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PROJECT PRODUCTION MANAGEMENT ONTOLOGY FOR STANDARDIZING ORGANIZATIONAL INFORMATION AND KNOWLEDGE IN INDUSTRIALIZED CONSTRUCTION

Yuan Zheng[1], Lars-Fredrik Forberg[2], Gunnar Skeie[2] and Olli Seppänen[1]
[1]Department of Civil Engineering, Aalto University, Espoo, Finland
[2]Mestergruppen AS, Oslo, Norway

Abstract

Ontologies are essential for formalizing information and knowledge in the construction sector, yet current implementations often fail to address specific needs of industrialized construction (IC) and integration with organizational insights. This paper introduces the Project Production Management Ontology (PPM) and its associated knowledge graph, designed to systematically represent organizational expertise for managing standardized house products and construction workflows in IC. The PPM ontology bridges IC processes and organizational knowledge, enabling improved knowledge and information management across the value chain. The PPM holds value for researchers, companies, and practitioners in IC, as it enhances knowledge reuse in supporting lean construction practices.

Introduction

The construction industry is inherently project-based, characterized by the uniqueness of each project and its specific production setup (Höök & Stehn, 2008; Vrijhoef & Koskela, 2000). This nature has often constrained the application of lean principles, which rely on standardization and continuous improvement (Koskela, 2003). To address this challenge, scholars have advocated for the adoption of industrialized construction (IC) methods, transforming housing construction with a product-based approach. Under the IC framework, companies can optimize production by incorporating manufacturing methods such as prefabrication and standardization. Furthermore, IC promotes the development of product platforms, which extend beyond singular projects to offer continuous and repetitive solutions presented in house catalogues, creating new business value chains (Lessing and Stehn, 2019).

Another characteristic of IC is capturing and reusing information and knowledge to achieve continuous improvement in workflow control and management (Hall et al., 2022). For example, site managers can utilize standardized information and knowledge derived from predefined designs and workflows to support planning, control, and performance measurement of task execution (Lessing & Stehn, 2019). On-site teams can efficiently access and reference this information to streamline their operations with error-proofing, thus reducing variability and minimize waste (Höök & Stehn, 2008).

To achieve continuous improvement of processes, standardized knowledge and information of workflows should be stored in digital systems (Lessing & Stehn, 2019). Ontologies offer a shared, machine-readable conceptualization of a domain, enabling the integration and reuse of diverse and fragmented information and knowledge. In construction, ontologies have proven effective in addressing challenges such as semantic data integration, process representation, and improving information exchange across systems. For instance, they can standardize terminology and relationships for workflows, materials, and resources, which are critical components of construction processes. However, existing ontologies cannot be used to formalize and integrate standardized workflows into organizational knowledge systems. This limits the industry's ability to fully capitalize on the benefits of IC, such as improved workflow control, reduced variability, and waste minimization.

To bridge this gap, this research introduces the Project Production Management (PPM) Ontology, specifically designed to align with IC principles. The ontology addresses the critical need for formalizing domain and organizational knowledge providing structural representation of information involved in the process and enhancing its reusability..

Background and related works

Industrialized Construction (IC)

Industrialized Construction (IC) represents a strategic and holistic approach aimed at transforming traditional fragmented construction practices into streamlined and organized production systems (Hall et al., 2022). Drawing inspiration from manufacturing, IC shifts onsite production to organized prefabrication, supported by advanced supply chain management. It centers on offsite manufacturing of building pre-assembly, where components are joined offsite, and modular construction, which designs and fabricates volumetric building modules in controlled conditions for transport and on-site assembly (Kauppinen et al., 2024).

In the housing industry, a key derivative of IC is the concept of Industrialized House Building (IHB), which emphasizes repetition and continuous improvement in technical solutions and processes (Lessing & Stehn, 2019). Standardization serves as a cornerstone of IHB and is applied in two primary forms: product standardization and process standardization. For product standardization, practical implementations like BoKlok—a collaboration between IKEA and Skanska—demonstrate how customer research can be integrated with standardized products to deliver cost-effective housing solutions. BoKlok exemplifies the advantages of streamlined processes. On the other hand, process standardization focuses on recurring activities in building and production. While IC retains onsite tasks such as assembly, installation, and certain construction activities, these efforts are significantly optimized using standardized building products (Biltoria & Roy, 2024). Aligning construction workflows with these standardized products enhances predictability, repeatability, and process efficiency. This alignment not only reduces variability but also facilitates the integration of lean construction principles, minimizing waste, improving resource allocation, and fostering better collaboration across the supply chain (Kauppinen et al., 2024).

