Received January 9, 2017, accepted January 21, 2017, date of publication February 8, 2017, date of current version April 24, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2665778

RFID and Multi-Agent Based Architecture for Information Sharing in Prefabricated Component Supply Chain

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This work was supported by Natural Science Foundation of Shanghai Project under Grant 15ZR1415000. The work of Dr Sugumaran was supported by a 2016 School of Business Administration Spring/Summer Research Fellowship from Oakland University.

ABSTRACT With the increasing volume and scale of prefabricated architecture in China, there is urgent and critical need for the seamless integration of prefabricated component supply chain, which covers project design, component production, logistics and transportation, construction, and maintenance. Due to the coordination problem between the links in the supply chain, the overall operating cost of the upstream and downstream enterprises becomes uncontrollable and the scale effect does not materialize. In this paper, based on RFID application and multi-agent simulation, an information tracking and supply mechanism for prefabricated supply chain are proposed. The research builds the information connections along the whole supply chain using RFID and creates the possibility of zero inventory of prefabricated components along the supply chain. Besides, in order to lower the impact of the demand fluctuation on the supply chain, the research proposes the industry alliance mechanism to satisfy the dynamic supply requirements. This paper, first, summarizes relevant studies on RFID, multi-agent, and industry alliance, and then proposes an RFID and multi-agent-based system architecture for prefabricated component supply chain for information tracking and coordination. It uses a case study involving underground precast tunnel segments to demonstrate the feasibility of the approach in addition to establishing an industry alliance to solve the problem of demand fluctuation.

INDEX TERMS Multi-agent, prefabricated component, RFID, supply chain, supply mechanism.

I. INTRODUCTION

With the revolution and improvements in the architecture and construction industry, the Chinese government is encouraging the development of prefabricated concrete, steel structure and other technologies, and promotes the precast and assembly within the construction industry [1]. Industrial construction, which is different from the traditional manual operation, assembles the parts on-site after large-scale production of the building components in a factory. The prefabricated component production not only increases the efficiency of construction but also improves environmental protection, it also restructures the architecture industry and cultivates industry clusters which lead to the economy of scale. However, the implementation and extension of prefabricated component architecture in China has met with many problems:

- Firstly, the prefabricated component information is lost or distorted along the stages of design, manufacturing, transportation and construction over the supply chain. The supply and demand information is difficult to transparently and immediately transfer along the supply chain and the bullwhip effect is serious, leading to higher construction cost and decreasing production efficiency.
- Secondly, the lack of the effective alliance mechanism between the component suppliers results in low production efficiency, production waste, and poor economies of scale.
- Thirdly, the lack of the prefabricated component standard limits the usage of prefabricated molds and also lowers the scale of capacity, and finally makes the assembly cost being much higher than residential cast-in-place production.

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Based on the above limitations, the new round of construction industrialization must focus on the deep integration and seamless connection of the prefabricated component supply chain and the establishment of Industry Supply Alliance, apart from considering the technical problems, such as standard design, factory production, and assembly construction.

As intermediate products and core resources, Prefabricated Components have different characteristics such as large volume, heavy capacity, and poor interchangeability. This requires integrating the 'information chain' in the sectors of design, manufacturing, storage, transport, lifting, assembly and other aspects to increase the value of information. This paper mainly investigates the usage of RFID and Multi-Agent technology to realize the information exchange along the prefabricated component industrial chain, which obtains accurate design information, efficient treatment of site information, and the core component information feedback. The proposed approach can improve the feasibility of the construction plan and facilitate dynamic adjustment in order to achieve pull production and minimize the inventory and delay for the assembler. In the face of possible shortage of supply capacity, the paper proposes the coordination of industrial alliance and seeks to optimize the total cost.

II. LITERATURE REVIEW

A. MULTI-AGENT SIMULATION IN SUPPLY CHAIN MANAGEMENT

Recently, multi-agent logistics management programs have gained more attention. The existing research mainly focuses on sampling and modeling personnel, vehicles and logistics in the phases of design, manufacturing, warehousing, transportation, assembly and maintenance, so as to achieve global control.

