Ontology-Based Information Integration and Decision Making in Prefabricated Construction Component Supply Chain

Full Paper

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Abstract

With rapid developments in cloud computing, the creation of a cloud based prefabricated component supply chain platform marks an important initiative signifying an industry breakthrough and innovation. The application of this cloud platform will effectively integrate the social resources of the prefabricated components supply chain and realize the reconfiguration of distributed resources. In order to facilitate this, much research is needed to develop a flexible prefabricated component data integration model using ontologies and semantics. Such a model can support adaptive heterogeneous system integration and interaction. In addition, this cloud platform can be used to support coordination within the supply chain using ontology rules. This can greatly enhance managerial decision support. This paper proposes a flexible distributed information integration mechanism and develops an ontology-based management support application, which will play an important role in resource integration and the optimal allocation of prefabricated components within the supply chain.

Key Words

Cloud Computing, Interoperability, Ontology Reasoning, Prefabricated Components, Supply Chain

Introduction

The continued high cost of components and low efficiency of prefabricated construction supply chain (PCSC) impede the industrialization of prefabricated construction industry (Polat 2010). Countries are trying to improve this industry and the supply chain of prefabricated construction in order to promote industrialization. The North American prefabricated construction industry has promoted the formation of alliances between enterprises in this industry from 2000, which aims to reduce the delivery time and cost, as well as improve the capability of prefabricated components supply chain (Sacks et al. 2004). The British Government has tried to use Building Information Modeling (BIM) technology to promote change in the supply chain of prefabricated construction industry, break down supply chain barriers, and promote the development of the prefabricated components market (Bew and Underwood 2009). Because of the problem of small market scale, low reuse rate of component mold, imbalance of capability between upstream and downstream enterprises, and the lack of efficient communication mechanism among the links, some Chinese enterprises have started to explore the establishment of industrial alliance in order to achieve the effective allocation and application of the components resources (Qinjian 2014).

The research on prefabricated components supply chain is focused on applying the practices from supply chain management in the manufacturing industry to the construction industry, specifically, the mode of production from manufacturing to the construction industry (Koskela 1992). However, compared to manufacturing, the prefabricated components supply chain has significant differences such as complexity, dynamic nature and risks. Especially, with the rapid development of prefabricated construction, there are industrial clusters around the complex supply chain network system whose upstream and downstream face plenty of new problems: (1) during the component design phase, there is lack of cooperation between

designer and component supplier, (2) during the component production phase, there is poor production planning, poor coordination between upstream and downstream, and ineffective competition among component suppliers, (3) during the component transportation phase, components are bulky and heavy and have high cost of warehousing and transportation, and (4) during the assembly and construction phase, lack of professional contract management and field coordinators. Based on the above problems, both the prefabricated construction industry as well as researchers have pointed out the need for a shared platform to support the supply chain using new network and communication technologies such as cloud computing, Internet of things, and building information model (BIM) (Abedi et al. 2014a; Tao et al. 2013).

Nowadays, some emerging B2B vertical business service platforms operate online and provide more integrated services to the stakeholders in PCSC (Saalmann et al. 2015). However, to establish a B2B business service platform based on prefabricated components' supply chain and realize its functions and operation of its service model, there are two issues that need to be solved. First, how to integrate and interface heterogeneous data and information systems under an integrated platform, and second, how to use the platform to support cooperation and dynamic equilibrium resource allocation along the PCSC. To solve these problems, this study proposes an ontology-based information and system integration method and explores rule-based reasoning solutions within a cloud-distributed e-Commerce environment.

Literature Review

This study builds on three research streams within the literature: (1) Interoperability in the PCSC; (2) Ontology-based supply chain integration and management decision; (3) Managerial decision support using a cloud-distributed platform.