From an industrial perspective, IC requires organizations to adopt a long-term approach focused on continuous improvement. This emphasizes the essential role of digital tools, particularly in performance measurement and the systematic reuse of organizational experience (Lessing and Stehn, 2019). However, achieving continuous improvement in IC is often hindered by the fragmented nature of data, information, and knowledge in the construction industry, which are typically distributed, unstructured, and generated within isolated systems or exchanged through various file formats (Zheng et al., 2021). To address this challenge, tailored digital solutions for IC practices should also take standardizing and integrating data across the value chain into account. Such standardization not only enables the reuse of organizational knowledge but also ensures consistency and interoperability, fostering process development and enabling a more scalable and efficient business model (Lessing and Stehn, 2019). By leveraging these standardized data structures, companies can significantly enhance their efficiency, effectiveness, and alignment with IC principles, paving the way for innovation in construction management practices.

Ontologies

The semantic web and linked data concepts provide technical standards for a standardized, formalized, and machine-readable representation of diverse data, information, and knowledge (Pauwels et al., 2017). Ontologies are core in the semantic web that define shared conceptualization of a specific knowledge domain among a community of users.

Recently, ontologies have been used to address challenges like data integration and knowledge management in AEC sector (Pauwels et al., 2017). Various ontologies have been developed specifically in the construction domain. Digital Construction Ontologies (DiCon) by Zheng et al. (Zheng et al., 2021), define entities related to broader construction workflows and facilitate data integration across diverse systems and contexts. Farghaly et al. (Farghaly et al., 2024) developed the CSite ontology to further extend DiCon and other relevant ontologies including PROV-O and BOT to fit with the requirement of representing the information on onsite production control. Similarly, Schlenger et al.(Schlenger et al., n.d.) also developed the Digital Twin Construction (DTC) ontology to describe the construction information to fit with the DTC framework addressed by Sacks et al.(Sacks et al., 2020).

Although these existing ontologies have shown the capability of formalizing domain knowledge and information, they have less attention on adopting the technologies deeper into the IC context. First, existing ontologies such as (El-Gohary & El-Diraby, 2010; Farghaly et al., 2024; Lima et al., 2005; Schlenger et al., n.d.; Zheng et al., 2021), only provide general and higher-level conceptualization of the construction process, but less details for specifically describing the workflow and product information in IC. This highlights the need for the expansion of these existing ontologies to better support the context of IC. Second, although (Cao et al., 2022) have proposed the manufacturing ontology for IC, their focus is on the product design aspect but misses the link between the products and onsite standardized construction workflows. In summary, an ontology that is adequate to formalize the IC-based construction workflow information the connection of this information with predefined design is missing. This also hampers the creation of enterprise-level knowledge graphs to store, manage, and reuse the knowledge and information for further improvement.

Methodology

Overall research method

This study adopts the Design Science Research methodology as the overarching approach, which is well-suited for addressing complex problems in construction management through the creation and evaluation of innovative artifacts. DSR emphasizes the iterative process of problem identification, artifact design, implementation, and evaluation, aiming to generate practical and scientifically grounded solutions (Hevner et al., 2004). In the context of this research, the artifact is the PPM Ontology, developed to formalize and integrate information and knowledge of standardized workflows and predefined house designs into organizational knowledge systems for IC. The DSR process for this study is divided into three iterative stages:

1. **Requirement Identification:** The requirement for a standardized ontology to support IC practices and the challenges of integrating workflows with organizational knowledge were identified through

the PPM framework was developed as prior knowledge to inform the design of the ontology.

2. **Artifact Development:** It structures standardized workflows and product specifications into core concepts such as work packages and job cards. These concepts form the basis for defining the ontology's scope, competency questions, and modular architecture.
3. **Evaluation and Refinement:** The PPM ontology was iteratively evaluated using automated consistency checking and task-based evaluation in industrial use cases, ensuring alignment with IC principles and practical applicability.

