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DEVELOPMENT OF A SPACE CONSTRAINT MANAGEMENT ONTOLOGY FOR LEAN CONSTRUCTION: ENHANCING CONSTRAINT MANAGEMENT IN STEEL FABRICATION PROJECTS

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ABSTRACT

Effective constraint management is critical for the successful implementation of the Last Planner System (LPS), particularly during the lookahead planning phase. However, space-related constraints are not well represented in current LPS implementation. This paper addresses this gap by introducing a Space Constraint Management Ontology (SCMO) to represent and manage the intricate spatial management constraints during construction tasks. The SCMO is developed using the Ontology 101 methodology, an accessible and feasible methodology for building ontologies through a well-structured seven-step process. Afterwards, the SCMO is applied in the context of a steel fabrication project. SCMO conveys steel fabrication logistics and space-related concepts, including safety distances between factory entities, following Alberta's Occupational Health and Safety regulations. This study advanced the constraint management process in current LPS practices, offering a valuable knowledge base for improving space management efficiency and safety in construction sites.

KEYWORDS

Lean construction, constraint management, semantic web, ontology, steel fabrication.

INTRODUCTION

As a well-established production planning and control method in the Lean Construction domain, the Last Planner System carries the key idea of providing a reliable workflow to the work crew by reducing the uncertainties in the production process (Ballard, 2000). It outlines the critical conditions necessary for the execution and elaborates on them to project teams through four stages: Master planning, Phase planning, lookahead planning, and weekly work planning (Karaz et al., 2024). Notably, the lookahead planning stage of the LPS emphasizes collaborative constraint management, where the prerequisites of construction tasks would be identified, analyzed and removed to reduce uncertainties.

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However, the management of constraints presents significant challenges during the lookahead planning stage. Issues such as improper recognition and analysis of production constraints have persisted due to inadequate coordination between construction site reality and the complexity of constraints (Karaz et al., 2024). Poor constraint management during lookahead planning disrupts the effective execution of the LPS, leading to production waste, poor quality, and project delays (Hamzeh et al., 2012).

The nature of the constraint management problem, as pointed out by (Chengke, 2021), is inherently defined by the triple relationship of entity-relationship-entity that links tasks and constraints. This creates an opportunity to address constraint management challenges by applying graph-based approaches, such as semantic web technologies. The semantic web can efficiently manage data with interconnected relationships while facilitating real-time interactions through specialized queries (Aleksa Vukotic, 2014). As such, studies have been conducted to pursue semantic web-related solutions to enhance LPS implementation by advancing constraint management.

Typical approaches to leveraging semantic web technologies for constraint management involve utilizing ontologies, a formal representation method that defines structured knowledge to represent task-constraint relationships, thereby enhancing constraint verification during the lookahead planning process (Gruber, 1995). Ontology-defined approaches in constraint management focus on defining domain-specific concepts to encode information into ontological knowledge bases and provide dynamic constraint checking during the LPS implementation. Studies (Koo et al., 2007; Soman et al., 2020; Tavakolan et al., 2021) show the effectiveness of ontology in coding and managing constraints, demonstrating its promise in addressing complex constraint modeling issues. However, existing ontologies fall short of representing space-related constraints (Agrawal et al., 2024). Space constraints, such as limited storage areas, restricted pathways, overcrowded work zones, and space for the safe operation of machinery, are important in construction and fabrication environments because they directly impact workflow efficiency, safety, and resource utilization. Without a clear representation of space-related constraints, the potential for enhanced ontology-supported constraint management in lookahead planning operations is limited.

To address this gap, this study aims to develop a Space Constraint Management Ontology (SCMO) to represent the intricate space requirements during the construction phase. The proposed SCMO has been further adopted and tested in the context of a steel fabrication project. We consider steel fabrication as an ideal testbed because it provides highly space-constraint environments and well-structured workflows. Unlike dynamic construction sites, the station-based fabrication process allows for a more controlled study of space-related constraints on workflow.

LITERATURE REVIEW

CONSTRAINT REMOVAL IN LAST PLANNER SYSTEM

Constraints are obstacles that hinder the completion of construction tasks. Typically, there are many different kinds of constraints in construction, such as time constraints, space constraints, and material constraints (Chuanni et al., 2023; Hylton et al., 2019). From the perspective of Lean Construction, a production management-based approach that aims to maximize value and minimize waste in construction (Koskela, 1992), effective constraint management minimizes workflow variation and improves productivity. Hence, constraint management is crucial for the overall success of a project (Ballard & Howell, 2003). With the evolution of Lean Construction theory, the well-established Last Planner System (LPS) offers a structured mechanism for guiding actions on specific activities to resolve constraints (Ballard, 2000).

