannedVersion ?activitycompversion.
 ?activitycompversion cSite:StatusCompleted ?status.
 ?activityC cSite:hasOrganization ?org;
  cSite:hasZone ?space1.
 ?activityversion cSite:discussedIn ?weekplan.
 ?activity cSite:hasPlannedVersion ?activityversion.
 ?activityversion cSite:StatusCompleted ?status1.
 ?activity cSite:hasOrganization ?org;
  cSite:hasZone ?space.
 ?space bot:hasStorey ?storey.
 ?space1 bot:hasStorey ?storey.
 BIND((NOW()) - "P0Y6M28DT0M0S"^^xsd:yearMonthDuration AS ?sixweeksago)
 FILTER(?date > ?sixweeksago)
 FILTER(?status = "Yes"^^xsd:string)
}
GROUP BY ?storey ?org
ORDER BY (?storey) (?Completion_Rate)
```

Listing 3. Who is the least performing subcontractor in the last 6 weeks in a specific storey?

6.1.4. Identifying locations with least productivity

Besides determining subcontractor productivity, it is essential to consider location-based productivity as well. This is because certain locations may have inefficient logistics and working plans, which can contribute to lower overall productivity. Assessing location-based productivity provides valuable insights that cannot be solely obtained from subcontractor productivity analysis. Listing 4 offers a query specifically designed to identify the floors with the lowest productivity. The query algorithm begins by examining all activities conducted within the past six weeks. It then evaluates the specific spaces in which these activities took place. Finally, it checks the completion status of each activity to calculate the completion rate. By analysing this information, areas or floors with lower productivity can be pinpointed and assessed for potential issues in logistics or working plans. This enables stakeholders to address these concerns and act appropriately to improve overall productivity in those specific locations. The output from Listing 4 is given in Table 8.

6.1.5. Identifying subcontractor productivities

In addition to obtaining subcontractor productivities per floor, it is equally crucial to determine the overall completion rate of subcontractors. This information plays a vital role in identifying underperforming subcontractors and taking necessary corrective actions. Listing 5 presents a query specifically designed to calculate the completion rate of various subcontractors on a weekly basis. The query algorithm retrieves all activities performed within the last six weeks and identifies the responsible subcontractor for each activity. Subsequently, it checks whether each activity has been completed and aggregates the data on a weekly basis for each subcontractor. The resulting output from Listing 5 is presented in Table 9, providing a comprehensive overview of the completion rates achieved by different subcontractors over time. This data aids in the identification of subcontractors with lower performance and assists in implementing appropriate measures to rectify any issues.

```
SELECT ?storey ((xsd:float(COUNT(DISTINCT ?activityC))) / (xsd:float(COUNT(DISTINCT ?activi
ty))) AS ?Completion_Rate) WHERE {
 ?weekplan cSite:CoversFrom ?date.
 ?activitycompversion cSite:discussedIn ?weekplan.
 ?activityC cSite:hasPlannedVersion ?activitycompversion.
 ?activitycompversion cSite:StatusCompleted ?status.
 ?activityC cSite:hasOrganization ?org;
  cSite:hasZone ?space1.
 ?activityversion cSite:discussedIn ?weekplan.
 ?activity cSite:hasPlannedVersion ?activityversion.
 ?activityversion cSite:StatusCompleted ?status1.
 ?activity cSite:hasOrganization ?org;
  cSite:hasZone ?space.
 ?space bot:hasStorey ?storey.
 ?space1 bot:hasStorey ?storey.
 BIND((NOW()) - "P0Y6M28DT0M0S"^^xsd:yearMonthDuration AS ?sixweeksago)
 FILTER(?date > ?sixweeksago)
 FILTER(?status = "Yes"^^xsd:string)
}
GROUP BY ?storey
ORDER BY (?Completion_Rate) (?storey)
```

Listing 4. Which level/storey has the least productivity in the last 6 weeks?

```
SELECT ?weekplan ?org (COUNT(DISTINCT ?activityC) AS ?N_completed_activities) (COUNT(DISTIN
CT ?activity) AS ?N_activities) ((xsd:float(COUNT(DISTINCT ?activityC))) / (xsd:float(COUNT
(DISTINCT ?activity))) AS ?Completion_Rate) WHERE {
 ?weekplan cSite:CoversFrom ?date.