Fox *et al.* [2] introduced an agent-based system for supply chain management and used the concept of Agent to abstract the organizational structure. Hinkkanen *et al.* [3] expanded the properties of an Agent and included an abstract description to logistics, information flow, and capital flow in the complex supply chain environment. Yung *et al.* [4] used agents and developed a web-based application to optimize the production and sales using a data sharing strategy in supply chain. Kimbrough *et al.* [5] built a supply chain model based on Agent theory, and introduced a genetic algorithm to study the optimal coordination mechanism between order and supply demand. Barbuceanu *et al.* [6] studied the communication mechanism between different Agents, and structured all the main components of the supply chain correspond to production activities one-to-one, building the whole supply chain model. Fox *et al.* [7] also designed a more complex supply chain system structure and framework to conduct in-depth research on the collaboration model among different participants. Swamnathan *et al.* [8] put forward a supply chain model including different enterprises in the supply chain, the factors impacting production and management, and the information communication mechanism. This model can be used for assisting in the management of different levels of enterprises. Wang *et al.* [9] compared serval optimization tasks in the gas/oil pipeline industry and proposed the modern population-based optimization technique as a promising method.

Allwood *et al.* [10] studied the supplier selection mechanism in the supply chain, i.e., how to choose partners based on different factors in a particularly competitive environment. Xue *et al.* [11] introduced the multi-object negotiation and the goal principle in a multi-role system. Li [12] drew Agent theory into the construction industry management, trying to analyze the model and framework of Agent system. Xinpei *et al.* [13] studied the negotiation mechanism of general contracting construction projects in the supply chain, putting forward a preference feedback model and obtaining the corresponding decision model. Fan and Feng [14] used the idea of multi-agent to abstract and model for information sharing in the supply chain, analyzing the operations of the whole system. Xinghui and Taoyon [15] studied the inventory management model based on SCOR model and Agent theory and suggested a new mode of inventory management. Jinju and Jie [16] also used multi-agent approach based on the ZEUS simulation tool for supply chain modeling and provided relevant analysis on the results.

Thus, multi-agent systems have been widely used because they provide coordination mechanisms and support supply chain optimization. However, within the prefabricated component supply chain, information about every single component becomes important, so it is necessary to introduce a reliable information carrier, such as RFID.

B. RFID USAGE IN PREFABRICATED ASSEMBLY LOGISTICS MANAGEMENT

RFID technology facilitates non-contact full duplex data communication through the radio frequency mode to realize the automatic recognition of the object. It has the advantages of waterproof, antimagnetic, high-temperature resistance, long service life, far reading distance, data encryption, larger data storage capacity and stored information free altering etc [17]. RFID can record data which increases the security and adaptability of the system and data, so as to achieve the purpose of flexible production and high precision production [18].

RFID applied in the production and logistics management has been quite mature and has huge potential for application in prefabricated components. RFID is a very efficient data acquisition technology, saving labor costs, accelerating the information technology and electronization in the logistics process. There are other advantages [19]: 1) RFID tag contains much information such as the volume of goods, weight, production date and batch number etc. Besides, the storage of information will not be lost because of using the passive tag. 2) High reliability and durability - there is no mechanical contact between the radio frequency card and the reader, so as to avoid the errors caused by the bad contact. Factors such as dust, dirt oil or other dark external harsh environment don't affect the reading and writing of the card. 3) Serving the whole logistics supply chain: RFID is the only identification for the intermediate links from manufacturers who produce products, through manufacturing, transportation, warehousing, sorting, distribution, until the assembler, so it has become the shared common data in a variety of industries. 4) The variability and easy maintenance - the RFID information in the component can be updated according to the production and assembly schedule and may become the carrier of information in the future and it is easy to maintain.

The application of RFID in traditional production and logistics is relatively mature and is traditionally used for encoding and reading relevant product information. However, when it comes to dealing with practical management issues, the multi-agent based approach could be a good tool because of its powerful simulation and optimization ability.