Prior knowledge for ontology development

Building upon the foundational principles of IC and IHB, we first developed the PPM framework. As shown in Figure 1, this layered and iterative framework integrates standardized **product portfolios, processes**, and a **technology platform.** By leveraging systematic data capture and reuse across different projects, the framework supports continuous improvement of standardizing construction products and processes, driving greater accuracy and efficiency over time. This information-driven approach aligns with IC's focus on capturing and reusing information and knowledge to support workflow control and management.

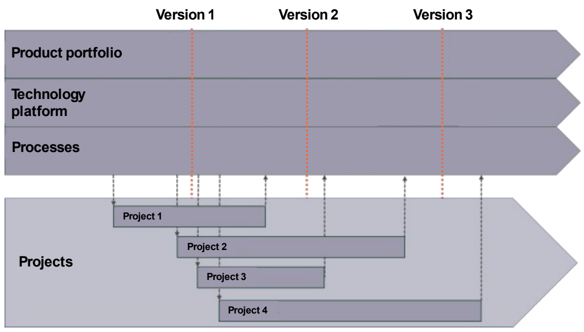

Figure 1: The PPM framework

The PPM framework consists of three iterative processes:

Specification: The specification process standardizes construction workflows and predefined house designs. In terms of workflow, two core concepts are defined as the basic units of construction tasks:

1. **Work Package:** A clearly scoped and continuous task that can be completed by a specific trade within a designated physical zone on the construction site, with a maximum duration of one week.
2. **Job Card:** A subset of work within a Work Package, with a maximum duration of one day.

Each Work Package and Job Card includes standardized work content information, collectively referred to as their specification. These specifications detail the prerequisites for resources, materials, dependencies, and preconditions required for each task. Additionally, the JobCard specifications outline empirical production rates for corresponding tasks.

PPM integrates JobCards and WorkPackages with predefined house models and quantity data, enabling precise labor and material planning. This structured approach ensures that site managers can access predefined information, facilitating efficient workflow control and error-proofing.

Planning and production: According to Lessing et al., Planning and control contributes to minimize errors and non-value adding activities and to establish a good workflow. Within the PPM framework, this process is divided into planning and production phases. During the planning phase, Work Packages and Job Cards are aligned with resource availability and schedule constraints. Materials and resources are synchronized for delivery, ensuring seamless production workflows. In the production phase, workers receive as-planned information as their daily task assignments through their mobile phones, to enhance on-site efficiency and communication. They can also report the progress or variability during their task execution via the phone application, such as completed tasks, including working hours, and deviations from the plan.

Learning: The learning process focuses on continuous improvement by capturing and analyzing data from diverse contexts. Reported information captured during the production, such as task deviations and performance metrics, is compared to the specification and as-planned data to support performance measurement and refinement. This detailed analysis provides actionable insights into on-site production performance, feeding back into the specifications to enhance the accuracy and predictability of future construction planning. By continuously refining processes and streamlining operations, the learning process aligns with IC's goal of leveraging standardized knowledge to optimize workflows and reduce waste.

From the PPM framework, we systematically derived the requirements for the ontology, expressed as Competency Questions (CQs). These questions define what the ontology must represent, which are presented in the following subsection.

Development of PPM ontology

To address the practical needs of the construction industry, this paper introduces the PPM Ontology, designed to model essential construction knowledge and information within the PPM framework. A hybrid methodology was employed to develop the PPM Ontology, combining the Linked Open Terms (LOT) approach (Poveda-Villalón et al., 2022) with ontology horizontal segmentation (Haller et al., 2018). LOT is an industry-oriented ontology development methodology that emphasizes practical engineering applications, making it particularly suitable for the development scope of the PPM Ontology. Given that PPM ontology aims to serve at application-level to support the PPM framework, it needs to build upon higher-level or reuse-related ontologies to ensure formal consistency and extensibility, as well as to minimize redundant modeling of concepts already represented in existing ontologies. Therefore, the development of the PPM ontology also incorporates the horizontal segmentation method suggested in SOSA/SSN ontology (Haller et al., 2018). This segmentation method addresses the need to reuse and extend the existing ontologies to fit with the purpose of the ontology. The development process of the PPM Ontology, illustrated in Figure 2, consists of three main phases:

1. **Specification:** Defining the scope, objectives, and requirements for the ontology.
2. **Conceptualization and Implementation:** Structuring and encoding the ontology using formal languages.
3. **Evaluation:** Assessing the ontology for its consistency, and practical applicability within the PPM framework.

