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A Shared Ontology for Logistics Information Management in the Construction Industry

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Abstract –

Logistics management plays an essential role in supporting the primary activities in manufacturing industries. Similarly, in the construction industry, logistics operations are a crucial part that directly influence the construction operations. Construction operations management requires various stakeholders to collaborate through effective communication and prompt information sharing. However, logistics management in construction is often challenged by insufficient information management, lack of formalized information standards and poor information interoperability among heterogeneous systems. Semantic Web technologies advance information management support and improve information interoperability. In this research, we present a domain-level ontology as a common information reference for standardizing and integrating construction logistics information, and finally to improve the efficiency and transparency of logistics information management. The proposed ontology provides information interoperability between logistics management and construction workflow management. The ontology was evaluated by automatic consistency checking and answering the competency questions (CQs) via SPARQL queries. Furthermore, we used actual schedule and material delivery data of a construction project to evaluate the proposed ontology to see if it could support the material kitting logistics practice. We provide a valid ontology that is able support the logistics information management for the construction. The research is limited to providing a single example application of the ontology. Future research should focus on extending the ontology for different specific solutions to yield standardized information management for construction operations.

Keywords –

Information; Construction logistics; Ontology; Construction operations

1 Introduction

Construction industry differs from the other industries because of the temporary project-specific organizations and strong interdependencies between the firms, materials and construction activities [1]. Fragmented construction supply chain makes it difficult to control the construction operations. Logistics practices support these operations and improve construction projects in terms of cost, schedule and planning [2]. Recently, logistics operations in the construction industry have been gaining importance. Logistics solutions are an important element for successful completion of the projects [3] and logistics specialists can improve on-site logistics to a large extent [4]. Due to the benefits of logistics in construction projects, companies are motivated to develop their own logistics processes [5].

During construction projects, significant amount of information is exchanged among the project partners. Construction logistics depend on detailed data and decisions about operations on-site and material needs [6]. Successful delivery of the materials is an important condition that affects the workflow and performance of the projects [7]. To achieve that, coordination is needed between the material supply chain and on-site operational decisions [6]. The logistics information should properly collaborate with the corresponding construction workflow to coordinate the logistics process to perform the operations. Because forecasting material deliveries is directly related to construction schedules, change in the material delivery impacts the execution of schedules [8]. Thus, accurate and timely information flow is required to manage the construction logistics activities efficiently [9].

Construction logistics can be considered complex due to the multiple stakeholders and fragmented tasks that are involved in the process [10]. Therefore, effective information exchange for communication and coordination among different stakeholders are vital for improving the management of the construction logistics process. This requires advanced information formalization and interoperability among the stakeholders and various information systems.

However, there is no adequate information management standard that could formalize the information from the construction logistics process. A gap exists for linking the on-site construction operation information with the supporting logistics process. In the information management domain, ontology tries to provide a definite classification of entities [11]. In terms of information systems, Semantic Web technology supports representing, obtaining and utilizing knowledge [12]. This research is based on the hypothesis that the advancements in Semantic Web technology can help alleviate the information bottleneck in construction logistics. Determining the information requirements for logistics operations is significant to develop logistics practices. Mapping construction logistics with ontology would bring opportunities for interoperating logistics information with digitized situational awareness systems to improve construction workflow management.

In this research, we present an ontology as a common information reference for linking the material logistics information with the construction workflow. We describe a possible conceptual map design for the logistics and product data flow in construction. Moreover, we extend the ontology to a domain specific level presenting kitting logistics practice information. Kitting is one of the recently developed industrialized JIT-based logistics practices in which requirements for information management are obvious. In the following, we present background for construction logistics, kitting practice and ontology. Then, we describe our methodology and present our findings based on the proposed ontology. Lastly, we provide discussion and conclusion.

2 Background

This research combines two research streams: 1) Material logistics in construction; and 2) Semantic Web, ontology and their applications in the construction and logistics domains. In kitting logistics practice, the information requirements are evident and straightforward. Hence, combining these two research streams: developing an ontology for kitting practice could result in an application where all the information requirements are ready to be utilized in any construction project.

2.1 Material logistics in construction

Logistics practitioners face integration problems regarding the material and logistics information in their operations. In the construction industry, only about 40% of deliveries are fulfilled with the correct amount, time, location and information [13]. However, most of these activities are still managed by humans. Materials could be purchased too late causing delays or too early and getting damaged in poor storage conditions on-site [4]. Delivering materials to the site without a timely notice causes extra material handling and labour cost [14]. Proper logistics management requires complete and accurate information regarding the materials and delivery that is communicated between the project parties.