C. ESTABLISHMENT OF PREFABRICATED COMPONENT INDUSTRY ALLIANCE

With features, such as customized, diversified, hard to transport, and long production cycle, as well as the lack of efficient channels to communicate among all participants, it is hard to achieve the industrial scale effect in prefabricated construction projects. The continued high cost of prefabricated components and the low efficiency of the supply chain impedes the industrialization of prefabricated construction industry [20]. The downstream of precast component supply also faces many new problems: 1) Component design stage: the lack of effective collaboration between designer and component suppliers, small batch components, and low mold reuse rate. 2) Component production stage: the difficult production planning, poor coordination between upstream and downstream, and no effective competition among component suppliers. 3) Component transportation stage: the components are large in size and heavy; so the unbalanced distribution of the component suppliers leads to high cost of storage and transportation. 4) Assembly and construction: the lack of professional contract management and on-site coordination of personnel makes it hard to achieve collaborative management, which leads to higher cost.

Countries all over the world are trying to improve the industry chain as well as the supply chain of prefabricated construction industry in order to promote industrialization, including the idea of establishing the precast industry alliance. The North American prefabricated construction industry has promoted to form alliances for 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 [21]. The British Government has attempted to use BIM Technology to promote change in the original supply chain of prefabricated construction industry, break down supply chain barriers, and facilitate the development of the market for prefabricated components [22]. Due to the problem of small market scale, low reuse rate of component mold, imbalanced of capability between upstream and downstream enterprises as well as among different regions, and the lack of efficient communication mechanism among the links, some Chinese enterprises started to explore the establishment of industrial alliance in order to achieve the effective allocation and application of components resources [23].

The research on prefabricated components supply chain is to apply ideas from supply chain management in the traditional manufacturing industry to the construction industry, along the lines of applying the same mode of production in manufacturing to the construction industry [24]. However, compared with manufacturing, the supply chain of prefabricated components has significant differences such as professionalism, complexity, dynamics and risk. Especially, with the rapid growth in prefabricated construction in China, a complex supply chain network of industrial clusters have been created, including the single kernel cluster supply chain as well as the multi-kernel cluster supply chain [21].

The research focuses on developing mechanisms to improve competition and cooperation in the supply chain of prefabricated components, and setting up reasonable industry alliances, which can have a positive impact on the whole industry.

III. PROPOSED RFID AND MULTI-AGENT-BASED INFORMATION INTEGRATION

Agent is an entity in the objective world with the characteristics of autonomy, distribution and coordination. Functionally, they have a certain organizational, learning, and reasoning ability; so they are suitable for use in large and complex systems. The main processes in the prefabricated construction supply chain include the design phase, component manufacture phase, logistics management phase, and site construction phase. This paper mainly focuses on the component manufacturing and logistics management phases in the prefabricated construction supply chain.

A. MULTI-AGENT ARCHITECTURE FOR MANUFACTURING AND LOGISTICS SYSTEM

In this paper, a multi-agent system with RFID is used to manage the automation and adaptability of the distributed prefabricated construction supply chain. A two layered agent based system (shown in Fig. 1) is introduced for coordinating the activities between various entities in the supply chain as well as sharing and integrating relevant information. These two layers are briefly described below.

- Plan Agent Layer. The Plan Agent is a high-level agent that is responsible for obtaining information about the state of each component from the BIM system, and create a master plan for the processes of each project. It can get information from all the underlying agents, as well as allocate and plan tasks according to the information and the task requirements from the BIM system. It assists in the main task of the production process, namely, the assignment of operators and the order of arrangement. Because its main tasks are to plan and arrange operators and set the orders, it is called the Plan Agent.