However, due to the highly complex and dynamic nature of constraints, implementing the Last Planner System (LPS) often generates enormous information, which requires the integration of dynamic spreadsheets with other construction information systems (Karaz et al., 2024). Hence, previous studies centered on incorporating information systems and LPS to better manage constraints. For example, Dave Bhargav (2013) developed a prototype software system, VisiLean, that integrates LPS and building information modelling (BIM) to enhance constraint management by providing a collaborative planning and control platform with a visual interface. Leão et al. (2014) investigates the integration of information technology and the Last Planner System (LPS) within a production control model to enhance constraint management by reducing informal work packages and making-do waste. Toledo et al. (2014) explored the integration of Building Information Modelling (BIM) and key LPS concepts, such as lookahead planning and constraint management, to improve communication and understanding of constraints.

Although these BIM-integrated methods presented a robust solution for constraint management, they primarily focus on using geometry clashing detection for space management. Such solutions lack a semantic understanding of knowledge beyond geometry, such as operational dependencies and regulatory compliances. In addition, the constraint-related data are dispersed across multiple heterogeneous datasets hosted on various servers, leading to interoperability challenges (Soman et al., 2020). Owing to the potential of semantic web technology in data interoperability, it offers a significant opportunity to improve constraint management by enabling the verification of constraint information through heterogeneous data sources (Agrawal et al., 2024).

SEMANTIC WEB IN CONSTRAINT REMOVAL

The semantic web is a transformation from the web of documents to the web of data, characterized by semantically interconnected and machine-readable data representation (Patel-Schneider et al., 2010). Ontology acts as the foundation technology for semantic web. It provides a shared understanding of a domain and facilitates interoperability among diverse applications (Farghaly et al., 2024).

Several studies have been found to use ontologies to support constraint management. For example, Cao et al. (2022) contribute to constraint management in the manufacturing workflow of prefabricated components by proposing an ontology-based approach that incorporates resource availability and space availability. Soman et al., (2020) proposed a linked-data-based constraint-checking (LDCC) method that used ontology to represent dynamic scheduling constraint violations, which enhanced the interoperability and decision-support for look-ahead planning in construction.

Despite efforts to apply ontologies in constraint management, prior studies have overlooked space-related constraints in LPS implementations. Meanwhile, previous ontologies cannot perform reasoning on geometric data, which limits their application in managing space-related constraints (Pauwels et al., 2017).

In summary, the literature review highlights that space constraints have not been sufficiently managed in the past, with the existing ontologies failing to address the complexities of space constraints. Therefore, there is a need for a new ontology to effectively support space-related constraint management. In response, this paper introduces the Space Constraint Management Ontology, designed to provide the necessary information and knowledge for managing spatial constraints.

ONTOLOGY DEVELOPMENT METHODOLOGY

This paper employed the Ontology 101 methodology (Noy & McGuinness, 2001). It is a structured methodology for building ontologies, consisting of seven steps: (1) Determine the domain and scope, (2) Consider reusing existing ontologies, (3) Enumerate important terms, (4) Define classes and class hierarchies, (5) Define the properties of classes, (6) Define the facets of properties, and (7) Create instances. Compared to other methodological approaches, Ontology 101 is more accessible and feasible for researchers and practitioners (Agrawal et al., 2024) and has been widely used in the construction sector (Wu et al., 2021).

In addition, to better understand the space constraint management process, we employed a local company, Carry Steel (C.W. Carry Ltd., 2024), as a case study for the space constraint management ontology development. Specializing in steel fabrication, Carry Steel engages in various operations, including cutting, welding, and assembly, each of which requires specific spaces and equipment. Additionally, the fabricating process frequently experiences workflow changes, leading to complex space dynamics. This provides an opportunity to explore the complexities of space management in detail.

The following section illustrates the building blocks of the proposed ontology representing the domain knowledge involved in space constraint management.