 ?activitycompversion cSite:discussedIn ?weekplan.
 ?activityC cSite:hasPlannedVersion ?activitycompversion.
 ?activitycompversion cSite:StatusCompleted ?status.
 ?activityC cSite:hasOrganization ?org.
 ?activityversion cSite:discussedIn ?weekplan.
 ?activity cSite:hasPlannedVersion ?activityversion.
 ?activityversion cSite:StatusCompleted ?status1.
 ?activity cSite:hasOrganization ?org.
 BIND((NOW()) - "P0Y6M28DT0M0S"^^xsd:yearMonthDuration AS ?sixweeksago)
 FILTER(?date > ?sixweeksago)
 FILTER(?status = "Yes"^^xsd:string)
}
GROUP BY ?weekplan ?org
ORDER BY (?weekplan) DESC (?Completion_Rate)
```

Listing 5. What is the completion rate for each week for each subcontractor in the last 6 weeks?

Table 4

Utilised ontologies in the csite ontology.

Prefix	Class	Relationship
bfo	Entity, Object, Equipment, MaterialBatch, Role	
bot	Site, Zone, Building, Space, Storey, Element	adjacentZone, containsZone, hasBuilding, hasElement, hasSpace, hasStorey, hasSub-element, intersectsZone
dice	Activity, BuildingObject, Location	hasRole
event	Event, Sub_event	hasSub_event
foaf		firstName, lastName
prov	Person, Organization	hadRole, wasAssociatedWith, wasAttributedTo, wasGeneratedBy
rdfs	Class, Resource	label, domain, range, subClassOf
xsd	dateTime, date, string, decimal, duration	
owl	Ontology	versionInfo

6.1.6. Identifying reasons for non-completions

Although identifying the completion rate can help identify the sub-contractor productivity. For making the best rectifying action, it is also necessary to identify the reasons for non-completion. The Listing 6 gives the query for identifying the subcontractor with highest number of non-completions and their reasons. The query first identifies the activities which are not completed in the last 6 weeks and associates the organization with these activities and the calculates which has the highest no of non-completions. Then it looks for the reasons for the non-completion and counts them. The output of execution of Listing 6 is given in Table 10.

6.1.7. Identifying activity that has been replanned the most, the reason and who is most affected

Frequent replanning of certain activities is a significant aspect that warrants investigation. Understanding the reasons behind these replans, as well as identifying the organizations involved and affected, is crucial. To address this, Listing 7 presents a query designed to fulfil these objectives. The query examines the number of times each activity has been replanned, investigates the reasons behind the replanning, identifies the responsible organization for non-completion, and determines the organization most impacted by these replans. The resulting output from Listing 7 is presented in Table 11, providing valuable insights into the replanning dynamics and their organizational implications.

```
SELECT ?org ?reason (COUNT(?reason) AS ?reasoncount) WHERE {
 ?activity cSite:hasOrganization ?org.
 ?activityversion cSite:discussedIn ?weekplan.
 ?activity cSite:hasPlannedVersion ?activityversion.
 ?activityversion cSite:ReasonForDelay ?reason.
 {
  SELECT ?org (COUNT(?activityversion) AS ?count) WHERE {
   ?weekplan cSite:CoversFrom ?date.
   ?activityversion cSite:StatusCompleted ?status.
   ?activity cSite:hasOrganization ?org.
   BIND((NOW()) - "P0Y6M28DT0M0S"^^xsd:yearMonthDuration AS ?sixweeksago)
   FILTER(?date > ?sixweeksago)
   FILTER(?status = "No"^^xsd:string)
  }
  GROUP BY ?org
  ORDER BY DESC (?count)
  LIMIT 1
 }
}
GROUP BY ?org ?reason
ORDER BY DESC (?reasoncount)
LIMIT 10
```

Listing 6. What is the organization responsible of the most of not completed activities in the last 6 weeks? What are their main reasons of non-completion?

```
SELECT ?storey ?org ?activityversion ?reason ?resporg WHERE {
 ?weekplan cSite:CoversFrom ?date.
 ?activityversion cSite:discussedIn ?weekplan.
 ?activity cSite:hasPlannedVersion ?activityversion;
  cSite:hasOrganization ?org;
  cSite:hasZone ?space.