Construction logistics is an inherent part of construction projects [15]. It impacts important aspects of construction projects such as cost, completion time and plan accuracy [2]. A great deal of energy is spent on coordinating fragmented operations, procuring the required goods and other resources, coordinating materials and resources on the construction site [16]. Problems associated with such mistakes could be prevented via proper logistics management [7].

2.1.1 Kitting as an information-intensive logistic practice

Kitting is a logistics solution that was originally used in the manufacturing industry. It represents delivering the products or components organized, packed and as one package [17]. Figure 1 illustrates the kitting process; the materials that are delivered to the logistics center from the material suppliers are kitted and delivered to the work locations. It has been proposed that the practice could be used in the construction industry as well [18][19]. Recently, Tetik et al. [20] conducted research on the applicability and impacts of using kitting in the construction industry. Construction workers spent around 20% of their time moving materials and equipment to the installation location [21]. Thus, the workers on-site spend less time searching for or moving the materials when the materials are delivered to the assembly location as pre-sorted kits.

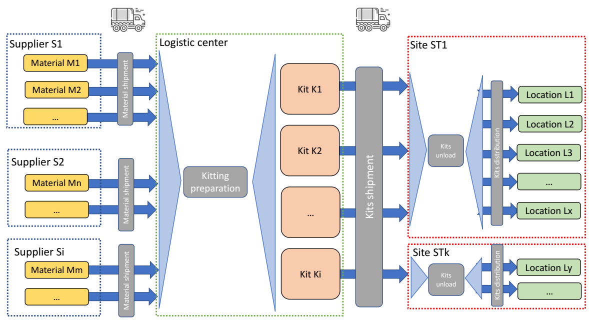

Figure 1. Kitting process

Kitting logistics practice is usually utilized with logistics centers and Just-in-time (JIT) delivery. Information required for kitting practice should be available to properly apply this solution. Currently, it requires manual efforts to collect and integrate this information during the planning phase of the projects.

Used together with logistics center and JIT delivery, improvements on waste and cost reductions as well as increase in production rates are possible with kitting practice [21][22]. Kitting logistics practice required a smooth information flow between operations [23]. Said and El-Rayes [6] proposed an automated construction logistics optimization system to minimize the logistics costs and integrate the project and supplier data. It could be integrated with kitting practice to ensure material and spatial requirements. Logistics centers can be configured to track materials via using information systems [8]. These advancements create potential for automation. Potential of kitting logistics practice in the construction industry motivates mapping this solution on ontology to generate future opportunities in terms of standardizing the information flow and improving efficiency.

Based on available literature on kitting in the manufacturing industry, information requirements for kitting are number of kits [24], information about the parts [25], item numbers and quantities as well as assembly location [26]. Based on the information we obtained for the use case from a renovation project, we determined that the information relevant to the kitting practice includes material type, quantity, unit, supplier, kitting date, delivery date, kit (name/number), task and location that the kit will be used. This information needs to be explicitly available to apply the kitting solution.

2.2 Ontology and its applications in AEC industry

Ontology originates from the philosophy domain and is recently widely adopted in the domains of computer science and engineering. Gruber [27] defined ontology as "an explicit formal specification of a conceptualization". In other words, ontology is a formal conceptualization of domain knowledge that formally defines the concepts (classes), properties and the interrelationships between the concepts, which thus could share common understanding of the structure of information and domain knowledge [28][29].

In the Architectural, Engineering, and Construction (AEC) domain, numerous efforts of ontology development have been made to solve the problems of data integration [30], knowledge management [31][32], and information utilization [30][33]. Construction is known as an information-intensive industry. The benefit of the ontology-based approach is that construction information can be stored and reused under a systematic information management framework. Moreover, with the machine-readable representation, ontology is able to make the information and knowledge accessible to both humans and computers for further computer-aided construction management tools [34].

Meanwhile, in terms of the logistics and supply-chain domain, ontologies have also been considered a solution for managing the logistics knowledge and information. Daniele and Pires [35] suggested ontologies are able to improve the enterprise interoperability in the logistics domain. A logistics ontology was developed by Lian et al. [36]to semantically represent the logistics situation. Hendi et al. [37] introduced a logistics ontology as a core of logistics optimization framework to support the logistics management. Although these ontologies efforts provided conceptualization of the general logistics process, they are insufficient to specifically expand to the construction domain.