Interoperability in Prefabricated Components Supply Chain

With the continuous growth of prefabricated components supply chain in the past twenty years (Eastman and Sacks 2008), researchers have begun to pay more attention to the integration of highly fragmented information in prefabricated components supply chain (Tommelein 2005; Lu et al. 2013). Aram et al. (2013) point out that in order to optimize supply chain activities, it is necessary to create error free information, effective integration of information as well as minimize no value activities. Related to the information interaction mechanism in prefabricated components supply chain, the literature mainly includes the following aspects: Sacks et al. (2004) suggested rebuilding the prefabricated components supply chain using 3D building models. In 2010, during the construction phase, the Sutter Medical Center used BIM models and tools to improve the problems such as separation of each ring, high error rate as well as promote the efficiency of the supply chain. Aram et al. (2013) indicated that establishing a common BIM model could reduce the contradictions and errors within the supply chain. Lackner (2012) reduced the time and cost of supply chain by using 4D production planning which is built using BIM technology. Čuš-Babič et al. (2014) proposed an automated information mapping method by using BIM model and algorithm for interactive design, production, and construction.

Ontology-based supply chain integration and management decision

The heterogeneity and dispersion of data raises the need for flexible integration (Wang et al. 2013). Based on this need, Rezgui et al. (2011) investigated the construction information interaction mechanism based on semantic technologies. Zhang and Issa (2012) proposed a storage and extraction mechanism for building information model based on ontology, which takes data from IFC file and ensures the integrity of the IFC-based ontology. Through the development of a bidirectional local model extraction algorithm, data extraction and integration is achieved. Lee and Jeong (2012) discussed the limitations of traditional representation of information based on the issue of collaborative interaction within the construction industry, and proposed an information storage and extraction mechanism. It separates the public and private space by establishing a filtering mechanism, as well as selecting the ontology and related knowledge. Park et al. (2013) proposed various criteria for the classification of faults which are used for proactive faults management. They have proposed a faults classification system for construction. They accomplish this by going through the stages of information collection, retrieval and reuse by ontology, and then integrating the criteria for the classification of faults to develop an integrated fault management system framework.

Managerial decision support under distributed-cloud platform

With the construction of cloud platform, Aram et al. (2013) analyzed the requirements of a BIM platform for prefabricated components supply chain, proposed to achieve information exchange and management through expanding and improving interoperability of the BIM model. This is expected to improve the productivity of the supply chain, and to carry out engineering experiments using various technologies. Abedi et al. (2014b) analyzed the main problems existing in each stage of prefabricated components supply chain and proposed the idea of establishing a collaborative platform based on cloud computing, however, no specific architectures and methods are given. Xing, Qian and Zaman (2016) proposed life-cycle assessment (LCA) using hybrid cloud platform as a potential way to coordinate and manage the environmental information and resources better in a networked supply chain.

Prior research has used semantics for construction information interoperability (Curry et al. 2013), however, flexible integration of information based on ontology needs effective connection among dynamic process and systems to achieve integration of data and processes. Much work is needed to improve the information sharing and integration. Hence, this paper focuses on developing a prefabricated components information communication and sharing model, which combines current management of prefabricated components industry and collaborative cloud platform technology. Using semantic web as the backdrop, our work integrates resources from various enterprises in prefabricated components industry cluster and realize the dynamic operation of its supply chain, and provide decision support.

Proposed Approach

Ontology-Based Information Integration Mechanism

The various stages of prefabricated components supply chain involves complex data and the component model (IFC Component Library) does not cover all the relevant information. Thus, highly dispersed heterogeneous data exist in discrete information models and systems. Moreover, the participants in the prefabricated components supply chain are quite different from each other. Therefore, there are huge differences in expressing and understanding the same data, which causes problems such as poor dynamic data access, low efficiency and complex data. The features of prefabricated components have special requirements for the integration and interaction of construction information. To address these issues, we develop a standard representation of heterogeneous data in the PCSC, ontology based modeling, and information integration on a cloud platform. Each of these aspects are briefly discussed below.