DETERMINE THE DOMAIN AND SCOPE OF THE ONTOLOGY

The development of the SCMO starts with determining the domain and scope of the ontology. To do this, we conducted detailed site visits to thoroughly analyze the space management requirements and their relationship with the operation processes. Through this analysis, a series of competency questions were formulated to define the scope and functionality of the ontology. The competency questions are a set of guidelines that help shape ontology development by identifying the queries the ontology should address (Noy & McGuinness, 2001).

The competency questions are categorized into three areas, as shown in Table 1.

Table 1: Competency Questions

Category	Competency Questions
Steel Fabrication Logistics	What are the materials and equipment required for specific tasks?
	How long will inventory last before being consumed by subsequent tasks?
	How will raw materials be consumed during operations?
	When and where will materials be required at specific stations to optimize inventory space?
Fabrication Scheduling Logistics	What are the schedules for the upcoming days?
	What are the precedence relationships between tasks, such as which tasks must precede or follow others?
	When and where will workers and equipment be occupied or used for specific tasks?
Space-related Safety Management in Factory	What is the space required to allocate equipment and materials?
	What are the recommended safety distances required between different items in the factory?
	What is the storage capacity limit in a specific space?

CONSIDER REUSING EXISTING ONTOLOGIES

To ensure that the SCMO provides comprehensive coverage of space constraint management knowledge in steel fabrication, we conducted a review of existing ontologies in relevant domains. Two online ontology databases, Linked Open Vocabularies (LOV) and Ontobee, have been reviewed. In addition, a literature review on Scopus was conducted to search for existing ontologies that would cover knowledge related to steel fabrication logistics, fabrication scheduling logistics, and space-related safety management in factories.

Despite no specific ontology being found for the representation of space constraint management in steel fabrication factories, some existing ontologies provide a general representation of steel fabrication logistics and scheduling logistics. For example, Lemaignan et al. (2006) developed a MAnufacturing Semantics Ontology (MASON), which provides a reusable framework for representing general concepts in manufacturing processes. Cao et al. (2022) developed a Core Reference Ontology for Steelmaking (CROS), which offers domain-specific concepts for steel fabrication processes and related supply chain information. These two ontologies have been chosen as valuable references for structuring SCMO. MASON was selected because of its structured representation of manufacturing workflows relevant to fabrication scheduling, while CROS provides domain-specific knowledge on steel fabrication processes and logistics, both aligning with SCMO's focus on space constraint management in steel fabrication.

ENUMERATE IMPORTANT TERMS IN THE ONTOLOGY

Despite the existing ontologies providing insight into the general reference of steel-making concepts, the detailed nuance still needs to be further studied. Hence, we conducted multiple site visits to systematically observe and document the key domain concepts in steel fabrication regarding fabrication logistics and scheduling logistics. The information ensures that the ontology accurately reflects real-world fabrication scenarios. The key concepts observed through construction site visits are categorized into six different domains, including (1) steel-making product category, (2) steel-making process, (3) materials, (4) facilities, (5) tools, and (6) people.

In steel-making products, commonly used items include beams, frames, and support brackets, alongside specific components such as half rings, spray shields, spacer plates, and anchor brackets. For the steel-making process, the site visits revealed processes including cutting, detailing, fitting, welding, sandblasting, painting, coding, and shipping. We also included broader processes such as annealing, casting, forging, and rolling. In terms of materials, we noticed that mild steel would be the main material for fabrication. General materials recognized through literature reviews such as iron ore, limestone, sinter, and steel scrap, have also been considered. Facilities encompass cutting, fitting, welding, and fabrication stations. For tools, we considered commonly used tools such as overhead cranes, drills, CNC (Computer Numerical Control) machines, and saws. Lastly, people include essential roles such as project managers, suppliers, laborers, safety managers, and fitters. This comprehensive conceptual framework ensures the SCMO captures domain-specific knowledge effectively.

For space-related management issues, we referred to the Alberta Occupational Health and Safety (OHS) regulations (Government of Alberta, 2025), particularly those relevant to worksite space conflicts and the use of lifting devices and overhead cranes. Key sections being recognized include hazard assessment (Part 2), specific provisions for cranes, hoists, and lifting devices (Part 6), the use of personal protective equipment (Part 18), and the safe operation of tools, equipment, and machinery (Part 25). For example, in part 6, regulations mandate that the movement of loads when worker safety is uncertain should be prohibited to prevent collisions between multiple lifting devices and avoid the passage of suspended loads over workers unless no practical alternatives exist and adequate warnings are provided. These rules provide foundational knowledge to help us understand the space management concepts better and integrate them into the ontology.