Developing an ontology for construction logistics could improve the information management by accurately specifying the information needs for materials and on-site as well as logistics center activities required to successfully perform the construction tasks. However, currently there are no ontologies that specifically represent the construction logistics process information, nor ontological works that create the links between construction and logistics ontologies. Thus, an ontology is developed for construction logistics in this study.

3 Methodology

Our chosen methodology is design science. Design science identifies a real-world problem and proposes and evaluates a solution to this problem [38]. Thus, we use design science to develop a solution to represent logistics practices in the construction industry with ontology to solve the practitioners' problems regarding logistics information integration.

Development of the proposed ontology requires its design to be described and desirably implemented. The scope of this paper does not include a real-life case implementation. However, we provide validation of the ontology and evaluate the ontology based on a real-life construction project's schedule and material information. Multiple data resources were used to develop and validate the ontology. We used document analysis and public materials to form an example use case. We used a planned project schedule from a company to realize the use case. We obtained the schedule and material list per kits of a renovation project. We used required material and kit information to answer the competency questions. The ontology was validated using competency questions and automatic consistency checking.

3.1 Ontology development approach

To develop such ontology, an ontology development approach is established initially. The ontology development approach in this research is a hybrid approach that draws mainly on METHONTOLOGY [39] and the approach by Grüninger and Fox [40]. The major steps of the ontology development approach are shown in the following Figure 2.

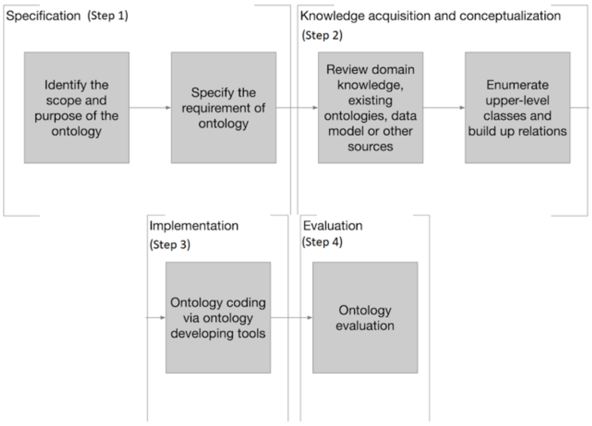

Figure 2. Ontology development process

3.1.1 Specification

The first step of the ontology development process is specification, which aims to first specify the scope and the purpose of the ontology by answering the following specification questions [39]:

What is the purpose? The purpose of the developed ontology is to formalize and structure the logistics information and simultaneously coordinate with the construction process information to improve the information exchange of the construction logistics operation.

What is the scope? The ontology is focusing on the construction logistics process and information flow of the material delivering. Meanwhile, the ontology is designed to be a higher-level ontology that only contains the higher-level concepts and relations of the construction logistics process.

Based on the scope and purpose, the requirement of the ontology can be identified with a list of competency questions. The competency questions (CQs) are a more detailed specification of the ontology requirements [40], that can be used to formalize the ontological model, concepts, hierarchy and relations. In this research, a workshop, consisting of participants from 17 Finnish AEC firms, was organized to define the CQs in compliance with the content of information that is required by all the stakeholders involved in the construction logistics (Table 1). The workshop showed that a material batch is an essential unit of analysis in logistics operations.

Table 1 A list of Competency Questions for the ontology

1. What is the content of the material batch?
2. When the material batch should be delivered?
3. What is the status of the material batch? (packaged, shipped, received, used)
4. Was the material batch delivered as planned?
5. What is the corresponding activity of the material batch?
6. What is the location of the corresponding activity of the material batch?
7. Who is the responsible worker or firm of the corresponding activity of the material batch?
8. What is the location of the material batch on site?

These questions were also used for further ontology evaluation to check if the ontology covered the desired content and if it can represent the domain knowledge.

3.1.2 Knowledge acquisition and conceptualization

After defining the ontology requirements specification, the second step of the ontology development process is to determine what domain knowledge for the ontology should be acquired and how it should be represented [39]. In this phase, relevant domain knowledge of the construction process and logistics process were reviewed. This is followed by the conceptualization process that all relevant terms of the concepts, class hierarchy, class properties including their range and domain in the ontology are defined to construct the ontological model.