Representation of Heterogeneous Data in PCSC

Different types of data related to various stages of prefabricated components such as design and production, storage, transport, assembly and other stages have to be captured and integrated. Different formats and representation of heterogeneous data exist in prefabricated components supply chain, which includes both IFC data presented by BIM generic data and relevant information during the production process such as warehousing, logistics and assembly (see Figure 1). This information is stored in different information systems and databases, having various forms. It is necessary to integrate these data into a loosely coupled integration data center within the prefabricated components supply chain as a central repository so as to realize the flexible data extraction and application.

| Stages	Design	Production	Transportation	Assembly
IT Systems	Design System	ERP System Pucurement System Production System nventory Management System	Transportation System	Construction Management System
Data Source and Format	IFC-based Design Data	Supplier Data Material Data Production and Planning Data Module Data Schedulling Data Inventory Data	RFID-based Location Data Transportation Data	Spatial Data Temporal Data

Figure 1. Heterogeneous IS and Data in PC Supply Chain

In the whole PCSC, each member uses a different data management system with different technical characteristics. In addition, these enterprises accumulate a large amount of business data using different storage methods which can vary from simple file based database to complex network database, and they constitute a heterogeneous data source for the enterprises. This heterogeneity of data increases the difficulty of information integration and sharing. Some of the data format will particularly be troublesome for sharing. Hence, it is important for the members to deal with the heterogeneity of data.

Ontology-Based Modeling and Mapping

A multi-layer ontology model of prefabricated components supply chain is built (see Figure 2), and a complete ontology model of prefabricated component is established based on it. This central ontology-based reference model will be used to realize the supply chain integration. In addition, mapping rules for heterogeneous data on ontology application are being developed to facilitate the application and extraction of heterogeneous data. By establishing different ontology reasoning mechanisms, the representation ontology can be used in the decision making process.

There are three kinds of ontologies, including application ontology, upper ontology and representation ontology. The application ontology relates to the specific problems, the upper ontology being a framework of knowledge having universal significance, and representation ontology relates to knowledge representation language. The application ontology is divided into IFC-based design ontology, production ontology, transportation ontology, and assembly ontology according to the different stages and the degree of the information acquisition. The PCSC ontology is an upper ontology that connects these four types of ontologies, which facilitates the exchange of information and improve the relationship between the four stages. Thus, using the PCSC ontology, enterprises can achieve management decision support by realizing the coordination between design, production, transportation, and assembly.
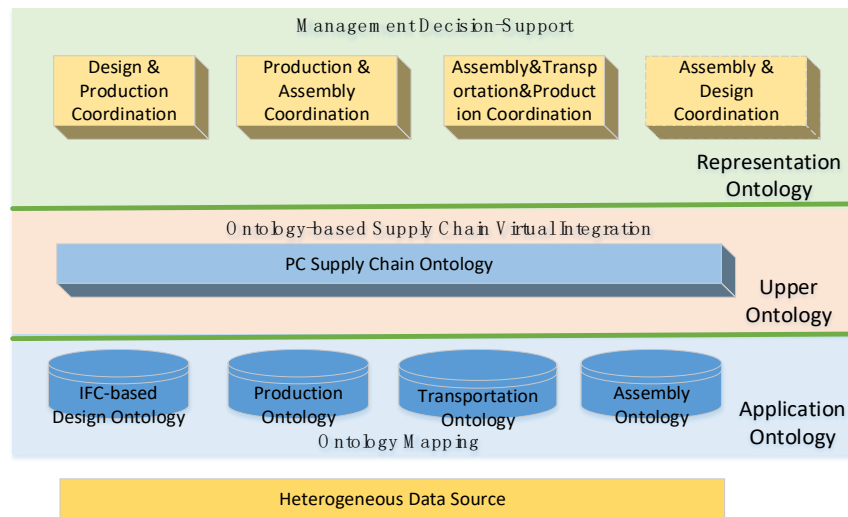
Figure 2. Multi-Layer Ontology Structure

Design Ontology: At the design stage, models are built mainly based on BIM technology. Many modeling software such as Revit have adopted the IFC standard at present. Figure 3 below shows some of the relationships in IFC by depicting a fragment of the IFC ontology. The component data and the relational information in the design phase are embodied in the design ontology. A fragment of the design ontology is shown in Figure 4.

Production Ontology: The production stage and the design stage exchange information through the BIM model and 2D drawings. The process information in the production stage including workshop scheduling information, human resources information, etc. are captured in the production ontology. A fragment of the production ontology is shown in Figure 5.

Transportation Ontology: The information in the transportation stage plays an important role in route planning and scheduling, which is helpful to reduce the transportation cost and inventory cost. Figure 6 shows a fragment of the transportation ontology.