ONTOLOGY DEVELOPMENT

The ontology development starts with building the class hierarchy to represent key entities, processes, and relationships we listed in previous steps. We used protégé, an open-source ontology development tool widely used for creating and managing OWL (Web Ontology Language) based ontologies (Musen, 2015). The ontology contains eleven top-level categories: Collision, Location, SafetyCommitment, SpaceRules, TimePeriod, FabricatingProducts, Facilities, Materials, People, SteelMakingProcess, and Tools, as shown in **Figure 1**. These categories were further extended to include specific subclasses. For example, FabricatingProducts includes key components such as Beams, Columns, and SupportBrackets, while Facilities encompasses various workstations, including CuttingStations, FittingStations, and SurfaceTreatmentFacilities.

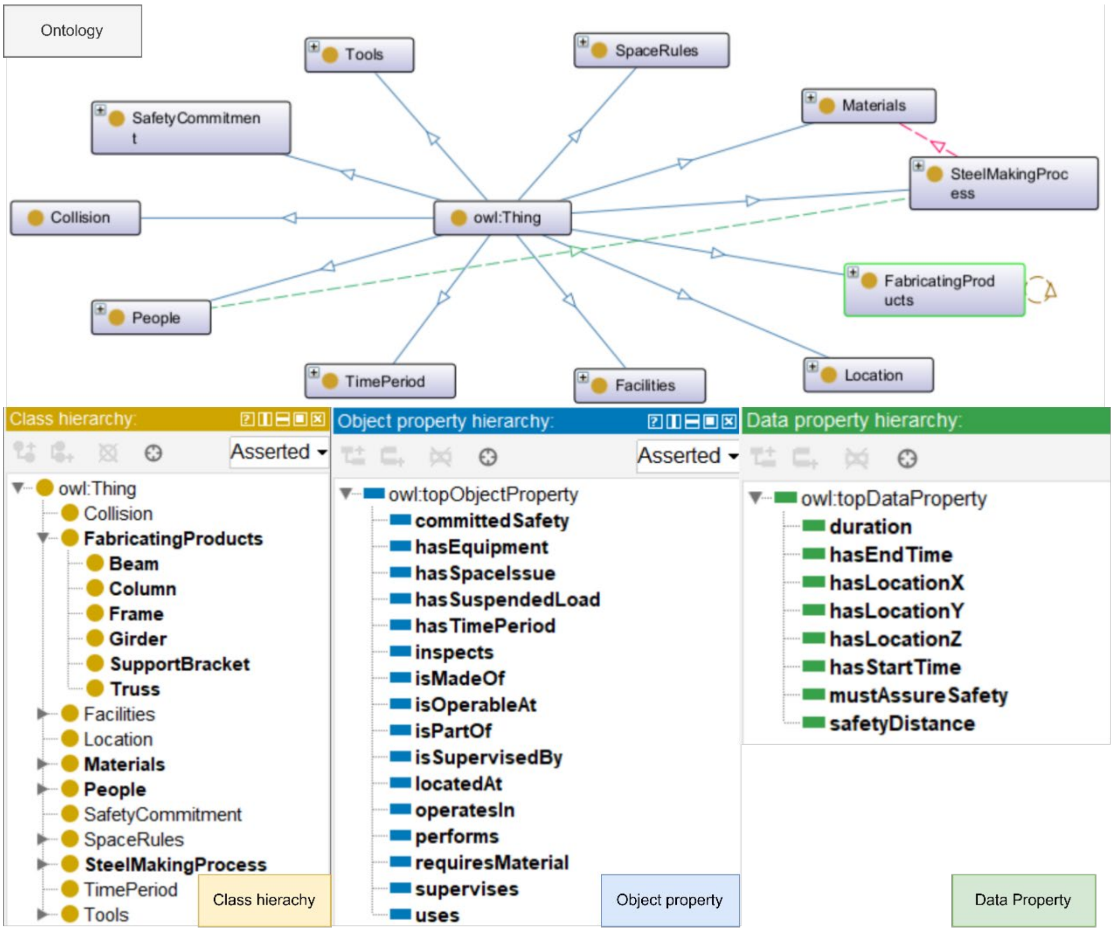

Figure 1: The proposed Space Constraint Management Ontology (SCMO)

Several classes such as SpaceRules, SafetyCommitment, and Location have been developed to convey the knowledge related to space constraint management in steel fabrication. For example, SpaceRules encapsulates regulations and guidelines provided by OHS for safe and efficient space management. SafetyCommitment conveys knowledge about the relationship between certain tasks and responsible members, such as crane operators with overhead crane operations. Location class provides the foundation for defining and organizing spatial data within the factory, such as the positioning of workstations, materials, and workers.