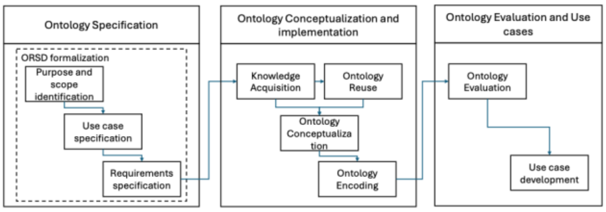

Figure 2: The development process of PPM ontology

Ontology specification

The ontology specification defines the purpose, scope, users, and requirements of the PPM ontology, ensuring alignment with organizational needs and practical applications in IC workflows. In this work, the ontology specification was carried out through the creation of an Ontology Requirements Specification Document (ORSD) (Poveda-Villalón et al., 2022). The subsequent sections summarized the contents fulfilled in the ORSD.

Purpose: The PPM ontology formalizes information and knowledge and provides a data schema to construct a knowledge base, representing information involved in the PPM.
Scope: PPM ontology is defined as an application-level ontology developed for organizational purposes, but it also has generic granularity to be used in broader cases.
End user: Direct end-users of the ontology include IT data engineers and application developers, while indirect end-users encompass stakeholders such as trade workers, foremen, site managers, and general contractors. The ontology supports them to reuse PPM information and knowledge.
Use cases: The intended use cases for the PPM ontology include constructing the organizational knowledge base to cover specifications of standardized house models and workflows, supporting essential information retrieval and performance analysis with task operation, project planning and control, and measuring performance.
Non-Functional Requirement (NFR): NFRs are a type of requirement that defines how the system should perform, behave, and operate rather than what the system should do. Various studies have already defined NFRs as criteria of ontologies. In the development of the PPM ontology, the following NFRs are to be adhered to 1. Consistency 2. Usability 3. Coverage.
Functional Requirements (FRs): The FRs are described as CQs that the ontology should be able to answer. In this paper, the CQs are derived from the PPM framework to describe the standardized information and knowledge of workflow and products. Table 1 lists the CQs to be answered by the proposed ontology.

Table 1: CQs of PPM ontology

Competency questions (CQs)
CQ 1. What prerequisites are predefined by a Work Package or Job Card Specification?
CQ1.1: What materials are predefined for a work package or job card based on their specification?
CQ1.2: What crew or workers are assigned to the work package or job card?
CQ 2. What work packages and job cards specification are defined for a particular standardized house model?
CQ 3. What as-planned and as-reported data are available for evaluating task performance in production?
CQ3.1 What is the as-report work hour of worker?
CQ3.2 what is the planned work quantity?
CQ3.3: What is the location of a work package or job card?
CQ 4. What is the work rate of specific work packages or job cards based on monitoring?

Ontology conceptualization and implementation

From the literature review, in IC practices, companies need to store their knowledge on standardized workflows and corresponding building designs, to support planning, control, and process optimization. To maintain conceptual clarity while addressing the comprehensive information needs within PPM, we structure the ontology concepts according to different parts of the PPM framework. These parts reflect specific information dimensions, including **Specification**, **Process**, **Context**, and **Variable**. The conceptualization of the PPM is illustrated in Figure 3.

The specification part corresponds to the specification process in the PPM. This part focuses on modelling the information and knowledge of standardized building products and workflows. In this context, the specification of predefined products includes the ppm:HouseModel and ppm:BuildingElementModel. The ppm:HouseModel is conceptualized as a standardized representation of a specific type of ppm:Building, encompassing a consistent set of design features, configurations, and properties. The ppm:BuildingElementModel defines the specifications for a particular type of building element, including its functional, structural, and material characteristics. This ensures standardized descriptions that facilitate the reuse and integration of these elements across projects.

In addition, ppm:WorkPackageSpecification and ppm:JobCardSpecification represent the detailed knowledge and information required for defining a specific type of ppm:WorkPackage and ppm:JobCard, respectively. These specifications encapsulate workflows, resource requirements, and procedural details for efficient task planning and execution.

