Ontology-Based Construction Progress Monitoring: A Conceptual Framework

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Abstract
Progress monitoring is a vital process in construction projects. With technological advancement and BIM implementation, there is a greater tendency towards automating the process, with many studies being carried out on automated progress detection and monitoring. However, most of these studies are conducted in isolation using a single or a fusion of several data-capturing techniques without giving proper attention to the interoperability of heterogeneous data generated throughout the construction process through multiple facets. Therefore, this study presents a conceptual framework for an ontology-based construction progress monitoring system through the fusion of heterogeneous data generated by multiple facets of construction. The proposed framework comprises a six-layered architecture comprised of data acquisition, integration, ontology, analytics, backend and frontend layers. The framework proposes a modular ontology design comprising five domain-based modules, such as product, process, resource, schedule, and data, which are integrated into a core module, forming a knowledge base. This study presents preliminary findings from an ongoing research study, with the proposed framework set to be tested and validated in future work.

Keywords
Ontology, construction progress monitoring, semantic web

1. Introduction

Progress monitoring is a fundamental aspect of construction project management, which ensures that as-built progress aligns with the as-planned schedule [1]. Over the years, many researchers have attempted to utilise emerging field data acquisition technologies to automate progress monitoring by adopting a single technology or combining several technologies [3,4]. Technologies such as Laser Scanning (LS), Radio Frequency Identification (RFID), Ultra-WideBand (UWB), Global Positioning Systems (GPS), and Wireless Sensor Networks (WSN) have been utilised for the automation process [4]. These technologies, together with Scan-to-BIM (Building Information Modelling), provide a visual and thorough evaluation of the as-built condition of construction projects, enabling efforts to enhance overall project performance [5].

However, the existing attempts at automated progress monitoring have primarily aimed at merely providing the physical progress of the site using a single or fusion of vision or laser-based data capturing methods without giving proper consideration to other data sources such as materials, labour, resources, etc. Throughout the whole construction period, the progress monitoring process should be conducted by collecting, recording and reporting information related to one or more facets of project performance by identifying progress discrepancies and allowing the project management team to initiate corrective measures promptly [6]. Thus, there should be a mechanism to integrate these heterogeneous data formats to provide a meaningful output [7].

One of the primary obstacles in automated progress monitoring is the interoperability challenges caused by the use of different data [8]. When considering progress monitoring, data should be

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collected from numerous domains. A reliable progress monitoring system has to possess the capacity to offer an efficient and effective way of assessing, acquiring, verifying, and quantifying as-built data indicating the progress in terms of cost, schedule, resources, procurement, and quality [6]. Further, the authors emphasised that the system should be capable of detecting and analysing critical information from a given progress scenario. Moreover, the system must deliver the analysed data in a timely manner, in a format that can be best interpreted by management, and at a suitable level of detail, to ensure corrective measures can be initiated on the progress scenario that produced the data in the initial instance.

Linked Data technologies have the potential to create an open and collaborative environment for sharing, integrating, and linking data from many domains and data sources [9]. The concept of the Semantic Web lies behind the linked data concept, which is the creation of a web of data with the help of data schemas termed ontologies [7]. Several researchers have attempted to utilise semantic web technologies and ontologies for construction management use cases [10, 7, 11]; however, these studies lack a comprehensive framework to monitor progress by integrating multi-faceted data. To fill this gap, this study focuses on introducing a conceptual framework for construction progress monitoring that integrates heterogeneous construction data using an ontology-based approach. This paper presents the rationale behind formulating the conceptual framework, proposed system architecture and its key components.

Compared to the existing methods, which mainly focus on progress monitoring through visual capture technologies, this study presents a conceptual framework that integrates multi-faceted construction data. This includes both planning and as-built data derived from BIM models, schedules, construction resources, physical progress through visual captures, event logs, etc., to ensure a comprehensive progress assessment. The novelty of this study lies in leveraging semantic web technologies and linked data for data fusion and automated progress inference, offering a structured, interoperable and scalable approach for progress monitoring.