Assembly Ontology: The assembly stage provides information about hoisting equipment, on-site personnel arrangement, safety engineering, and on-site personnel, which are closely related. Making full use of this information can effectively organize on-site personnel requirement, reduce the waste of resources, and improve the safety. A fragment of the Assembly Ontology is shown in Figure 7.

Supply Chain Ontology: The supply chain ontology facilitates the interaction between the members of the supply chain. The knowledge contained in this ontology can be divided into organizational knowledge, business flow knowledge, and transaction processing knowledge. The organizational knowledge describes a specific domain; business flow knowledge describes the business logic in the supply chain, i.e., supply chain workflow knowledge; transaction processing knowledge is used to describe the steps and decision making method to perform some task. A fragment of the supply chain ontology is shown in Figure 8.

The organization ontology is composed of the role ontology and the entity ontology. The role ontology refers to the design, production, transportation and assembly and each role is modeled in the application ontology. Entity ontology refers to the information transmitted on the PCSC. This information includes the IFC modeling information in the design stage and process information in the production stage, transportation and installation, such as component geometry information, material information and performance information. This information forms the common basis for understanding and communication among members of the PCSC.

The business flow ontology describes the 'exchange' knowledge in the supply chain, reflecting the business processes and relationships in the supply chain. The business flow in the supply chain needs the ontology model to deal with the extraction, storage and reuse of knowledge.

The transaction processing ontology is related to a specific activity or behavior in the PCSC. Each role of the supply chain needs to perform a specific activity or behavior. Each behavior of a role corresponds to a decision. The transaction processing ontology is composed of the behavior ontology and the decision ontology. The behavior ontology expresses the relationship between a specific role and some business.
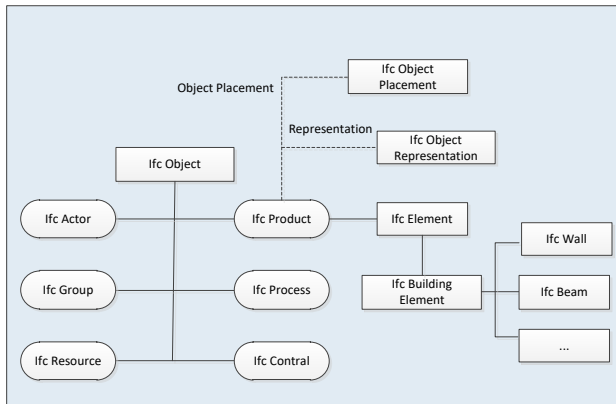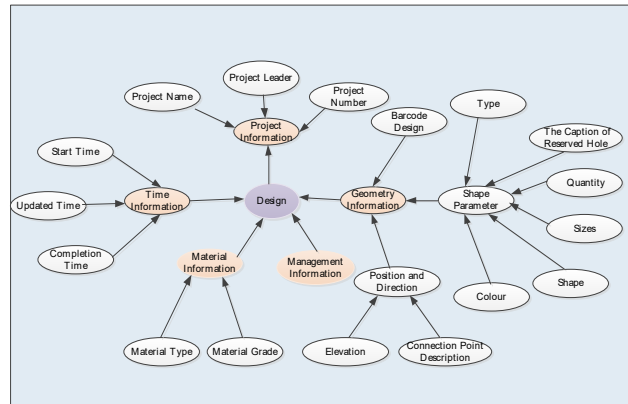