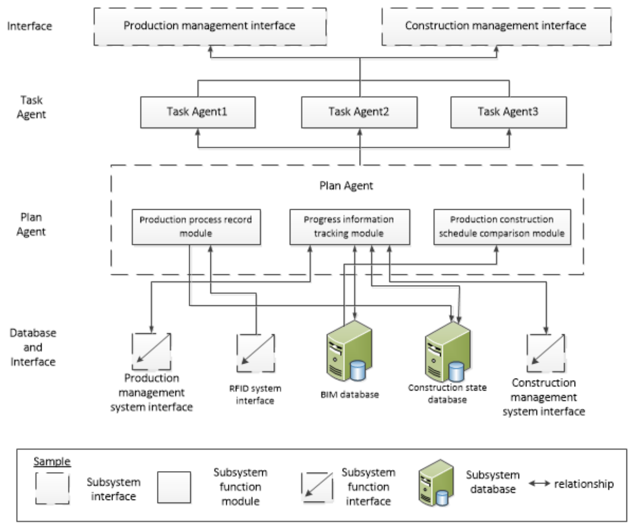

FIGURE 1. Multi-Agent supply chain information integration architecture.

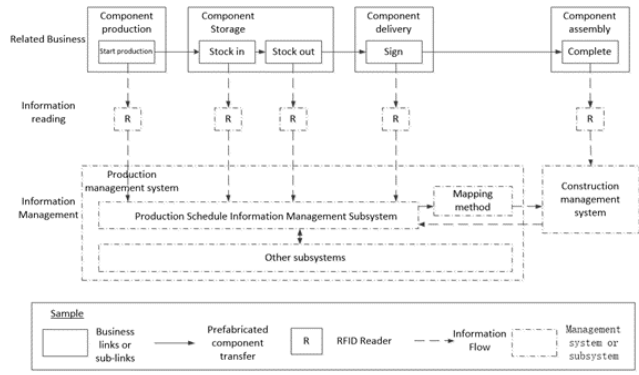

FIGURE 2. Information tracking mechanism using RFID.

The Plan Agent is responsible for allocating tasks according to the priority and capability. It reads the information, such as component type and delivery time, contained in the RFID tag, and allocates resources based on this information and current pipeline status in order to achieve optimal resource utilization and maximum production efficiency.

- Task Agent Layer. The second layer in the Multi-Agent system is the set of Task Agents. They represent each of the components arranged by Plan Agent and interact with agencies in each phase of the supply chain until the assembly is completed. It represents a task in the supply chain, and hence called the Task Agent.

The Task Agent is in charge of accurate control of each component. It reads the RFID information at each supply chain phase, exchanges data with the backend database, and sends orders.

B. THE ROLE OF RFID DATA IN MULTI-AGENT SYSTEM

The main use of the RFID data is for coordinating and allocating resources according to different priorities and supply capacity. Besides the basic information of the component, the RFID also includes geographic location, assembly location, planning time, delay time, transportation vehicles and other information. The Plan Agent will allocate the resources according to these data and current supply chain situation in order to achieve optimal resource allocation and higher efficiency of the supply chain.

The RFID data is also used for accurate control of the tasks. The Task Agents will read the RFID information and determine how best to execute the task based on that information. They also get exact meta-data from the backstage BIM database to allocate tasks, in order to achieve accurate and flexible task allocation and execution.

Thus, the two layers of agents in the proposed multi-agent architecture have different functions, containing different automatic and dynamic capabilities. They communicate and collaborate with each other to make the whole system work properly.

C. RFID AND MULTI-AGENT-BASED INFORMATION INTEGRATION ARCHITECTURE

The underlying data including RFID information will be sorted, processed and allocated through the two layers of agents. The component's manufacturing, and transportation information, as well as its assembling plan will be sent to production management personnel and construction management personnel. As shown in Fig. 1, the main modules of the Plan Agent include the production process record module, the progress information tracking module and the production construction schedule comparison module. The progress information tracking module is mainly responsible for mapping the relationship and show the manufacture, transportation and assembly process information in the form of an Excel spreadsheet or a BIM model. The production schedule comparison module is mainly responsible for analyzing the progress data gathered by the progress information tracking module, so as to support users' decision making.

In this proposed agent-based system, when the design is completed, the construction size, location, time and other data will be stored in the BIM plan model, and will be written into RFID chips during manufacturing. Since the information in the production process are constantly updated, the demand could be forecasted accurately and orders could be sent in advance, thus making the pull manufacturing possible.

D. INFORMATION TRACKING AND INTEGRATION IN BIM

1) TRACKING MECHANISM USING RFID

Based on the system discussed above, we have developed a precast production and assembly process integration tracking mechanism, as shown in Fig. 2. This mechanism focuses on three main aspects: business process, information gathering and information management.