Following the introduction section, this paper is structured to provide an overview of the current research on automated construction progress monitoring and the application of semantic web technologies for construction management. It then proposes a conceptual framework for ontology-based construction progress monitoring. Finally, the paper highlights the key findings and explores future research directions.

2. Background

2.1. Automated Construction Progress Monitoring

Construction projects that fall behind time and have disparities between the as-built and intended baseline plans are both undesirable situations that might frequently occur [12]. Thus, real-time progress monitoring and tracking of building components is still crucial to managing projects and is key to meeting project objectives. Numerous studies have been conducted to examine the possibility of using advanced technologies, such as LS, GPS, RFID, and UWB, in the construction industry [12]. Furthermore, several researchers have deployed a fusion of two or more data capture techniques.

A key observation in existing research on automated progress monitoring is the predominant focus on using object detection; while useful, it limits the ability to provide meaningful insights into the construction status and for informed decision-making. Progress monitoring through visual capture technologies can mainly be categorised into two methods as occupancy-based and appearance-based approaches [13]. The occupancy-based approach depends on geometric modelling and is less effective in tracking non-geometrically modelled activities. Studies such as [14, 15, 16], etc., have utilised this approach. In contrast, the appearance-based method detects visual features/characteristics of construction tasks using image data. Several studies have adopted the appearance-based approach, including those by [17] and [18]. Depending solely on these techniques limits progress monitoring to binary assessment of building elements [13]. Moreover, studies on providing percentage completion are limited, and the integration of construction schedules is scarcely explored. Therefore, significant advancements are required to enhance and optimise these approaches. Additionally, existing research on vision-based monitoring often lacks semantic depth [19]. Here, the primary focus has been on object detection with limited attention on capturing meaningful relationships and dependencies between the objects, activities and workflows. Moreover, detecting objects and activities alone is insufficient for comprehensive progress monitoring [18]. Furthermore, there are numerous other means of capturing progress-related data in a construction site except for visual capture methods such as material utilisation, labour utilisation, inspection reports, event logs, schedules etc. Therefore, to provide a more accurate and comprehensive representation of project progress, a monitoring system should be capable of integrating data from multiple domains and facets.

The dynamic nature of construction projects and varied data inflows from multiple stakeholders representing different domains, tools and workflows make automated progress monitoring complex [7]. Moreover, construction projects generate a vast amount of textual and numeric data in terms of event logs, reports, material delivery schedules, etc., which contributes to a holistic understanding of the project status. Furthermore, due to issues such as erroneous data, missing data, undetected activities, etc., it becomes challenging to derive insights into project status. Rule-based reasoning and inferencing mechanisms can be incorporated to address these gaps and limitations while providing accurate and reliable progress estimation [6]. Furthermore, without a comprehensive semantic representation of construction progress, it is difficult to enable automated reasoning, integration with other domains, and intelligent decision-making [20]. Integrating data from every facet of construction assists in precise situational awareness, which is mandatory for effective production planning and control to ensure efficient allocation of resources and input flow management [21].

Therefore, this study aims to bridge these gaps by introducing a conceptual framework for ontology-based progress monitoring that can semantically represent construction progress, integrate heterogeneous data sources, and infer progress insights dynamically. By leveraging Semantic Web technologies, this system can overcome interoperability issues and provide a unified, machine-readable representation of progress data, ensuring seamless integration with existing BIM and project management systems.

2.2. Semantic Web and Construction Monitoring

The Semantic Web standards lay a solid basis for interoperability in the construction industry, necessitating networked data [7]. Furthermore, data is made machine-readable and machine-interpretable when ontologies are used. The concept of the Semantic Web allows various domains engaged in AEC projects to semantically represent building information on a specific entity in a manner that could be integrated with data from other domains [8]. Over the last decade, the digital project model and model interchange formats have been the objects of study and standardisation, with the Industry Foundation Classes (IFC) schema at the heart of interoperability and supporting project stakeholder engagement [22]. Nonetheless, this could be inadequate when formalising complicated socio-technical systems, which require the incorporation of different hardware, software, stakeholders, and wider community traits [23]. Furthermore, according to [24] three major benefits of applying the Semantic Web: interoperability, linking across domains, and logical inference and proofs.