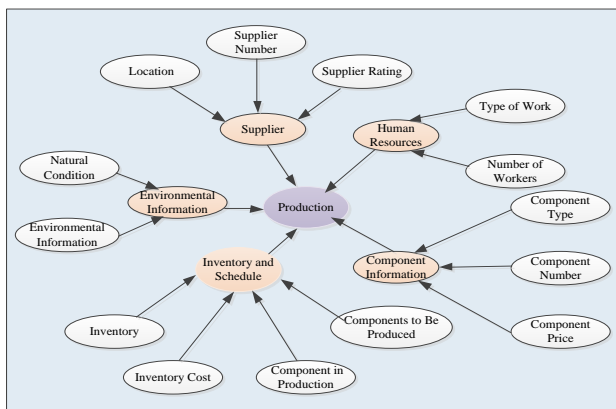**Figure 3. Sample of IFC Ontology**

Figure 4. Design Ontology

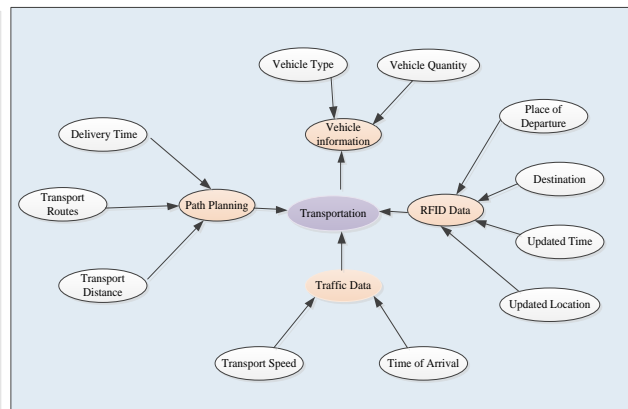**Figure 5. Production Ontology**
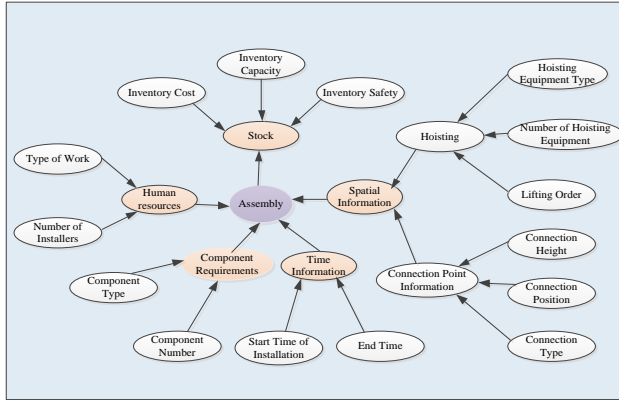

Figure 6. Transportation Ontology
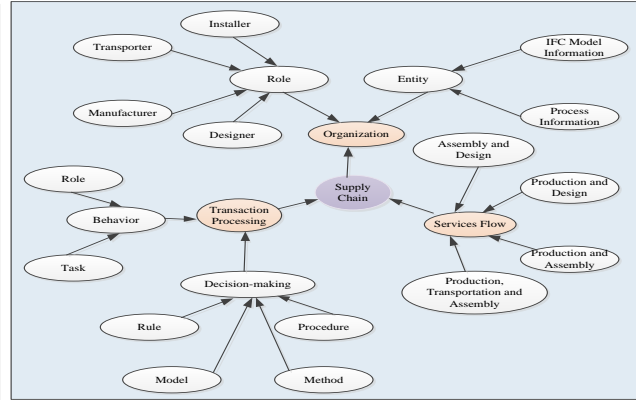
Figure 7. Assembly Ontology

Figure 8. Supply Chain Ontology

The decision ontology is represented by rules, procedures, or specific decision models. Decision-making method includes methods of component production, transportation and so on. For example, the transportation decision includes the transportation mode, route, the choice of transportation vehicle for the specific component, and so on. Figure 8 shows the overall supply chain ontology.

Information Integration on Cloud Platform

A cloud-based prefabricated components model and electronic market platform could be established to achieve data interoperability. A core service mechanism and collaborative platform for interoperability is set up to promote the integration and sharing of multidimensional and heterogeneous information systems through a combination of cloud computing and internet of things technology (e.g. RFID & GPS). This platform will also provide decision support through ontology-based reasoning.

The prefabricated components supply chain cloud platform based on ontology as a core, is not only the interaction center for different information, but also provides supply and demand balance service from the view of resources integration and allocation. The cloud platform provides the following services:

(1) Collaborative design and production - the efficiency and accuracy of the supply chain can be improved by effective collaboration between the IFC data in the design system and the component model at the production stage. (2) Coordination of production and assembly - match supply ability and assembly stage, therefore, realizing the effective coordination of these two stages through ontology. (3) Coordination of production, transportation and assembly – manage the demand within the supply chain dynamically; owners change the demand and design constantly and at the same time, suppliers may lack capacity leading to supply shortages and lack of intermittent demand. The cloud platform can help in effective coordination during production, transportation and cooperation stages. (4) Coordination of assembly and design – assist in the assembly according to the design specification, including the accuracy of spatial information and the effective control of time sequence. The coordination of assembly and design is implemented in the cloud platform through management and decision support using the ontology.