 ?space bot:hasStorey ?storey.
 ?activityversion cSite:hasVersion ?version;
  cSite:ReasonForDelay ?reason;
  cSite:responsibleForNonCompletion ?resporg.
FILTER((xsd:integer(?version)) > 1 )
FILTER(?date > ?sixweeksago)
{
 SELECT ?storey ?org (COUNT(?activityversion) AS ?n_orgreplanned) ?sixweeksago WHERE {
  ?weekplan cSite:CoversFrom ?date.
  ?activityversion cSite:discussedIn ?weekplan.
  ?activity cSite:hasPlannedVersion ?activityversion;
   cSite:hasOrganization ?org;
   cSite:hasZone ?space.
  ?space bot:hasStorey ?storey.
  ?activityversion cSite:hasVersion ?version.
  FILTER(?date > ?sixweeksago)
  FILTER((xsd:integer(?version)) > 1 )
  {
   SELECT ?storey (COUNT(DISTINCT ?activityversion) AS ?n_replanned) ?sixweeksago WHERE {
    ?weekplan cSite:CoversFrom ?date.
    ?activityversion cSite:discussedIn ?weekplan.
    ?activity cSite:hasPlannedVersion ?activityversion;
     cSite:hasZone ?space.
    ?space bot:hasStorey ?storey.
    ?activityversion cSite:hasVersion ?version.
    BIND((NOW()) - "P0Y6M28DT0M0S"^^xsd:yearMonthDuration AS ?sixweeksago)
    FILTER(?date > ?sixweeksago)
    FILTER((xsd:integer(?version)) > 1 )
   }
   GROUP BY ?storey ?sixweeksago
   ORDER BY DESC (?n_replanned)
   LIMIT 1
  }
 }
 GROUP BY ?storey ?sixweeksago ?org
 LIMIT 1
 }
}
GROUP BY ?storey ?org ?activityversion ?reason ?resporg
ORDER BY (?activityversion)
```

Listing 7. Which level/storey has the highest number of replanned activities in the last 6 weeks by whom, why and most affected organization?

6.2. CSite validation

To validate that the cSite ontology and its query capabilities met end-user requirements, interactive workshops were held onsite with construction experts. Researchers presented autogenerated dashboards populated with data drawn from SPARQL queries on the ontology. The end users analysed the dashboards and provided feedback on their effectiveness in addressing the previously gathered requirements. This collaborative process enabled iterative refinements to the queries rather than the ontology itself based on the users' domain knowledge. Starting the development from end user requirements facilitated tailoring the queries to their needs, while the hands-on validation workshops confirmed it produced the desired results. The end users were impressed with the ability to quickly generate informative reports through queries, customizing the data to their priorities. The positive reception at the workshops underscored that the ontology successfully delivered the production control insights requested by the end users. This user-centred validation method ensured the ontology and querying capabilities aligned with the needs of domain practitioners.

The implementation of the cSite ontology in construction control rooms has yielded several notable benefits during the workshops, leading to its favourable reception among end-users. Firstly, the efficient digitalisation and connectivity features have significantly reduced the time required for information manager to prepare for weekly meetings by 5 h per week. The reduction in weekly meeting preparation time was quantified through timed observations and surveys of the information managers before and after implementing the cSite ontology. Prior to using the ontology, the information managers spent an average of 8 h per week manually gathering, consolidating, and preparing reports on construction progress from disparate sources to present at the weekly meetings. This involved accessing multiple systems, spreadsheets, and paper documents to collect and compile the needed data. After integrating these data sources through the cSite ontology, the information managers spent an average of 3 h per week on meeting preparation. The unified data environment enabled them to directly query, and extract needed information through SPARQL queries on the ontology. Automated report dashboards could also be generated (Fig. 6). To validate the time savings, researchers directly observed and recorded the time spent on preparation by the information managers over a 4-week period. This enhanced efficiency has streamlined operations and improved overall productivity.

Moreover, the introduction of more efficient and integrated dashboards for the weekly meetings has brought about increased visibility benefits. These dashboards have facilitated better collaboration and communication among project stakeholders, resulting in shorter meeting durations. Decisions can now be made promptly, based on documented datasets rather than relying on assumptions. This has enhanced the accuracy and effectiveness of decision-making processes. Furthermore, the accessibility of datasets to all subcontractors has fostered a sense of transparency and predictability. By gaining a

Table 5
Output for Listing 1.