All specification classes (HouseModel, BuildingElementModel, WorkPackageSpecification, and

JobCardSpecification) are defined as subclasses of dici:Catalogue, which serves as a container for organizing standardized data. The dici:CatalogEntry class functions as the data repository for storing precise and detailed specifications within the ppm:SpecificationContext. Each catalog entry provides a dataset that includes exact information about the respective specifications, enabling clear and consistent communication of design and workflow details.

The process part represents information related to construction processes and integrates seamlessly with the Planning and Production phases of the PPM framework. As shown in Figure 3, the PPM ontology reuses and extends existing DiCon modules. Within PPM ontology, **ppm:ScopeOfWork, ppm:WorkPackage** and **ppm:JobCard** are defined as subclasses of **dicp:Activity**. As subclasses of *dicp: Activity, ppm:ScopeOfWork, ppm: WorkPackage,* and *ppm: JobCard* have seven prerequisites based on the flow view from Lean Construction (Koskela, 2000), including crew, materials, equipment, external conditions, information, space, and the completion of the previous work package. Furthermore, each *ppm:WorkPackage* and *ppm:JobCard* has predefined work contents based on their corresponding specification information. The *ppm:Building* class refers to the standardized product of construction, which is an assembly of standardized *ppm:BuildingElement*.

The Context part manages and distributes data across multiple contexts within the PPM framework. It ensures that data from the different contexts such as specification, planning, and production, phases is appropriately categorized and accessible for information retrieval and inference. This part defines three predefined contexts:

1. **ppm:SpecificationContext:** Represents the as-designed data, including standardized house and building element models, as well as preset specifications for ppm:WorkPackage and ppm:JobCard. This context ensures that design-level information is readily available to support planning and production phases.
2. **ppm:AsPlannedContext:** Contains schedule-derived, as-planned data, aligning work packages and job cards with resource availability and schedule constraints. It supports synchronization of materials, crew, and equipment, ensuring seamless workflows during production.
3. **ppm:AsReportedContext:** Captures all data reported from the construction site, reflecting the actual on-site situation. This includes progress updates, deviations, and variability encountered during task execution. By comparing this context with the ppm:AsPlannedContext, the PPM framework supports real-time learning and dynamic rescheduling to adapt to evolving project conditions.

Variable part is designed to model the dynamic states of all entities involved in PPM processes. It builds on th e conceptual foundation of the DiCon Variable module, using dicv:Property and dicv:PropertyState to describe state changes in entities such as work packages, job cards, materials, equipment, and space. By tracking these dynamic states, PPM ontology provides a mechanism to adaptively manage change information that occurs during design, planning, production, and on-site execution.

Based on the result of conceptualization, ontology implementations aim to encode the concepts and vocabulary into a standardized and machine-readable format. In this research, the Semantic Web Ontology Language (OWL) was selected to model the ontologies, ensure their formal structure, and make them accessible to ontology-based applications and tools. The implementation process is conducted in the Protégé environment. Protégé is an open-source OWL editor widely used by scholars and ontology engineers worldwide for building intelligent systems. The latest version of developed PPM ontology has been made publicly available for review and reuse at https://mestergruppen.github.io/Appetite-for-