Afterwards, a set of object properties, as shown in **Figure 1**, has been defined to represent the relationship between these classes. For example, the committedSafety links processes or tools to the corresponding operator or responsible entity. The hasEquipment, uses, and requiresMaterial properties capture the dependencies between processes, tools, and materials. Spacial relationships are addressed through properties such as locatedAt and hasSpaceIssue. Temporal and Supervisory relationships are defined using hasTimePeriod, isSupervisedBy, and supervises. Lastly, properties such as isMadeOf, performs, and operatesIn allow us to represent the knowledge related to material composition, task execution, and workspace allocation.

Finally, we defined a set of data properties, as shown in **Figure 1**, to represent essential attributes. Temporal aspects are represented through duration, hasStartTime, and hasEndTime. Spatial attributes are detailed using hasLocationX, hasLocationY, and hasLocationZ. For space considerations, we introduced safetyDistance and mustAssureSafety, which define minimum safe distances between entities and ensure compliance with safety protocols.

CREATE INSTANCES AND EVALUATE THE ONTOLOGY

To evaluate the ontology's effectiveness in addressing space constraint management in steel fabrication factories, we created sample instances and applied reasoning rules in Protégé. Specifically, we selected three OHS rules that reflect the aforementioned competency areas and coded them in Semantic Web Rule Language (SWRL). Pallet was selected as the reasoning engine due to its robust support for OWL-based ontologies and its seamless integration with Protégé (Sirin et al., 2007).

The three OHS rules and their corresponding SWRL representations are shown in **Table 2**. Among them, Rule 1 addresses space-related safety concerns by making sure that the responsible operator is committed to the operation. Rule 2 touches upon space-related safety management and steel fabrication logistics by guaranteeing spatial separation between workers and suspended loads. Rule 3 focuses on representing fabrication scheduling logistics by preventing collisions between lifting devices.

The reasoning results are shown in **Figure 2**, where anticipated results have been yielded. For instance, in rule 1, two lifting devices at the same location and time were not inferred as operable due to safety concerns. However, in Rule 2, we removed one device and added safety commitment information from the operator. This allows the ontology to infer the operable property. For rule 3, when a worker and a suspended load were located at the same coordinates during the same time, the ontology generated a hasSpaceIssue property for both entities. It also referenced the relevant OHS rule, which details the information on space violations in the case.

The use case demonstrates the effectiveness of the SCMO by addressing space constraints-related management scenarios, such as identifying the operability of lifting devices within the work environment where safety commitment, workers, and suspended load have been involved. It enhances the decision-making process during the LPS implementation, ensuring more reliable planning and execution.

Table 2: OHS rules and their corresponding SWRL representations

	OHS description	SWRL representation
Rule 1	If the operator of a lifting device has any doubts about the safety of workers in the vicinity of the lift, the operator must not move any equipment or load until the working conditions are assured to be safe.	*LoadingEquipment(?e) ^:SafetyCommitment(?s) ^ Location(?l) ^ TimePeriod(?t) ^ LiftingDeviceOperator(?o) ^ locatedAt(?e, ?l) ^ hasTimePeriod(?e, ?t) ^ uses(?o, ?e) ^ committedSafety(?o, ?s) ^ locatedAt(?s, ?l) ^ hasEquipment(?s, ?e) ^ hasTimePeriod(?s, ?t) -> isOperableAt(?e, ?t)*
Rule 2	A worker must not stand or pass under a suspended load unless effectively warned of the danger, and the operator is aware of the worker's presence.	*People(?p) ^ LoadingEquipment(?e) ^ SuspendedLoad(?sl) ^ Location(?l1) ^ Location(?l2) ^ hasSuspendedLoad(?e, ?sl) ^ locatedAt(?p, ?l1) ^ locatedAt(?sl, ?l2) ^ hasLocationX(?l1, ?xl1) ^ hasLocationY(?l1, ?yl1) ^ hasLocationX(?l2, ?xl2) ^ hasLocationY(?l2, ?yl2) ^ swrlb:equal(?xl1, ?xl2) ^ swrlb:equal(?yl1, ?yl2) -> hasSpaceIssue(?p, OHSRule69_3) ^ hasSpaceIssue(?sl, OHSRule69_3)*
Rule 3	An employer must develop procedures to prevent collisions when two or more lifting devices are in use, and there is potential for collision between their loads or components.	*LoadingEquipment(?e1) ^ LoadingEquipment(?e2) ^ TimePeriod(?t) ^ People(?p) ^ SafetyCommitment(?s1) ^ SafetyCommitment(?s2) ^ hasTimePeriod(?e1, ?t) ^ hasTimePeriod(?e2, ?t) ^ hasEquipment(?s1, ?e1) ^ hasTimePeriod(?s1, ?t) ^ hasEquipment(?s2, ?e2) ^ hasTimePeriod(?s2, ?e2) ^ committedSafety(?p, ?s1) ^ committedSafety(?p, ?s2) ^ differentFrom(?e1, ?e2) ^ differentFrom(?s1, ?s2) -> isOperableAt(?e1, ?t) ^ isOperableAt(?e2, ?t)*