There are numerous efforts made by a number of researchers across multiple domains in the construction industry, such as construction information extraction from BIM models [25], cost estimation [26], compliance checking [27], etc. These studies demonstrate the potential of incorporating semantic web technologies and linked data for construction industry-related operations. One of the major milestones in ontology research in construction is the formulation of the ifcOWL ontology. Building upon this foundational work of [28, 29], [30] executed a direct mapping of the Express schema to OWL, producing the ifcOWL ontology. However, the ifcOWL ontology comprises two main limitations: 1.) complicated structure providing implications such as inefficiency in the reasoning process, unmanageable nature, and difficulties in understanding the ontology, 2.) large size hampering its extensibility and modularity [31]. While providing a solution for this issue, the Linked Building Data (LBD) Community Group of the World Wide Web Consortium (W3C) has developed several lightweight ontologies such as BOT, PRODUCT, PROP, etc. Among these, BOT focuses on representing topological relationships between elements. Furthermore, DiCon is a suite of ontologies that aims to provide a high-level representation of construction workflows by integrating heterogeneous data from different information and communication technology (ICT) platforms [20]. Moreover, ontologies like SSN for sensor networks and QUDT for quantities and measurements can be further incorporated in expanding the domains covered by ontologies primarily focusing on the construction industry.

Despite the availability of multiple ontologies, the AEC industry faces a major challenge in ontology adoption. The overlapping scopes of various ontologies often result in fragmented and inconsistent data models, slowing down the widespread adoption of Semantic Web technologies. For construction progress monitoring, selecting the most suitable ontology is critical to ensuring data integration, reasoning efficiency, and interoperability across systems. In lieu of developing new redundant ontologies, researchers have to prioritise reusing existing ontologies, which are accepted by a wide range of communities. In compliance with this approach, this study leverages and extends existing ontologies while ensuring interoperability with widely accepted ontologies. The proposed ontology-based progress monitoring framework is designed to acquire, manage and semantically integrate heterogeneous as-planned and as-built data for more efficient construction progress monitoring. The ontology-driven data fusion framework proposed in this study addresses the gaps in multi-source data integration and reasoning, ensuring automated progress tracking, compliance analysis, and decision support. The following sections will detail the ontology development process and the proposed framework for construction progress monitoring.

3. Proposed Framework

3.1. Construction Progress Monitoring Expert System

A reliable progress monitoring system has to offer an efficient and effective way of assessing, acquiring, verifying, and quantifying as-built data indicating the progress in terms of cost, schedule, resources, procurement, and quality [6]. Further, the system should detect and analyse critical information from a given progress scenario. Moreover, the system must deliver the analysed data to managers and executives on time, in a format that can be best interpreted by management, and at a suitable level of detail for the people who will be using it, to ensure corrective measures can be initiated on the progress scenario that produced the data in the initial instance. Therefore, the following sections describe the key considerations taken during the formulation of the proposed conceptual framework.

3.1.1. Key Considerations for System Design

This section represents key considerations when designing the progress monitoring system.

- Physical Progress

The system should be capable of representing physical progress and visualising it by superimposing the as-built model over the as-planned model [13]. Here, the progress related to construction elements is displayed colour-coded. Furthermore, physical progress should be represented with element IDs, locations, quantities and associated tasks, subtasks, dependencies, prerequisites, and resources.

- Compliance with the Schedule

Determining whether the project is progressing according to the as-planned schedule and whether there are any deviations from the original schedule in terms of being behind or ahead of the schedule [32]. Furthermore, the system should be capable of determining whether key milestones in the project are met or not and identifying reasons for non-compliance to the schedule.

- Inspections and Formalities

When performing the progress in a construction site, construction managers are required to perform various tasks and procedures for inspection reports, defects identification, risk identification, etc., including evidence such as photographs, videos, reports, required data, etc and generating approvals for inspection reports. The system should integrate these compliance-related activities, providing automated approvals for inspection reports and ensuring that necessary corrective measures are initiated when required.