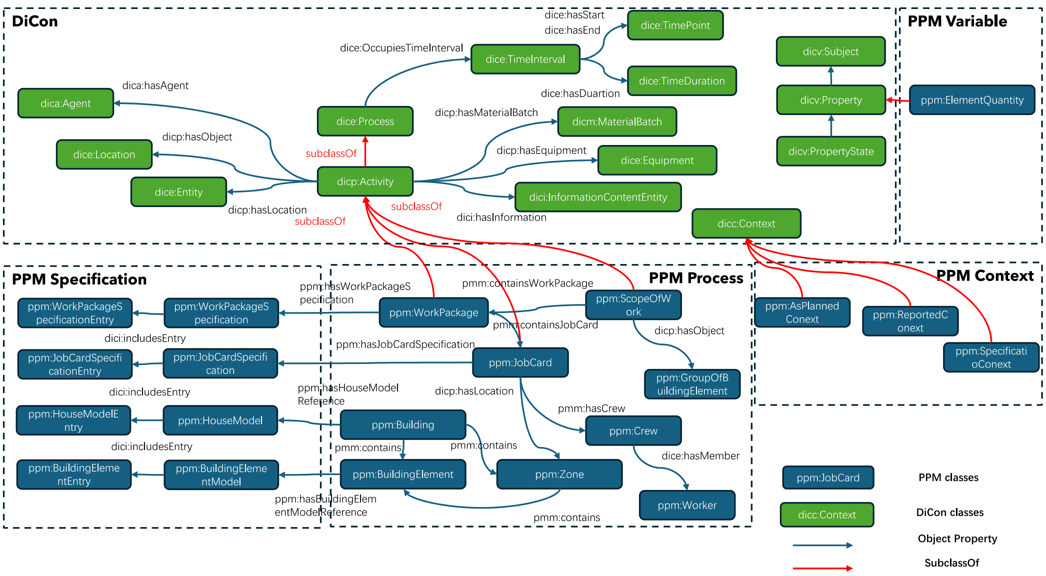

Figure 3: The architecture and core conceptualization of the PPM ontology

Construction/, with detailed documentation to facilitate ease of using and extending by practitioners.

Ontology evaluation

Ontology evaluation is essential to ensure that the developed ontology meets all predefined requirements outlined in the specification process (Fernández-López et al., 1997). Different evaluation methods can be used to check compliance with different criteria (El-Gohary & El-Diraby, 2010; Zheng et al., 2021). This research evaluates the proposed PPM ontology through automated consistency checking and task-based evaluation through a practical use case.

Automatic Consistency Checking: Automated consistency checking aims to assess the developed ontology's consistency, guaranteeing no logical conflicts or inconsistencies. This process is achieved with description logic (DL) reasoners to assess the logical coherence of the ontology and maintain its integrity by ensuring there are no contradictions. Regarding the PPM, the automated consistency checking was conducted within the Protégé environment using the built-in Pellet reasoner. The automated consistency checking results showed that the PPM is consistent and coherent.

Task-based Evaluation: Task-based evaluation focuses on verifying the ontology from two aspects (Zheng et al., 2021): first, to assess the ontology's ability and coverage to support specific PPM tasks aligned with its intended purpose by answering the CQs with practical data; second, to demonstrate the ontology's practical application through real-world examples. In this research, the task-based evaluation is conducted via an implementation of establishing an enterprise knowledge graph to manage and reuse the organizational knowledge created from the company's PPM practices.

Industrial use case: Enterprise PPM knowledge graph

The architecture of the implementation is shown in Figure 4. Three types of practical information and knowledge were acquired from the existing MongoDB database of the company: 1) the specification information including predefined house model, work package and job card specification; 2) as-planned information of scheduled work package and job card; 3) reported information of the completeness of a job card and a workflow. These information sources were converted to Resource Description Framework (RDF) named graphs in different contexts associated with the PPM ontology. Then the RDF graphs were integrated and stored in GraphDB to build the enterprise PPM knowledge graph for further use cases. Example data of the specification is shown in Figure 5.