storey	weekplan	count
cSite:005	cSite:THISWEEK-WeeklyPMUpdate220318.xlsx	2
cSite:005	cSite:THISWEEK-WeeklyPMUpdate220325.xlsx	2
cSite:006	cSite:THISWEEK-WeeklyPMUpdate220318.xlsx	8
cSite:006	cSite:THISWEEK-WeeklyPMUpdate220325.xlsx	8
cSite:011	cSite:THISWEEK-WeeklyPMUpdate220318.xlsx	1
cSite:011	cSite:THISWEEK-WeeklyPMUpdate220325.xlsx	1
cSite:011	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	1
cSite:011	cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	1
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220401.xlsx	8
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220401.xlsx	12
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220318.xlsx	14
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220325.xlsx	14
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220311.xlsx	6
cSite:006	cSite:THISWEEK-WeeklyPMUpdate220401.xlsx	3
cSite:005	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	1
cSite:005	cSite:THISWEEK-WeeklyPMUpdate220401.xlsx	1
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	12
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	21
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	7
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220311.xlsx	18
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220318.xlsx	13
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220325.xlsx	13
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	17
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	16
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	5
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	8
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220401.xlsx	20
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220318.xlsx	12
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220325.xlsx	12
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	10
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	3
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	7
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220527.xlsx	30
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220527.xlsx	26
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220422.xlsx	13
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	11
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	19
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	32
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220422.xlsx	26
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220311.xlsx	8
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	10
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	25
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220527.xlsx	1
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	4
cSite:004	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	2
cSite:007	cSite:THISWEEK-WeeklyPMUpdate220311.xlsx	1
cSite:007	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	2
cSite:008	cSite:THISWEEK-WeeklyPMUpdate220311.xlsx	1
cSite:008	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	2
cSite:004	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	3
cSite:005	cSite:THISWEEK-WeeklyPMUpdate220408.xlsx	2
cSite:004	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	1
cSite:011	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	1
cSite:011	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	1
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	1

Table 6
Output of Listing 2.

storey	weekplan	count
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	3
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	7
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	8
cSite:001	cSite:THISWEEK-WeeklyPMUpdate220527.xlsx	30
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220527.xlsx	4
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	5
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	7
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220422.xlsx	8
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	10
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	14
cSite:002	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	15
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	3
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	5
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	6
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	7
cSite:003	cSite:THISWEEK-WeeklyPMUpdate220422.xlsx	13

Table 7
Output of Listing 3.

storey	org	Completion_Rate
cSite:001	cSite:CompanyF	0.5
cSite:001	cSite:CompanyL	0.6363636
cSite:001	cSite:CompanyC	1.0
cSite:001	cSite:CompanyN	1.0
cSite:001	cSite:CompanyO	1.0
cSite:002	cSite:CompanyO	0.6666667
cSite:002	cSite:CompanyL	0.72727275
cSite:002	cSite:CompanyF	1.0
cSite:003	cSite:CompanyM	0.4047619

ontology for accomplishing these benefits. Moreover, they emphasised the universality and scalability of the implementation. It transcends the limitations of specific cases and possesses the potential for expansion into a 'plug-and-play' construction management platform. Therefore, the ontology not only contributes to the successful execution of individual projects but also paves the way for a broader, innovative approach to construction management, signifying its crucial role in the larger eco-solution.

7. Discussion

Driven by advancements in Industry 4.0 technologies and techniques, the built environment sector is undergoing a rapid transformation towards a smart building ecosystem, not only during operation but also throughout the construction phase. It has become increasingly common for building owners to demand the presence of construction digital twins. Extensive research has demonstrated that the design and management of dataset integration for effective construction production control are complex, primarily due to the varying breakdown structures of datasets and the existence of data silos. To facilitate the development of construction digital twins, this research focuses on addressing the challenge of dataset integration for efficient production control. Within the scope of this study, our primary emphasis was on the development of an ontology, termed cSite, which encompasses crucial aspects and domains relevant to construction production control. These aspects encompass construction activities, deliverables such as documents and submittals, resources including materials, labour, and

Table 8
Output of Listing 4.