Cloud platform framework

The business activities in PCSC always involve a large number of documents, charts and reports. These unstructured information sources have different modes of expression, and are applied in different situations. The tasks, jobs, and processes of the enterprises in supply chain have the need for information processing, such as the plan for components production, the choice of component transportation decisions, etc. Therefore, the cloud platform based PCSC takes information integration and information sharing at its core. The cloud platform framework is created for handling two different aspects, the first being the information flow in cloud platform, the second being providing the overall architecture for supporting the proper functioning of the PCSC.

Information flow in cloud platform: The following is a brief description of the ontology integration module on the upper left and the information sharing module on the right shown in Figure 9:
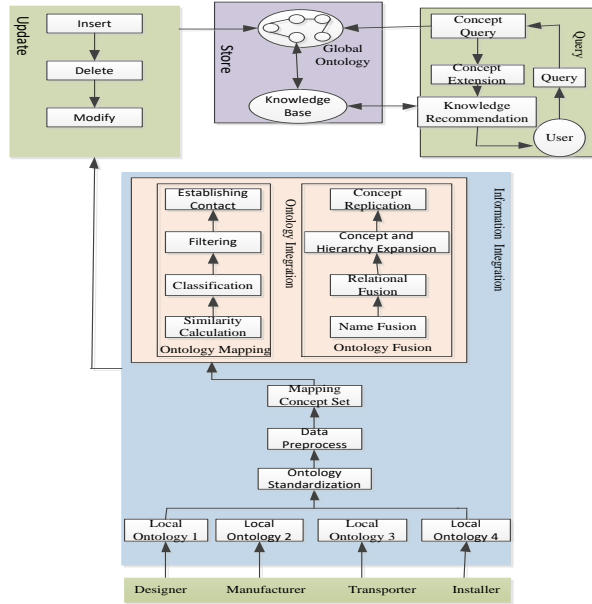
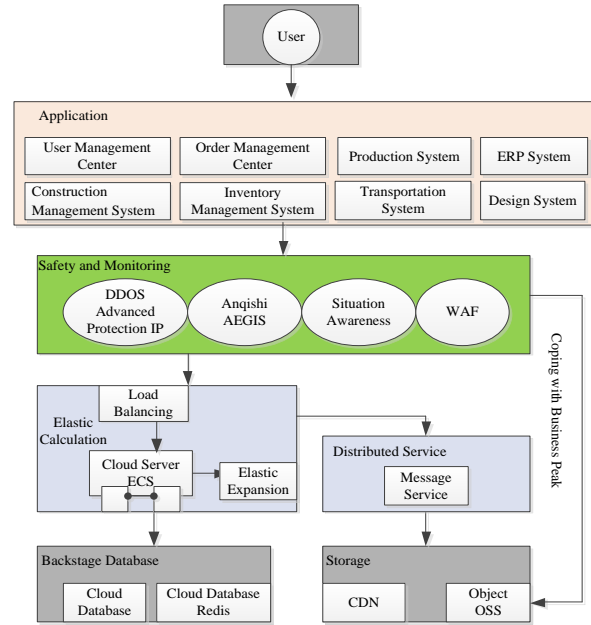**Figure 9. Information Flow in Cloud Platform**

Figure 10. Holistic Architecture in Cloud Platform

The ontology integration module performs the following tasks: a) *Ontology Standardization*: The local ontology maybe stored in different forms using different data structures. So, the ontologies have to be converted to the OWL format for standardization, which facilitates ontology mapping. b) *Data Preprocessing*: For OWL documents, the system selects candidate mapping sets according to the assumptions. c) *Ontology Mapping*: First, the semantic similarity is calculated by combining the concept name, attribute and level similarity. Then, based on the experience and knowledge of the field experts, the classification is performed according to the mapping relationship. Finally, the contact is established through filtering. d) *Ontology Fusion*: Similar concepts obtained through ontology mapping need to be integrated using the name, attribute and hierarchical structure to form an integrated global ontology.