3.1.3 Implementation

In terms of further implementation and application, the ontology should be implemented with a machine-readable format. This comprises the third step of the ontology development process (see Fig.2). In this research, the ontology was coded using Semantic Web Ontology Language (OWL) by using the Protégé environment. OWL is a computational ontology language that is designed for ontology development, which is a W3C recommended ontology language [41].

3.1.4 Ontology evaluation

Ontology evaluation aims to check whether developed ontology is satisfied with the specifications, fulfils its intended purpose and meets all the requirements, which consists of verification and validation [34]. In this research, the ontology evaluation consisted of automated consistency checking (verification), answering the competency questions based on a practical case example (validation). In the following sections, we present our results, namely the proposed ontology and its evaluation.

4 Findings: construction logistics ontology

In this section, the Digital Construction Logistics Ontology (DCL-Onto) that is developed based on the previously discussed approach is presented in detail as a result. The evaluation of the ontology is discussed in the following section.

4.1 Ontological model

Figure 3 illustrates the ontological model. In the DCL-Onto, *Entities* are used to represent the basic classes within the domain of construction and logistics processes. Moreover, the DCL-Onto can be subdivided into two major parts. The first part is the construction process part, which aims to provide an abstraction of the construction process on a generic level and structure the information of the construction operation to reveal the constitutes of actual construction activities. The second part is the logistics process part, which aims to formalize the information and entities in the construction logistics process via various logistics systems by multiple stakeholders. The logistics process is regarded as an extension of the general construction process. Meanwhile, the interaction of two parts can be used for coordinating the construction logistics process with the on-site construction operations. Furthermore, the specific application for the kitting practice is also developed in the logistics part to exemplify the usage of the developed ontology.

In the construction process part, the main entities (as depicted with the deep blue colour in Figure 3) include Building Element, Agent, Equipment, Location, Information Content Entity, Group, Activity and Constraint. These provide a generic level abstraction on construction entities that involve in the construction process. The proposed ontology considers the construction process as constituted by several domain entities, including activities, locations, agents, equipment, material batches, and information content entities. Activity refers to a superclass for all work or aggregations of works that are carried out in the construction process. Activities also have precedence relations with other activities. Object Activity is a subclass of Activity which has the target of a certain object. Therefore, Logistics process is a subclass of the Object Activity whose target objects are Material Batches.

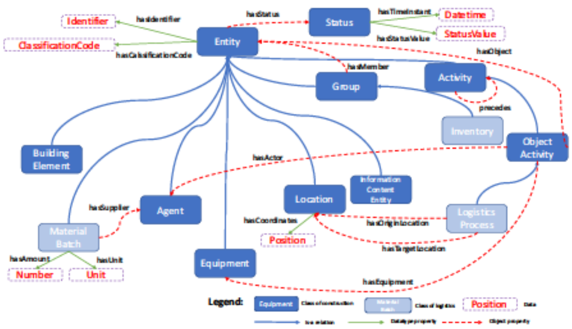

Figure 3. Ontological model of DCL-Onto

4.2 Representing the construction logistics process

The main concepts of the construction logistics process are coloured with the light blue colour in Figure 3. The logistics process part is designed to be able to represent the essential logistics information with a formal unified structure. The logistics process part comprises two main sub-components. The first is the information about the logistics process and the second is the product information of the material batches. Figure 4 illustrates the kitting logistics solution's ontology model in detail. *Material kit* is a *Group* that consists of *Physical Objects* of materials that are collected from *MaterialBatches*. *Inventory* consists of *MaterialBatches*. The information on which materials the kit consists is obtained from the *Information Objects*.

4.3 Evaluation of the ontology

4.3.1 Automatic consistency checking

Consistency checking aims to identify contradictory facts in an ontology based on Description Logic (DL) principles, such as logical conflicts or inconsistent classes. Consistency checking is enabled by Description Logic reasoners, which are able to perform various automated inferencing services [42]. In this research, consistency checking of the proposed ontology was conducted using the Pellet which is a Protégé built-in DL reasoner. Pellet is an open-source OWL-DL reasoner that is able to support the reasoning of checking the ontology consistency [43]. The result of the automatic consistency checking for the DCL-Onto is that the ontology is consistent and coherent that without logical conflicts.

4.3.2 Answering the competency questions

In terms of DCL-Onto, a set of CQs for its conformance are predefined CQs in the previous "Methodology" section. In this research, the procedure of answering CQs were conducted as a task-based evaluation by answering the specified CQs based on the instance data of the following practical case and using the SPARQL Protocol and RDF Query Language (SPARQL) for querying and retrieving the information to answer sample queries based on the practical information in the following use case.