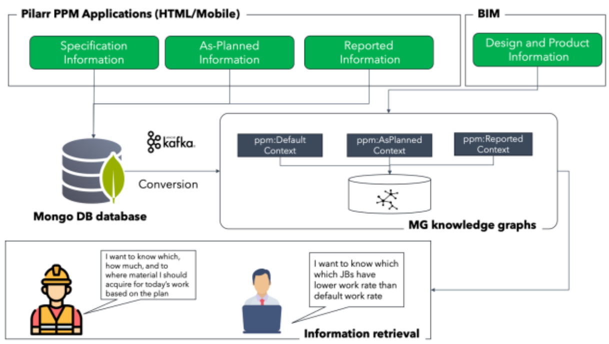

Figure 4: The architecture of the enterprise knowledge graph establishment

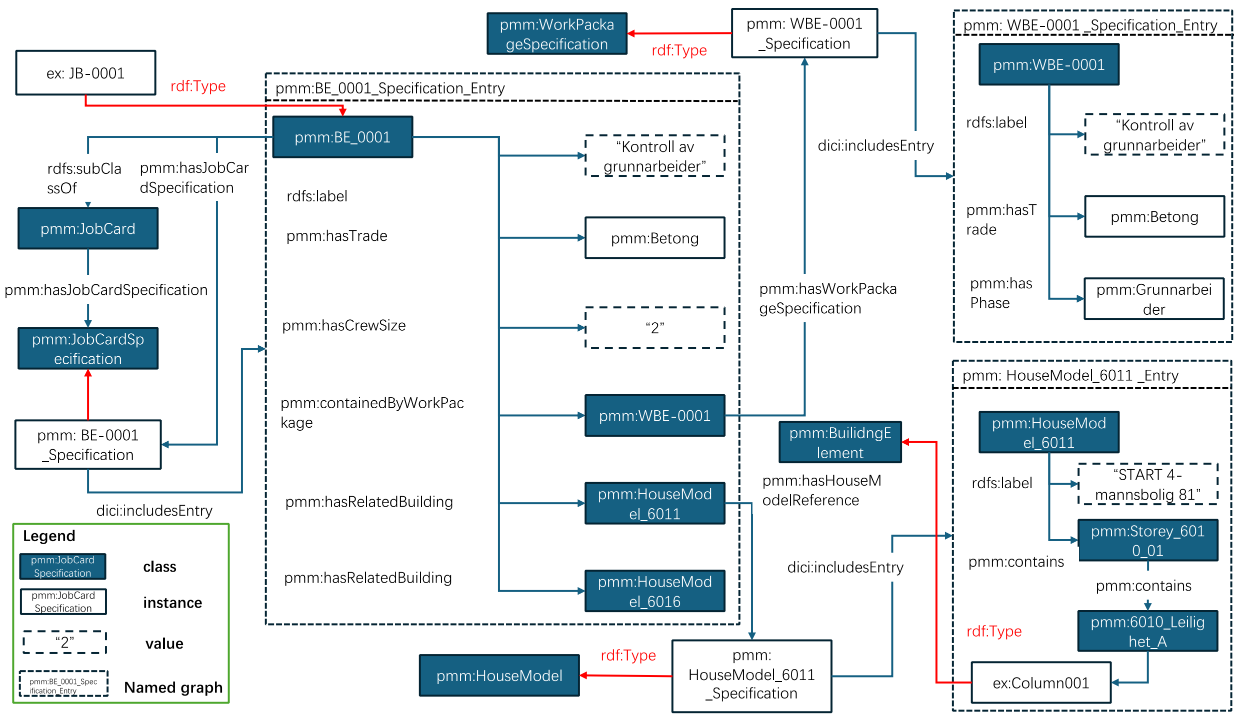

Figure 5: Example of Specification information

Use case 1: Information Retrieval for Production

Based on the developed enterprise knowledge graph, two use cases are conducted. The first use case demonstrates how predefined material information for job cards can be retrieved from corresponding job card specification to support planning and production in the PPM framework (corresponding to CQ1 and 2). So, craftsmen can access detailed material requirements, enhancing task preparation and execution efficiency. A SPARQL query was executed on the AsPlannedContext and DefaultContext named graphs to retrieve material information associated with the job card. This information provides the craftsman with clear instructions on which materials are required and in what quantities for the execution of the job card. The SPARQL query is presented in Listing 1.

Listing 1: SPARQL query for production information retrieval

```
PREFIX ppm: <https://mestergruppen.no/ontologies/projectproductionmanagement#>
PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#>
PREFIX ex:  <https://example.com/ppm/>
PREFIX dici: <https://w3id.org/digitalconstruction/0.5/Information#>
PREFIX dicv: <https://w3id.org/digitalconstruction/0.5/Variables#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT (CONCAT(?materialname, " ", STR(?quantity), " ", ?unit) AS ?materialinformation)
WHERE{
GRAPH ex:AsPlannedContext { ex:Worker1 ppm:participates ?jobcard  .
?jobcard a ?jobcardtype .}
GRAPH ex:DefaultContext {?jobcardtype rdfs:subClassOf ppm:JobCard.
?jobcardtype ppm:hasJobCardSpecification ?jobcardspecification .
?jobcardspecification dici:includesEntry ?jobcardspecificationentry .}
GRAPH ?jobcardspecificationentry {?jobcardtype
ppm:includesTemplateMaterialList ?materiallist .}
GRAPH ?materiallist {?materialset a ppm:MaterialSet .
        ?materialset rdfs:label ?materialname.
        ?materialset dicv:hasUnit ?unit .
        ?materialset ppm:hasMaterialQuantity ?quantity}}
```