- Progress Analysis and Report Generation

To facilitate data-driven decision-making, the system must be capable of generating structured reports and visual analytics [10; 32]. This includes tracking key performance indicators (KPIs) and presenting insights through graphs, charts, tables, and a 3D visualisation model. By superimposing as-planned and as-built BIM models, stakeholders can assess near real-time or weekly progress in a more intuitive and interactive manner.

3.1.2. System Design Features

Building on the key considerations, the following design features have been identified to enhance the functionality and usability of the proposed framework.

- Near real-time tracking (weekly update frequencies)
- Ability to be a single source of truth to get the most accurate progress insights through data integration.
- Ability to be used collaboratively [22]
- Considerations on the granularity level of the system
- Clear visual representation of the progress [32]
- Proper analytical representation of the progress [10]
- Capability of tracking activities within the site [13]
- Capability of generating progress reports
- Assisting in look-ahead planning based on progress data [11]
- Actual vs Planned dashboard representation [10]

3.1.3. System Use Cases

In line with the overarching aim and objectives of the study of formulating a construction progress monitoring framework that integrates heterogeneous data sources to support project stakeholders in making informed decisions and timely actions, the proposed framework should cater to the following use cases.

- Integration of heterogeneous data sources for informed and data decision-making, enabling a holistic representation of the construction progress.
- Assessment of the construction progress and performance to determine the adherence to as-planned workflow through key performance indicators (KPIs).

- Monitoring the adherence to the as-planned schedule and assisting in generating future schedules and LookAhead plans.

3.1.4. System Architecture

The proposed ontology-based construction progress monitoring follows a six-layered system architecture focusing on data acquisition, integration, processing, storing, and visualisation. At the heart of the proposed system lies an ontology layer developed following a modular ontology development workflow. Each layer of the proposed framework serves a distinct purpose, as illustrated below in Figure 1.

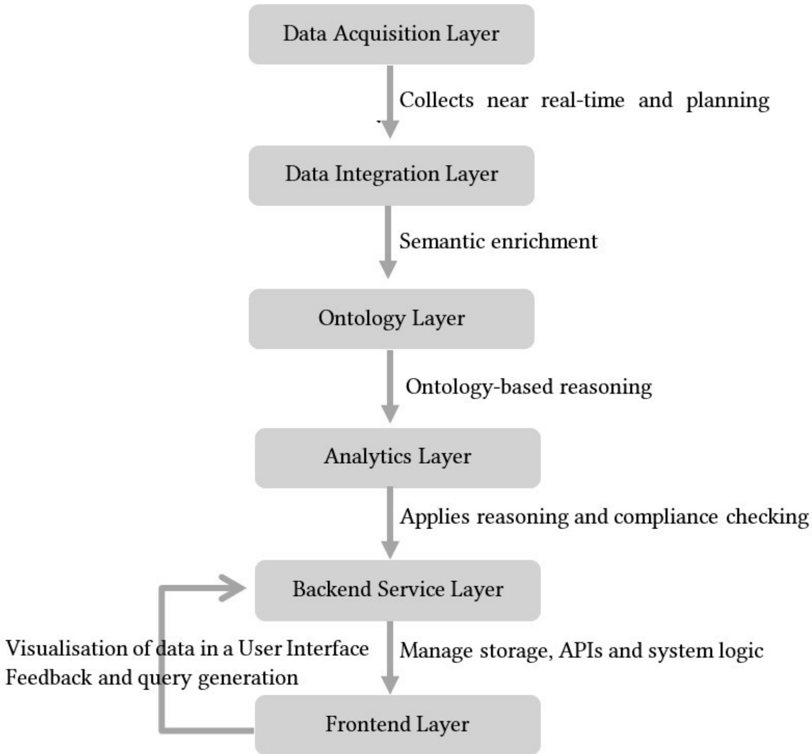

Figure 1: Proposed Framework

1. Data Acquisition Layer

The data acquisition layer focuses on collecting both planning and construction data. These data are collected from various means and streams such as BIM models, schedules, visual captures, event logs, external conditions such as weather, etc. This layer will ensure a continuous inflow of near real-time data crucial for status monitoring.