Use case

To verify the coverage of the ontology and also validate the usability of the ontology towards practical construction logistics cases, a use case example was formed based on an actual construction logistics case that applied the kitting method. In this case, the practical construction project applied the takt planning and controlling method [44], and the logistics process of the material is coordinated with the takt plan and actual progress on the site. The obtained static information sources include the construction project schedule and material kit information, moreover, the project progress information and corresponding updated material delivery schedule are also acquired. An extension of the ontology for the kitting process can be seen in Figure 4, in which a *Material Kit* is defined to represent the material kits that are groups of material batches. All the information will be integrated based on the ontology.

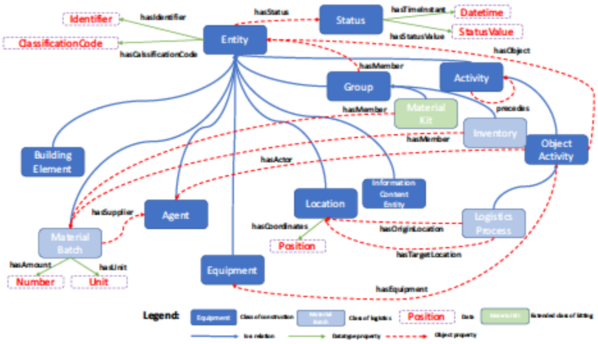

Figure 4. DCL-Onto extension for the kitting practice

The data were manually mapped with developed ontology in the Open Refine software and then converted to Resource Description Framework (RDF) format based on the ontology. Subsequently, the RDF graph was stored in the Graph DB software. In the Graph DB environment, a set of SPARQL queries were conducted which aims to answer the CQs for evaluating the ontology. The query result can be seen in Table 2, in which the CQs of the ontology were specifically defined based on the practical case, and the query results are fitted with the practical data.

Table 2 . Specified CQs and answers based on the case

Competency Questions	Answers
1. What is the content of the ***Material Batch 12***?	*Kiilto 60, 25 bags*
2. When the ***Material Batch 12*** should be delivered?	*24.10.2017*
3. What is the status of ***Material Batch 12***?	*Delivered*
4. Was ***Material Batch 12*** delivered as planned?	*True*
5. What is the status of the corresponding activity of ***Material Batch 12***?	*In progress*
6. Where is location the Material Batch 12 should be delivered based on the location of the corresponding activity?	*Apartment2*
7. Who is the responsible worker or firm of the corresponding activity of the material batch?	*Carpenter*
8. What is the location of the material batch on site?	*Apartment2*

5 Discussion

In this research, a novel ontology for construction logistics was proposed. The developed ontology makes it possible for humans to understand and machines to use the information required for construction logistic operations and their management. The ontology defines the information requirements to properly integrate a logistics solution in practitioners' practices in the project. By having the required information available, practitioners can utilize the ontology in their logistics systems to integrate the information transferred from their partners and material suppliers with the project-specific information. Machine-readable format makes it possible to automate the practice in the future.

As has been demonstrated in the use case part, the proposed ontology is able to formalize and integrate the information regarding construction logistics. Furthermore, it can be envisioned from the case that the ontology can be used in further applications for planning and control of construction logistics processes, such as through information retrieval. The proposed ontology can be used for information standardization and integration to support selected logistics practices, such as kitting with JIT delivery and consolidation centers, towards fully industrial logistics systems.

Conventional methods in construction have reached their limits, and automation and robotics become omnipresent in our daily lives [45]. Hence, it is valuable to represent logistics information with an ontology to generate opportunities for construction logistics to derive towards automation and robotics technology.

For the digital transformation of the construction industry, establishing the information standards is significant [46]. The ontology development contributes to determining the information requirements. Thus, the developed ontology can be used and further developed to coordinate the construction logistics and integrate the information required to perform these activities from different information sources involved in a standard way.

6 Conclusion

In this study, we have described an ontology for logistics operations in the construction industry. The ontology can be applied to specific logistics solutions. We have provided a use case example to illustrate the application of the ontology in a project setting. The research was limited to not having a real project application of the ontology. Since there was not a logistics system in use to our knowledge that operates with a full kitting logistics information model, it was not possible to obtain enough data to test the ontology from a real project. Future work should focus on implementing the developed ontology in real-life applications. Moreover, for future research, an ontology-based solution needs to be developed taking advantage of computing technologies to support the logistics management practices.

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