For the purpose of coordinating the construction schedule, this mechanism tracks only the main business situations, without tracking too much of the business details.

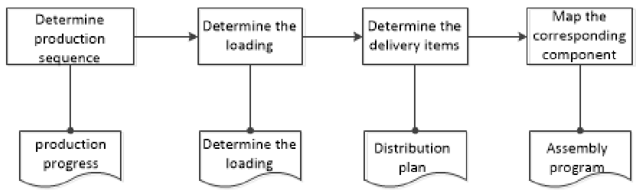

FIGURE 3. Mapping process of prefabricated components.

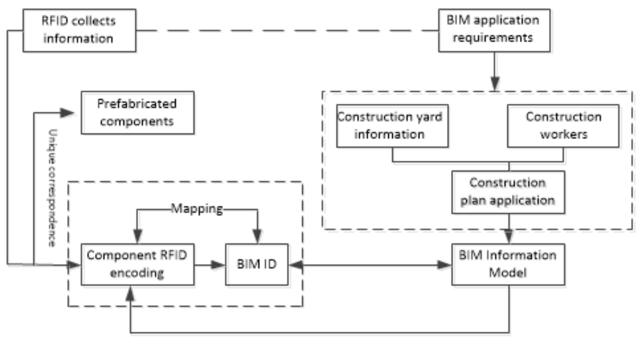

FIGURE 4. Information transfer in the system.

In addition, the tracking mechanism takes into account the movement of goods between two adjacent businesses, so the data could be recorded at following nodes: the start of production, component library, when the component is in storage, when the component is out of the library, when the component is delivered and the assembly is completed. Accordingly, the states include unmanufactured, manufacturing, storage, transportation, waiting for assembly and completed.

E. RFID CODING AND BIM INFORMATION MAPPING

With respect to the components under manufacturing, the flow for finding the corresponding component entities in the BIM model is shown in Fig. 3. Firstly, according to the current production schedule, the order for manufacturing specific components could be confirmed. Secondly, since the first delivery needs to load first, and combining with the loading plan, the specific vehicle for each component could be determined.

Then, according to the distribution plan of each vehicle, the transportation plan could be determined. And finally, according to the on-site assembly plan, the specific location of each component cloud be determined in the BIM model. Its Implementation process is shown as Fig. 4.

Through the mapping of RFID coding and BIM information, the foundation for information sharing and communication is formed. The RFID code is in correspondence with the component entity and the operation process and forms the information exchange with BIM component. This opens up the interaction between the entity information and the design information.

Thus, the dynamic information collected by the RFID system can be connected with the components in the BIM model. At the same time, BIM model can import many applications such as the construction schedule, through the RFID system scanning to achieve the corresponding plans to specific components.

In summary, our proposed RFID-based multi-agent architecture realizes the information transparency and sharing in all phases of the prefabricated assembly supply chain. Moreover, the manufacturing and assembly schedule and planning information can be acquired and updated in real time, which makes the pull manufacturing of the supply chain possible.

IV. CASE STUDY

In section three, our proposed RFID and multi-agent based architecture was introduced to realize the pull manufacturing. However, to realize the low inventory and minimal delay for the assembler, the supplier's productivity problem should be solved. To that end, the prefabricated component supplier industry alliance is proposed to solve the problem of insufficient production capacity. In this section, the industry alliance of prefabricated component suppliers is established based on the example of Shanghai rail tunnel construction. The influence of this industry alliance on the total cost of the supply chain is investigated to propose an optimal management method.

A. EMPIRICAL STUDY

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 undertaken 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.

B. EXPERIMENTAL PREPARATION

1) SIMULATION CONDITIONS AND ASSUMPTIONS

The case study uses Anylogic as the modeling and simulation tool, and in order to simplify the analysis of the model to a certain extent and to reduce the interference factors, the following assumptions are made to reduce the complexity of the model:

1. Assuming that the assembler only needs to be responsible for the tunnel construction project, there is no problem of path and location, and each component manufacturer has its own warehouse.