storey	Completion_Rate
cSite:003	0.4047619
cSite:002	0.67901236
cSite:001	0.9056604

comprehensive understanding of the hotspots within the planning process, subcontractors are better equipped to identify potential issues and implement effective mitigation strategies. This level of insight and initiative-taking approach to problem-solving has further contributed to the positive reception of the research findings. Overall, in the use cases, the successful implementation of the cSite ontology has brought about tangible benefits in terms of time savings, improved collaboration, and enhanced decision-making capabilities. These positive outcomes have been well-received by users, highlighting the value and potential for wider adoption in the construction industry.

The analysis underscores the integral role of the holistic eco-solution in realising the aforementioned benefits. It must be stressed that these benefits cannot be directly attributed to the proposed ontology alone. The experts, in their consensus, substantiate the indispensability of the effective integration made possible through the implementation of this

Table 9

Output of Listing 5.

weekplan	org	N_completed_activities	N_activities	Completion_Rate
cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	cSite:CompanyC	1	1	1.0
cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	cSite:CompanyO	9	9	1.0
cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	cSite:CompanyL	12	19	0.6315789
cSite:THISWEEK-WeeklyPMUpdate220415.xlsx	cSite:CompanyM	7	19	0.36842105
cSite:THISWEEK-WeeklyPMUpdate220422.xlsx	cSite:CompanyO	8	13	0.61538464
cSite:THISWEEK-WeeklyPMUpdate220422.xlsx	cSite:CompanyM	13	26	0.5
cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	cSite:CompanyO	10	11	0.90909094
cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	cSite:CompanyN	2	4	0.5
cSite:THISWEEK-WeeklyPMUpdate220429.xlsx	cSite:CompanyF	1	4	0.25
cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	cSite:CompanyO	20	20	1.0
cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	cSite:CompanyM	5	7	0.71428573
cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	cSite:CompanyL	1	2	0.5
cSite:THISWEEK-WeeklyPMUpdate220506.xlsx	cSite:CompanyF	1	3	0.33333334
cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	cSite:CompanyO	2	2	1.0
cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	cSite:CompanyL	3	3	1.0
cSite:THISWEEK-WeeklyPMUpdate220513.xlsx	cSite:CompanyM	3	25	0.12
cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	cSite:CompanyO	1	1	1.0
cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	cSite:CompanyL	6	6	1.0
cSite:THISWEEK-WeeklyPMUpdate220520.xlsx	cSite:CompanyM	6	32	0.1875
cSite:THISWEEK-WeeklyPMUpdate220527.xlsx	cSite:CompanyO	34	52	0.65384614

equipment, external constraints such as weather conditions, and any associations that interrelate these aspects. While previous works have proposed control room environments for construction data, they lacked a repeatable integration approach, and they are mostly closed all-in-one solutions requiring organizations to overhaul their existing platforms and workflows. The cSite ontology addresses this gap by enabling consolidated analytics across data silos. The development process combines inductive, synthetic, and collaborative techniques to ensure comprehensive coverage aligned to end user needs.

The cSite ontology makes several notable contributions. First, it provides a unified schema for semantically integrating heterogeneous construction data sources to enable consolidated analytics focused on production control. Second, cSite consolidates and extends concepts from established but disconnected domain ontologies into an integrated ontology spanning planning, monitoring, and collaboration. Third, the development process advances ontology engineering methodology through its user-centred hybrid approach. Fourth, cSite demonstrates and validates the utility of ontology-driven data integration to enhance construction project visibility. Finally, the ontology establishes relationships between data, processes, products, and context to support cross-domain reasoning. In summary, cSite delivers a comprehensive ontology co-developed with end users that bridges data silos, enriches semantics, and provides the integrative foundation to meet key production control challenges through improved analytics. By leveraging this ontology, construction professionals can improve their ability to efficiently manage construction projects and effectively address production control challenges. The positive user reception underscores how leveraging an ontology can tangibly improve decision-making, collaboration, and efficiency.