The Ontology Server has four basic functions: integration, query, storage and update. As the enterprise nodes in PCSC, the heterogeneous data is transformed into local ontology. Based on the mapping and integration of Local ontology, the global ontology is integrated and provides a unified view of user query. When the ontology is updated, it can be operated by inserting, modifying and deleting the update module. The retrieval process of knowledge and information are as follows: the user input query, search the global ontology in storage system concept, concept has been expanded, including the definition, property relations, etc.; then the system call knowledge base concept identification, identified with the user consistent knowledge recommendation, and finally returned information to the corresponding user.

Holistic architecture of the cloud platform: Figure 10 shows the cloud platform, which consists of: a) Database, b) Distributed Service, and c) Elastic Calculation. These modules are briefly described below.

The *Database* in cloud platform can be divided into two parts: the background database and storage. The background database is used to store dynamic data and the latest update data, and the storage is used to store more stable data which is not easy to change. The *Distributed Service* enables the platform to cope with all parties' data in the supply chain, and as the amount of data will be increasing, a data backup is necessary. Also, to improve performance, the data needs to be deployed to multiple servers. The *Elastic Calculation* deals with the increasing number of enterprises. As the volume of data becomes huge, the cloud platform needs to expand CPU and memory and also manage security and monitoring of the data.

Sample Application

In this section, an ontology-based multi-agent model is proposed to conduct multi-objective optimization of the prefabricated component supply chain. To demonstrate the feasibility of our approach, we apply it to the underground tunneling prefabricated component supply chain and use this as an empirical case

study. The project is the 9th tunnel construction of the Shanghai metro line, from No.1 air shaft to Cao Ying Station. This project was under-taken by Shen Tong Group 17 Line Company. The length of the tunnel is 1737.266 meters, and the construction took place from July 13, 2015 to March 8, 2016.

Simulation conditions and objectives

The case study uses *Anylogic* modeling and simulation tool. Al the factories, transportation companies and assemblers are modelled as agents. In the current simulation scenario, since the construction project is led by the government, there is only one assembler responsible for the tunnel construction project. Hence, there is no need to consider the influence of other assemblers. Furthermore, there are three component factories and two transportation companies involved. Hence, the aim of this simulation is to optimize production and transportation resources within the supply chain through matching of the suppliers, transportation companies and the assembler for various components. The case study aims to optimize the supply chain with respect to cost, time, safety and available resources.

To optimize for time, the experiment selects the appropriate manufacturers and transportation units according to the requirements of the installation schedule, the manufacturer's production capacity, price, match between transport vehicle and the components, and distance. Furthermore, the system also selects the optimal path based on real-time traffic situation. To optimize for cost, the experiment keeps total cost of supply chain to a minimum, while meeting the time requirement. Both the manufacturing cost and transportation cost have a great impact on the total cost, so the system has to develop a reasonable routing plan, select appropriate transport vehicles, consider the transport capacity of the vehicles. To optimize for safety, the number of on-site installers is an important measure of project safety. According to the progress indicators and task arrangements, the number of staff per day has to be determined.

Data collection

The data comes from tunnel assembler's daily update, and is stored in a database. The data is displayed using Excel and ordered by week. The demand for tunnel segments basically follows a normal distribution, which indicates the fact that the construction speed is slow at the start and end of the project and fast in the middle. In addition, the speed of construction is affected by typhoon, heavy rains, as well as holidays, which cause the sudden reduction in demand, and the fluctuation is obvious. Based on the above-mentioned ontology structure, this paper uses Protégé4.3 to construct the ontology (see Fig. 2.) and relevant data is obtained from the ontology-based integration mechanism (see Table 1).