Use case 2: Performance Measurement for Learning

The second use case focused on the learning process of PPM, that is to measure the performance of a certain job card. This is achieved by comparing the empirical production rate specified in the job card with the calculated work rate derived from reported information (corresponding to CQ 3 and 4). As shown in Listing 2, the SPARQL query first retrieves the quantity of work, crew size from the as-planned named graph, then retrieved the reported work hours of job cards from reported graph to calculate the reported production rate. Second, comparing the reported production rate to the default work rate in the specification context to evaluate the performance.

Listing 2: SPARQL query for performance measurement

```
PREFIX ppm: <https://mestergruppen.no/ontologies/projectproductionmanagement#>
PREFIX dicp: <https://w3id.org/digitalconstruction/0.5/Processes#>
PREFIX dice: <https://w3id.org/digitalconstruction/0.5/Entities#>
PREFIX ex: <https://example.com/ppm/>
PREFIX dici: <https://w3id.org/digitalconstruction/0.5/Information#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?jobcard ((?plannedworkquantity / (?reportedworkhour *
COUNT(DISTINCT ?worker))) AS ?reportedworkrate) ?defaultworkrate
WHERE { GRAPH ex:AsPlannedContext {  ?jobcard a ?jobcardtype .
?jobcardtype rdfs:subClassOf ppm:JobCard.
?jobcard ppm:hasWorkQuantity ?plannedworkquantity .
?jobcard ppm:hasCrew ?crew .
 ?crew dice:hasMember ?worker .}
GRAPH ex:DefaultContext {?jobcardtype
ppm:hasJobCardSpecification ?jobcardspecification .
?jobcardspecification dici:includesEntry ?jobcardspecificationentry . }
GRAPH ?jobcardspecificationentry {?jobcardtype ppm:hasWorkRate ?defaultworkrate .}
GRAPH ex:ReportedContext {?jobcard ppm:hasWorkHour ?reportedworkhour. }
FILTER(?reportedworkhour > 0)}
GROUP BY ?jobcard ?plannedworkquantity ?reportedworkhour ?defaultworkrate
```

These two cases represent essential tasks in reusing the information and knowledge in the PPM framework to support the production and learning process. They effectively illustrate the capability of the PPM ontology in formalizing and enhancing the reuse of information and knowledge IC expertise.

Discussion

This study presents the development of a novel ontology that integrates IC principles into the PPM framework for practical business applications. Unlike higher-level ontologies designed primarily for academic contexts, the PPM ontology allows for a granular representation of information and knowledge tailored to IC-related concepts such as house models, work packages, and job cards. By structuring this information in alignment with the PPM framework's three iterative processes—specification, planning and production, and learning—the ontology bridges the gap between theoretical advancements and practical implementation.

Overall, the PPM ontology provides an ontology-driven approach to enhancing information and knowledge management in IC. It serves as a data standard for structuring a graph-based enterprise knowledge base. This graph representation links to PPM framework and promotes the reuse of information and knowledge to improve construction management practices. For example, in the specification process, the ontology supports the definition and reuse of standardized work packages and job cards. In the planning and production phase, it facilitates information retrieval to support the planning and production processes. During the learning phase, the ontology supports the performance measurement through comparing multi-contextual data.

Importantly, the presented PPM ontology serves as the foundational step toward a comprehensive digital PPM information management platform currently under development by our team. Compared to conventional relational database solutions, ontology provides essential advantages such as flexibility in handling evolving information, semantic interoperability among diverse stakeholders, and reasoning capabilities. These features support the envisioned platform aims not only to systematically manage and reuse standardized project production information but also to embed intelligent AI agents directly into the workflow management process. These advancements aim to enable intelligent human-computer interactions and extend the ontology's applications to more complex tasks within Product Lifecycle Management (PLM) platform.

Conclusion

This paper developed the PPM Ontology to standardize organizational information and knowledge in IC. The proposed ontology enables structured knowledge representation for standardized product and process information. This work is relevant for advancing lean practices in IC through improved information and knowledge management. Future research will explore integration with AI agents and expansion into broader PLM applications.

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