2. Data Integration Layer

The data integration layer focuses on the semantic enrichment of incoming data and converting those into RDF format. This will ensure the data are mapped with the developed ontology framework for the data fusion and reasoning process. Moreover, SHACL-based data validation will be conducted to ensure integrity. While the proposed framework accommodates visual captures as inputs, it does not currently include object and activity detection within its framework. Thus, the proposed framework will rely on pre-processed visual data. The integration of object detection capabilities will be explored in future research.

3. Ontology Layer

This layer defines the semantic structure and relationships within the construction project's domain, facilitating interoperability and data fusion across heterogeneous data sources. The ontology will be developed using the Protégé ontology editor, encompassing classes, properties and constraints that represent building elements, tasks, resources, and data streams. The proposed ontology design takes a modular approach and will be extended and mapped with established industry standard ontologies such as ifcOWL, BOT, QUDT, DiCon, BFO, etc. Furthermore, this layer will serve as the backbone for knowledge graph generation, supporting SPARQL queries and reasoning.

4. Analytics Layer

The analytics layer focuses on conducting semantic reasoning, compliance checking, progress estimation and KPI calculations to provide insights into the status of construction. Moreover, this layer will execute SWRL rules and OWL reasoning to infer missing information and violations.

5. Backend Service Layer

This layer focuses on data strategy, management, retrieval and API request handling. This will be developed using frameworks such as Flask to host RESTful APIs for data manipulation, integration and retrieval; Apache Jena Fuseki triple store will be used as the triple store and SPARQL query execution will be handled in here.

6. Frontend Services Layer and User Interface

This layer provides interfaces and visualisation tools to interact with the stakeholders and interpret construction progress data effectively. Unity Engine will be utilised for 3D visualisation by overlaying the as-built model on an as-planned model. The dashboard created using AngularJS will illustrate the progress reports, graphs and KPIs.

The proposed architectural framework will be utilised in progress monitoring through the integration of diverse data sources, efficient data handling and to provide data driven insights into the status and progress of the project through a visualisation tool. Upon the development of the prototype application, this will be tested and validated through a case study.

3.2. Ontology Development

For this study METHONTOLOGY ontology development approach was selected [33]. This ontology development approach consists of several phases, as illustrated in Figure 2 below.

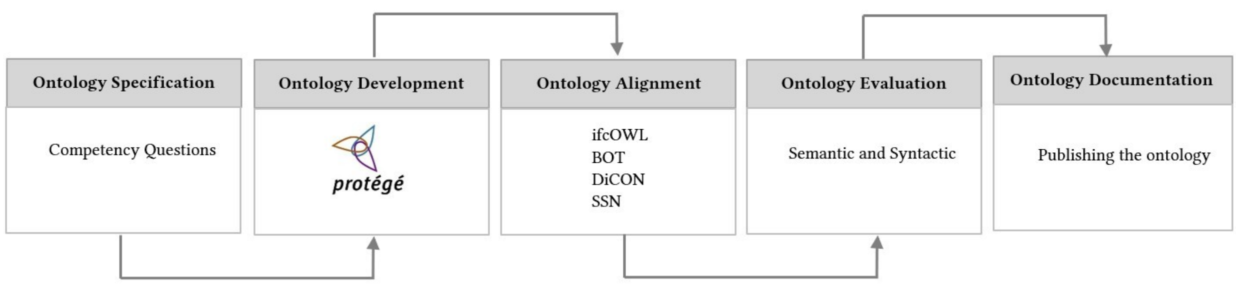

Figure 2: Ontology Development Approach

3.2.1. Purpose and Scope

A clear definition of requirements, such as its purpose, scope and end users, should be identified to develop an ontology [8]. These requirements create the pathway for determining concepts, relationships, and reasoning rules [34]. Therefore, the purpose, scope and end users for the proposed ontology framework are as follows;

- Purpose: Facilitate automated construction progress monitoring through the integration of heterogeneous data sources, enabling interoperability and semantic reasoning. The ontology will assist in determining project progress in near real-time (with weekly update frequency) by comparing as-planned data with as-built data to provide insights on physical progress, schedule compliance, milestone achievements, etc.
- Scope: Data integration in timely manner and construction activity representation, mapping tasks, dependencies and resource requirements.
- End users: This includes construction managers, site engineers, quantity surveyors, and project stakeholders who require accurate and timely insights into construction progress, schedule adherence, and resource availability. By leveraging ontology-driven reasoning, the system provides stakeholders with automated compliance checks, alerts for deviations, and decision support.