2. It is assumed that the supply capacity of the component factories in the industry alliance is strong enough to meet the output that the original component plant is unable to meet.

3. It is assumed that each component, once completed, will be shipped to the assembly site and start assembly, so the cost of warehousing at the component plant and assembly site is not included.

4. It is also assumed that if the project is delayed for lack of stock in assembly center, the component factory needs to pay the corresponding postponement costs.

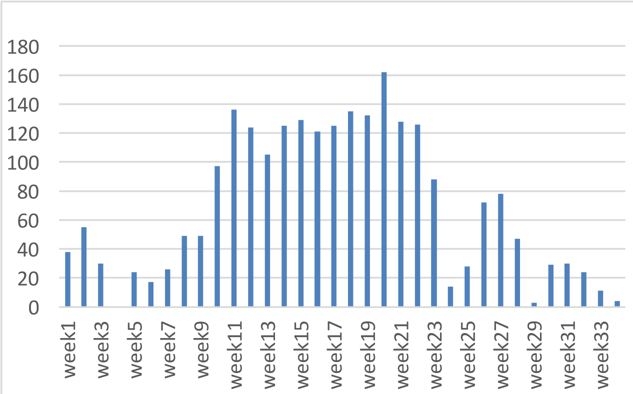

FIGURE 5. Demand of segements per week.

TABLE 1. Experimental parameters.

parameter	Supplier 1	Supplier 2
Manufacture speed	10	25
Manufacture cost per	100	10*R
Transportation cost per	100	10*R
Postponement cost per unit per day	500	

5. The tunnel project is a state-managed project, so it seeks the minimum cost among the whole industry chain, which is the sum of the cost of production, transportation and postponement cost.

2) 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. As an example, the demand for tunnel segments per week is shown as Fig. 5.

The demand of tunnel segments basically shows a normal distribution, which meets the features 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.

3) SETTING PARAMETERS FOR THE EXPERIMENT

The project has one original component factory and one alliance component factory, and one assembler. The simulation cycle of the model design is 34 weeks. The unit cost of each Agent will not change during the simulation process. The experiment only analyzes the influence on the total cost and postponement cost.

4) SIMULATION PROCESS

This section describes how the simulation is conducted and how the cost is calculated. The simulation interface is shown in Fig. 6. The user can change the maximum delay time and the price, and see the total cost as well as postponement cost directly.

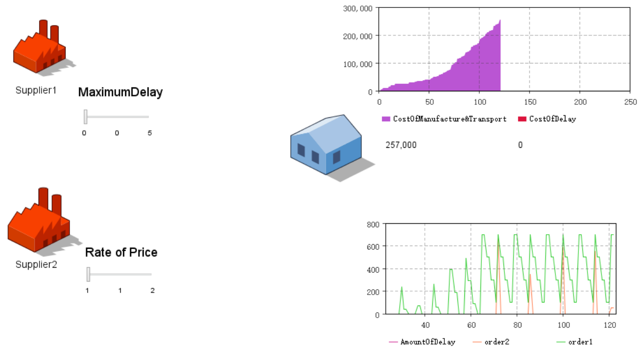

FIGURE 6. Simulation interface.

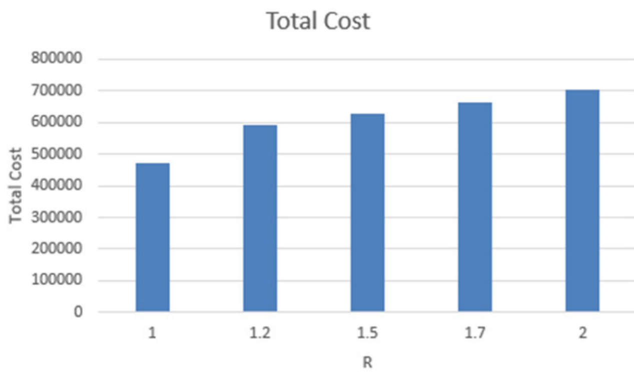

FIGURE 7. Realtionship between Total cost and R.