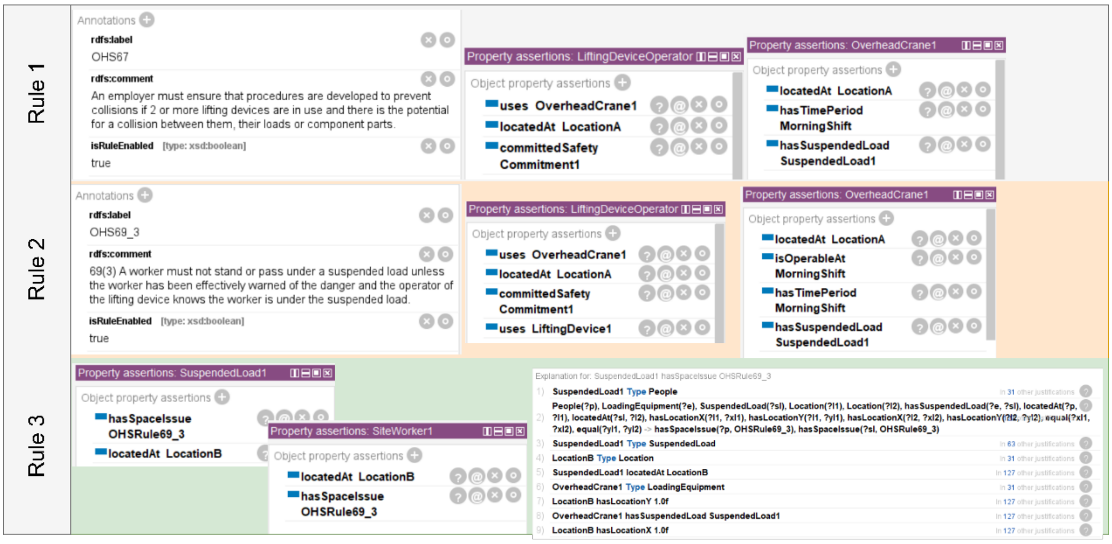

Figure 2: Reasoning results in protégé

CONCLUSION

This study developed a Space Constraint Management Ontology (SCMO), which addresses the gap in current LPS research by representing the complexities of space constraints. By following the Ontology 101 methodology and integrating with key concepts such as spatial rules, safety commitments, and temporal relationships, SCMO can represent steel fabrication logistics, scheduling, and space constraint management.

The paper advances the current Last Planner System (LPS) by improving constraint management with a focus on spatial aspects. By integrating ontology-based reasoning to detect and resolve space constraints, SCMO supports LPS in achieving more reliable planning and execution during decision-making.

Future studies will pursue live construction project adoptions of SCMO by integrating it into digital twin systems. For example, SCMO can be combined with BIM models and real-time spatial monitoring technologies in project management tools to help detect and resolve space constraints during production scheduling and task operations. Meanwhile, future studies shall pursue more comprehensive validation, such as quantitative validation, of the SCMO through more diverse construction settings in the LPS environment. Moreover, extending the SCMO to more visualized environments, such as Extended Reality, to enable further visualization and interaction with space-related information will also be a critical area of exploration.

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