Competency questions can be formulated in line with the identified purpose, scope and end users of the ontology [35]. These competency questions provide detailed insights into the ontology requirements, assisting in the ontology modelling process. The competency questions relevant to the study are listed below in Table 1.

Table 1
Competency Questions

No.	Competency Question
1	What is the considered progress period?
2	What are the expected tasks, associated building elements, and scheduled task durations for the considered progress period?
3	What are the prerequisites associated with planned tasks?
4	Does the task belong to the critical path, and its completion corresponds to a milestone accomplishment?
5	What data captures available for the considered progress period?
6	What metadata is associated with each data capture?
7	Information regarding what tasks and building elements are available in the data captures?
8	What different data sources provide information about the same entity during the same period?
9	What is the current progress of the tasks and building elements scheduled for the considered progress period?
10	What tasks show delays and causes for delays?

3.2.2. Ontology Development – Modular Approach

Followed by the specification phase, the next phase is the conceptualisation where all the necessary terms, concepts, class hierarchy and properties are formulated to construct the ontological model [35]. The industry is evolving towards modular, domain-specific ontologies rather than depending on single, comprehensive or monolithic models to capture the full building lifecycle [35]. This modular approach enables each module to be independently extended or integrated, promoting flexibility, reusability, and collaboration within construction data management. The proposed ontology system of this study comprises five domain-specific modules and a core module that integrates them into a comprehensive knowledge framework. The ontology development process was conducted using the Protégé ontology developer. A brief overview of the modules that comprise the proposed ontology system is provided below;

- **OntoProduct** (Product Module): Represents physical and spatial components in a construction project, including building elements, materials, and site structures. This module extends the BOT ontology.
- **OntoProcess** (Process Module): Defines construction workflows, task dependencies, and execution sequences.
- **OntoResource** (Resource Module): Represents labour, equipment, and materials used in construction.
- **OntoSchedule** (Schedule Module): Handles scheduling concepts, milestones, and timeline constraints.
- **OntoData** (Data Module): Focuses on data acquisition, management, and near real-time monitoring.
- **OntoPMS** (Core Module): Integrates all other modules, providing logical axioms, reasoning rules, and cross-domain relationships for progress monitoring.

Figure 3 illustrates the modular approach adopted in this study. Furthermore, it should be noted that due to its iterative nature, the proposed ontology model is still under development and will be tested and validated in the future.

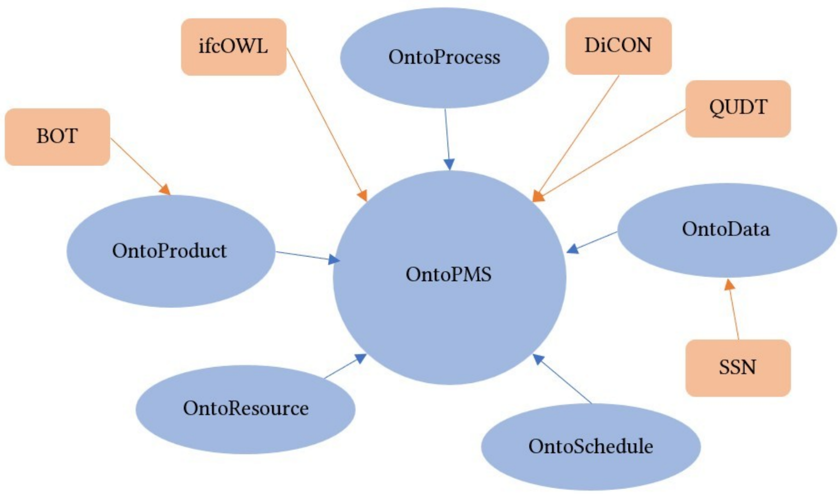

Figure 3: Modular Ontology Design

3.2.3. Semantic Reasoning

A key advantage of the ontology-based framework is its ability to infer new knowledge using semantic reasoning. This layer represents validation, constraints and query rules in a machine-interpretable language [36]. By leveraging reasoning engines such as Pellet and HermiT, and rule languages such as SWRL, axioms and queries through SPARQL and SHACL, the ontology supports:

- Schedule compliance checks, determining if the actual progress aligns with the planned schedule.
- Progress estimation, inferring partially completed or undetected activities based on related task dependencies.