By grounding our development in a user-centric approach, we not only contribute to academic discourse but also offer a robust, actionable framework for practitioners. The extensibility of cSite ontology facilitates diverse applications, such as integrating multiple projects for headquarters-level analysis and expanding to include external factors like weather and supply chain. Moreover, the ontology can serve as the

foundation for executing supervised learning algorithms that effectively generate look-ahead based on integrated datasets. More broadly, as construction digital twins increasingly become a staple in construction sites, the demand for effective and interoperable ontologies is set to rise correspondingly. Our work also serves to advance construction digital twin capabilities, presenting a methodology to amalgamate disparate systems into a unified data environment. This is a significant step in harnessing the potential of Industry 4.0 techniques within the built environment. The development of the unifying cSite ontology fills a critical gap by bridging data and communication silos and thereby transforming construction management. With a positive reception, this ontology-driven integration paradigm exceeds existing literature by offering not just a new integrative ontology, but also empirical evidence of its utility for enhancing project performance. Therefore, this research offers multifaceted contributions, ensuring its long-term relevance by furnishing both academic scholars and industry stakeholders with actionable insights.

One of the main limitations inherent in this research pertains to the identification of classes, which relied on either existing ontologies or the creation of new classes. However, it should be acknowledged that other ontologies may contain classes with either different or similar names to those utilised in this research. A key objective of this study is to not introduce new classes unnecessarily, opting instead to leverage existing classes and ensure compatibility not only with the selected published ontology but also with other relevant ontologies. Hence, future work will involve aligning the classes related to the cSite ontology with diverse existing ontologies. Another limitation concerns the evaluation, which was conducted solely on a single project. To establish the efficacy and applicability of the ontology, it is essential to subject it to testing in multiple projects. This broader assessment is necessary to ensure that the ontology adequately addresses the requisite information and possesses the capacity for reusability and extension, thereby enabling its seamless integration as a plug-and-play solution for construction digital twin requirements.

8. Conclusions

This paper highlights the utilisation of an ontological solution to provide semantic descriptions for various domains in construction. By linking multiple datasets and applying an algorithm, the aim is to automate the production and control processes on construction sites. Additionally, the paper highlights how the generated, integrated, and visualised production information can enhance transparency and productivity in construction projects. To validate its effectiveness, the

Table 10

Output of Listing 6.

org	reason	reasoncount
cSite:CompanyO	Activity Durations	18
cSite:CompanyO	Construction Logic	5
cSite:CompanyO	Subcontractor & Supplier design Information	5
cSite:CompanyO	Design approvals	2
cSite:CompanyO	Any Re-Work Required	1

Table 11

Output of Listing 7.

Storey	Org	Activityversion	Reason	Resporg
cSite:003	cSite:CompanyM	cSite:2–6000-QSO-003-0227-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–6100-QSO-003-0092-No	Access and Logistics	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–6100-QSO-003-0103-No	Construction Logic	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–6100-QSO-003-0147-No	Outstanding Design	cSite:CompanyT
cSite:003	cSite:CompanyM	cSite:2–6200-QSO-003-0080-No	Access and Logistics	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–6200-QSO-003-0135-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–6200-QSO-003-0157-No	Outstanding Design	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–6500-QSO-003-0046-No	Activity Durations	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–6500-QSO-003-0090-No	Access and Logistics	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–6500-QSO-003-0237-No	Temporary Works	cSite:CompanyX