Supplier 1 is the original component factory, and Supplier 2 is the alliance component factory. Through the simulation, the order quantity and the costs can be obtained intuitively.

Firstly, when the order comes in, the system will calculate whether the original components factory is able to complete the order on time, if not, the rest of the order will be sent to the alliance component factory, and their manufacturing cost and transportation cost will be calculated every day, respectively. Furthermore, the assembler will also calculate every day the delay cost by comparing when the components should be completed and when they are actually completed. Finally, these costs will be summed up and support the decision-making process.

C. SIMULATION AND ANALYSIS

First, the scenario without an alliance supplier is simulated; all orders are completed by the original component factory. The original component factory is unable to meet all the needs, resulting in a large number of delays. In this situation, the cost of production and transportation is computed to be RMB 472,200, the postponement cost is as high as RMB 353,500, and the total cost is RMB 825650.

In the second scenario, the alliance is introduced. The variable R is the ratio of the alliance factory's manufacturing and transportation cost per unit compared to the original factory. Fig.7 shows the relationship between R and total cost.

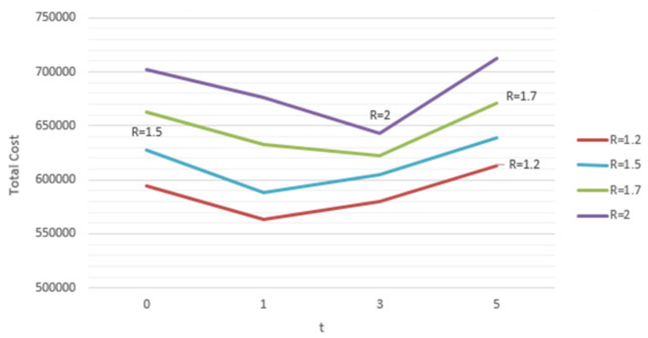

FIGURE 8. Realtionship between total cost and t.

It is obvious that the total cost in the supply chain can be effectively reduced when the alliance mechanism is introduced.

Based on this result, in order to further optimize the total cost of the supply chain, variable maximum delay time of t days is introduced. T represents the maximum number of days that can be delayed in the case of alliance. This variable will affect the order allocation and postponement between the original factory and the alliance factory, which in turn affects the total cost. The experiment will examine the relationship between the allowable extension time and the total cost when the price ratio R is determined. The results are shown in Fig.8.

It can be seen that, in the case of R=1.2 and R=1.5, the total cost comes to the minimum when t=1; and in the case of R=1.7 and R=2.0, the total cost comes to the minimum when t=3. That is because, when the cost of the alliance factory is too high, the appropriate increase of delay time could reduce the order size for the alliance factory, and achieve the optimization of total cost. However, when the delay time is too long, it will lead to rapid growth in postponement costs, resulting in a higher total cost.

D. CASE STUDY SUMMARY

The use of Anylogic simulation platform based on the multi-agent architecture could simulate the complex supply chain accurately. Based on the experiments conducted, we can draw the following conclusions:

1. When there is industry alliance, the total cost of the supply chain will be significantly reduced; the incorporation of industrial alliance is valuable.

2. When the price of alliance factory is determined, a maximum delay time t can be found to optimize the total cost of the supply chain, indicating that there is still room for further optimization in the supply chain.

3. Without considering the supply capacity of the alliance factory, the cost should be as low as possible.

V. CONCLUSION

In order to alleviate the increasing travel and housing pressure, China is promoting the construction industry to become more green and efficient. Optimization of the supply chain meets the industry's consistent interests. However, the prefabricated assembly building is still in the initial stages in China. A mature and standardized system is yet to be formed, and there is a lack of related research, technology and management in this domain. This paper uses RFID as a carrier of information and a multi-agent system to interact with the information, and has provided a new supply chain coordination model. It has also proposed the use of a new industry alliance to deal with the problem of insufficient capacity. The paper has focused on the theoretical aspects of the RFID and multi-agent based architecture for information sharing and coordination within the prefabricated component supply chain and the industrialized construction industry. Our future work will focus on algorithm logic and improve the model and the system to get better optimization results.

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