3.2.4. Ontology Alignment

In compliance with the W3C best practice guideline, it is essential to map the developed ontology/s with existing ontologies to enhance interoperability, data integration, semantic consistency, and reuse of existing resources. The process of creating relations between terms (classes or properties) and/or individuals from different ontologies is called an ontology alignment. Ontology alignments can be conducted through three approaches, namely, checking terminology, internal structure, and external structure. Currently, the developed ontologies are being mapped with existing standards and domain ontologies, including ifcOWL (for BIM models), BOT (for building topology), and DiCon (for construction workflows). Furthermore, alignments will be created with more high-level ontologies such as BFO and PROV-O.

3.2.5. Ontology Evaluation

Ontologies can be evaluated both semantically and syntactically [37]. Currently, the syntactic evaluation is conducted using the pellet reasoner. Furthermore, through a case study, the ontology will be validated semantically to determine whether it provides answers to the competency questions formulated during the ontology specification stage.

3.2.6. Ontology Documentation

When it comes to semantic web technology, interoperability and shared ontologies (ideally accessible online) are crucial. This makes it possible for the applications used by different stakeholders to reliably reuse the terminology in their own datasets and tools and to search for definitions of terms in the datasets they have been given. Since the ontology development process is an iterative process, the ontology is not currently documented online for users to see. However, upon the completion of the development process, the ontologies are planned to be documented and published online.

4. Conclusions and Future Work

This study presents a conceptual framework for ontology-based construction progress monitoring through the fusion of heterogeneous data sources. The existing research lacks a comprehensive framework for construction progress monitoring capable of handling multiple data sources and types in a timely manner. The inclusion of an ontology layer and semantic web technologies provides a solution to the long-standing issue of interoperability and linking across domains. Moreover, the proposed data-driven semantic reasoning framework is intended to assist in timely interpretation of acquired data and can be used as a decision support tool. By addressing data fragmentation and interoperability challenges, this framework will assist in the digitalisation of the construction progress monitoring, creating a pathway to more efficient, automated and intelligent information systems. The ontology layer of the proposed framework comprises a modular architecture comprising five domain-specific modules and a core ontology that integrates those modules and forms a knowledge base. Furthermore, alignments and mappings will be made with industry-standard ontologies such as ifcOWL, BOT, DiCON, BFO, etc., to achieve seamless data integration and interoperability. A key consideration when designing the proposed framework is to provide the system with the ability to infer missing information using rule-based reasoning. By applying SWRL rules and SPARQL queries, the system is expected to determine task prerequisites and schedule adherence, reducing reliance on manual tracking and reporting.

However, performing object and activity detection of visual progress captures such as images, scans and videos is out of the scope of the proposed framework. Therefore, pre-processed visual data will be utilised as inputs to the system, ensuring focus remains on integrating structured object-detected data with as-planned and as-built data. Moreover, the proposed framework attempts to link data inputs with their corresponding construction activities, enabling reasoning-based progress tracking, milestone verification and compliance analysis. Many improvements are essential for further enhancement of the proposed framework in terms of scalability, accuracy and industry adoption. The proposed framework will undergo testing, validation and continuous improvement. Future research directions in par with this study could focus on integrating machine learning-driven reasoning along with rule-based reasoning and inferencing. Furthermore, the framework could be extended to areas such as delay prediction, anomaly detection, risk and safety management etc.

Declaration on Generative AI

During the preparation of this work, the author(s) used ChatGPT, Grammarly in order to: grammar and spelling check, paraphrase and reword. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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