cSite:003	cSite:CompanyM	cSite:2–6500-QSO-003-0244-No	Temporary Works	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–7000-QSO-003-0064-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–7000-QSO-003-0075-No	Coordination of Trades at the Work Front	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7000-QSO-003-0076-No	Activity Durations	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7000-QSO-003-0097-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–7000-QSO-003-0108-No	Coordination of Trades at the Work Front	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:2–7000-QSO-003-0197-No	Any *Re*-Work Required	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7050-QSO-003-0077-No	Activity Durations	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7050-QSO-003-0121-No	Are any instructions required	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7500-QSO-003-0067-No	Activity Durations	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7500-QSO-003-0078-No	Activity Durations	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:2–7500-QSO-003-0122-No	Procurement of Subcontract Works	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:3–6100-QSO-003-0092-No	Construction Logic	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:3–6100-QSO-003-0103-No	Construction Logic	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:3–6100-QSO-003-0106-No	Coordination of Trades at the Work Front	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:3–6200-QSO-003-0069-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:3–6200-QSO-003-0157-No	Any Re-Work Required	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:3–6500-QSO-003-0090-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:3–7000-QSO-003-0075-No	Coordination of Trades at the Work Front	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:4–6000-QSO-003-0227-No	Access and Logistics	cSite:CompanyN
cSite:003	cSite:CompanyM	cSite:4–6100-QSO-003-0073-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:4–6200-QSO-003-0102-No	Coordination of Trades at the Work Front	cSite:CompanyM
cSite:003	cSite:CompanyM	cSite:4–6500-QSO-003-0068-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:5–6500-QSO-003-0090-No	Activity Durations	cSite:CompanyU
cSite:003	cSite:CompanyM	cSite:6–6100-QSO-003-0070-No	Activity Durations	cSite:CompanyU

proposed solution was assessed in a case project using real data from a construction site. The proposed solution encompasses three key components. Firstly, there are several ontologies specifically designed to address the production control scenario, covering domains such as planning schedules, resources deliveries, construction documents and deliverables, and project typology. These ontologies serve as the foundation for integrating data across these diverse domains. Secondly, the cSite ontology acts as a unifying framework, enabling the integration and mapping of heterogeneous data sourced from different platforms. It includes SPARQL queries that address the competency questions derived from end-user requirements, aiming to facilitate effective production control in construction sites. Finally, the solution offers a resilient decision support environment, providing stakeholders with access to the integrated data and enabling them to retrieve the required information in a user-friendly manner. To ensure usability and meet expectations, the dashboards within the environment are co-designed with users, considering their preferences and requirements during weekly progress meetings.

This paper contributes to the existing knowledge in digitally enabled production control and holds significance for academics involved in lean construction, construction digital twins, integration through ontological solutions, and visualisation using control rooms in construction sites. It expands the understanding in these areas and offers valuable insights for researchers working in these domains. Our future research endeavours will concentrate on three primary areas. Firstly, we aim to expand the mapping of the cSite ontology to include additional existing ontologies, thereby enhancing its interoperability and integration capabilities. Secondly, we plan to further validate the effectiveness of the solution by evaluating it on a wider range of construction case studies. This will help ensure that the solution can be easily implemented and utilised in various scenarios, achieving a plug and play functionality. Lastly, we intend to broaden the scope of the ontology to encompass other critical
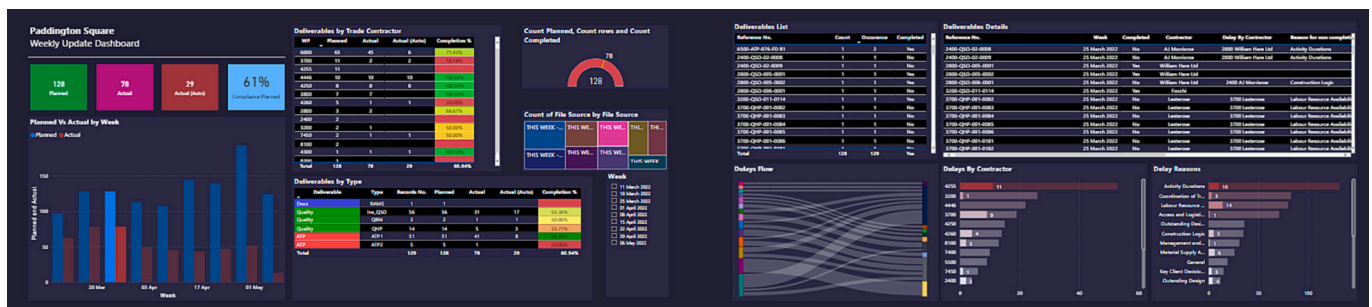

Fig. 6. Snapshot of one of the dashboards shared in the workshops, with company names redacted to ensure confidentiality.

aspects of production and control in construction, such as weather conditions, safety measures, and sustainability considerations. By incorporating these additional dimensions, the solution will provide a more comprehensive and integrated approach to production and control on construction sites.

CRediT authorship contribution statement

Karim Farghaly: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ranjith Soman:** Writing – original draft, Validation, Software, Investigation, Funding acquisition. **Jennifer Whyte:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition.

Declaration of Competing Interest

Karim Farghaly reports financial support was provided by Innovate UK.

Data availability

The data that has been used is confidential.

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