Suppliers	Transporters	Assemblers
Component type and number	Transportation price	Hoisting equipment type
Unit price	Distance to installation site	Number of hoisting equipment
Component inventory	Transit time	Number of Installers
Production time	Transport vehicle type and number	Number of jobs
Number of workers	RFID positioning information	Inventory capacity
Inventory cost	GIS location information	Inventory cost

Table 1. Relevant data retrieved from ontology model

### Simulation process and analysis

The simulation interface is shown in Figure 11. Data and conditional constraints are imported in advance, when the assembler issues an order. The assembler agent will match one or more suppliers according to the order quantity and required time. Then the supplier agents will find one or more suitable transport organization to ship the components. The capacity of suppliers and transporters will be affected by the current situation, so it is a dynamic matching process.

Case study summary

The supply chain ontology makes it possible to achieve detailed heterogeneous data sharing among the prefabricated supply chain. Furthermore, the multi-agent technology supports interoperability, modularity, flexibility and extensibility of the system. Ontology is the foundation of multi-agent modeling,

and the corresponding relationship between the attributes of ontology and the parameters of multi-agents can be established. The ontology can integrate the heterogeneous data in the early stage, and provide the decision basis for the complex decision problems using the association rules and logic reasoning in the later stage. Thus, the simulation experiment based on a multi-agent framework yields more accurate and complete set of results. Through the simulation of multi-objective optimization, a number of factors can be varied at different levels to achieve a more efficient, low cost, safe and environmentally friendly prefabricated components supply chain. This will also help managers in making effective decisions and develop appropriate strategies.
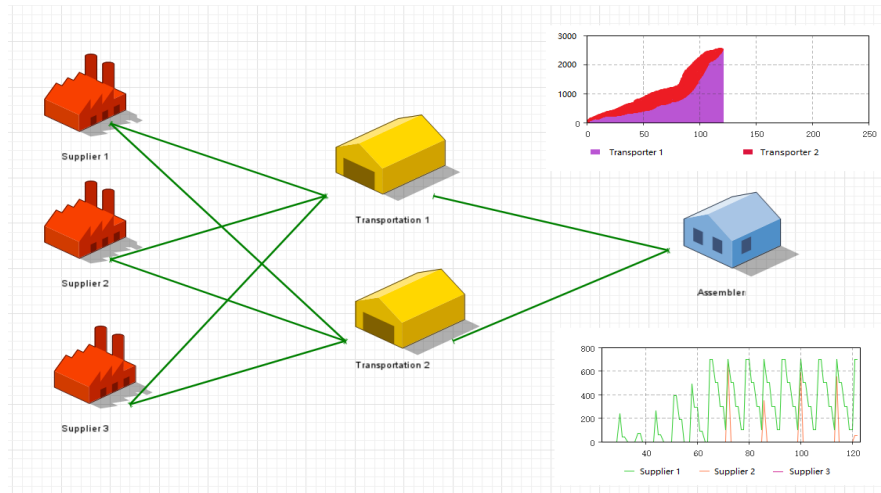
Figure 11. Simulation Interface

Discussion

Cloud computing provides an important platform for the integration of heterogeneous data and heterogeneous systems. A flexible data integration mechanism is needed to achieve effective complex data association and integration without affecting or changing the existing state of heterogeneous construction data. Therefore, on one hand, it is necessary to establish flexible data association through effective logical expression and data structure, which can quickly respond to the information extraction and processing requirements under limited resources consumption. On the other hand, it is necessary to open data association and exchange between multiple collaborative applications. The global ontology serves as a mediator that connects the data definition ontology at the bottom layer to the application ontology at the top layer effectively, so as to facilitate the interoperability between heterogeneous data and systems. The ontology-based association rules will facilitate intelligent decision-making within the supply chain and solve the complex information management problem across the enterprise platform. This results in the management and application of a lean resource management system.

Conclusion

Heterogeneous information integration based on ontology can effectively support integration and interoperability of data. Moreover, the application of cloud platform provides a good network environment for heterogeneous data and heterogeneous system integration. The main contribution of this work is developing a framework to solve the complex management decision and coordination problem in prefabricated components supply chain. In addition, the paper integrates several features of building information and supply chain, information integration and sharing, as well as data management decisions. As part of future work, the accuracy and effectiveness of management decisions driven by ontology will be verified through quantitative analysis.

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