Paper:

Automatic Construction of Virtual Supply Chain as Multi-Agent System Using Enterprise E-Catalogues

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In Industry 4.0, a network of enterprises and factories is constructed collaboratively and dynamically according to the cyber physical system (CPS) paradigm. It is necessary to build smart supply chains according to this concept. A network of component enterprises in a supply chain would be modeled as a virtual supply chain in the cyber world. From the viewpoint of Industry 4.0, virtualizing a supply chain is the foundation for constructing a CPS for a supply chain. The virtualization of a supply chain makes it easier for companies to study their integrating and expanding opportunities. By using this CPS, comprehensive and autonomous optimization of the supply chain can be achieved. This virtual supply chain can be used to simulate the planning phase with negotiation, as well as the production phase. In this paper, instead of specific mathematical modeling for each supply chain, a general configuration method of a virtual supply chain is proposed. The configuration method of a supply chain model is proposed as a virtual supply chain using enterprise e-catalogues. A virtual supply chain is constructed as a multi-agent system, which is connections of software agents that are automatically created from each selected enterprise model in the e-catalogues. Three types of component enterprise models are provided: manufacturer model, part/material supplier model, and retailer model. Modeling templates for these three types of enterprises are prepared, and each template is a nominal model in terms of enterprise's behavior. Specific component-enterprise models are prepared by filling the appropriate template. Each component enterprise agent is implemented using the enterprise model selected from the catalogues. Manufacturer, retailer, and supplier e-catalogues, as well as an automatic construction system of a virtual supply chain, are implemented. Methods for developing templates for the manufacturer, retailer and supplier were provided, and the construction system for specific enterprise models (as e-catalogues) is implemented as a trial.

Keywords: smart manufacturing, supply chain, digital transformation, multi-agent simulation, enterprise agents

1. Introduction

Industry 4.0 is a network of collaborative and dynamic factories based on the cyber physical system (CPS) paradigm. Smart supply chains must be built according to this concept. In the cyber world, a network of component enterprises in a supply chain is modeled as a virtual supply chain. It is expected that supply-chain planning and control can be enhanced by applying simulation-based optimization to this virtual supply chain. For this, a general configuration method of a virtual supply chain is required instead of specific mathematical models for each supply chain.

Herein, a flexible and generally applicable modeling method for constructing a virtual supply chain is proposed. The objectives of this study are 1) to propose that a virtual supply chain can be constructed by connecting software agents that are automatically created from each selected enterprise model in the e-catalogue and 2) to provide methods for modeling an enterprise's behavior and cataloging them for the flexible construction of a virtual supply chain.

2. Related Works

Without an integrated information system, merging processes and activities of various enterprises in a supply chain is impossible. Information sharing is one of the vital components of supply chain management strategies [1]. The use of information models for supply chain management has been widely studied, leading to the development of new concepts such as the virtual supply chain [2], web-based supply chain [1], and virtual e-chain [3]. The concept and applications of virtual supply chains have been researched extensively. Having a belief in the importance of transparency in supply chain operations and collaboration, Gumasekaran and Ngai [4] studied the virtualization of companies' supply chains with regard to the strategies, methods, and technologies. They investigated the success factors for a virtual supply chain, e.g., strategic alliances, web-based information systems, automation for business process re-engineering, supply chain visibility, and a performance evaluation system. They proposed a framework and evaluated it via a case study for a company in Hong Kong, China. In [5], the virtual supply chain was examined from the viewpoint of systems and control to investigate the role of virtual integration in helping manufacturers achieve flexibility and cost reduction. Their findings indicated that although the supplier responsiveness significantly affects the manufacturer performance, which can be regarded as a threat because of environmental uncertainty, this threat can be turned into an opportunity by using a virtual supply chain and information technology.

The virtualization of supply chains makes it easier for companies to study opportunities for integrating and expanding the supply chains. Examining two possible collaboration and integration opportunities for two multinational textile enterprises by Wang and Chan [6], they explored the obstacles of these integrations in both upstream and downstream supply chains. Their analysis indicated that the virtual organization approach can be a mutual solution for both enterprises. After the integration, the responsiveness and flexibility of the supply chains are enhanced because of the information technology capabilities. Verdouw et al. [7] exploited the abilities of virtual supply chains for monitoring, planning, and optimizing business processes remotely and online. They virtualized a fish supply chain from the Internet of Things (IoT) viewpoint to evaluate the expected benefits with the help of companies and industry experts. One of the important advantages of virtualizing the supply chain is the resulting agility for the business entities. This was addressed in [8], where a conceptual model was developed for investigating the role of the virtual supply chain in enhancing the agility of the supply chain system, and the agility level was empirically evaluated. The results of the empirical studies can help decision makers allocate resources according to the importance of the proposed factors.

The concept of object virtualization was studied in [9], and the capability of a virtual supply chain to provide an enhanced control model was demonstrated. Object virtualization is based on IoT and provides redesign options in supply chain planning and re-planning procedures, providing flexibility for investigating the effects of different decisions before applying them to the real system. The authors applied their control model to multiple case studies involving Dutch floriculture. In a recent study, Matsuda et al. [10] examined a virtual supply chain through a CPS. They divided the supply chain into three component enterprises: manufacturer, retailer, and supplier. They investigated the virtualization from the viewpoint of the manufacturer and developed an enterprise model by integrating a data model and a mathematical model. In [11], environmental concerns were considered in a virtual factory which was called a digital eco-factory. The digital eco-factory reflects the real factory; the machines and parts are simulated as agents, and the amount of CO_2 emissions and energy consumption of each machine can be calculated and monitored. To verify the accuracy of the developed system, the results were compared with a real production line output.

One of the main research streams in the field of virtual supply chains involves multi-agent and agent-based systems, which attract considerable attention from many researchers. The supply chain performance can be significantly enhanced by exploiting the autonomous support provided by a multi-agent system approach [12]. Because the supply chain consists of many entities, the operations planning and management and communications among these entities are complex tasks. Thus, a framework for negotiation into a software agent design that allows negotiating agents to join, stay, or leave the system freely was introduced [13]. Choy and Lee [14] studied a virtual enterprise using the multi-agent system technique with the aim of managing the entire order fulfillment process and customer service. They reported that their proposed architectures had the following advantages: the capability to identify the most qualified suppliers, facile information sharing, and the capability to develop better designs with the assistance of partners. The necessity of considering dynamic decision making in planning the supply chain was studied in [15], and a methodological and technical basis for supply chain analysis, modeling, structuring, and scheduling using a multi-agent approach was provided. The analysis, which involved comparing the object and agent oriented approaches, confirmed the superiority of the latter because they allow activities and competition among agents. Ahn and Park [16] studied the information sharing among agents with regard to inventory and demand on a local scale because of the complexity and difficulty of information sharing among all the members of the supply chain. They modeled the proposed framework using a multi-agent system and evaluated the performance of the model via simulation. Additionally, the results of the simulation experiment were compared with the results of an alternative method. In contrast to [16], because the globalization of the production system causes the supply chains' agents to be spread widely worldwide, researchers have attempted to analyze and optimize the overall supply chain as a single system. The long distance between the entities may affect the lead time, leading to fluctuations in product demand. To overcome this type of risk and provide a supporting system for the overall optimization of the supply chain, a new model using big time series data was proposed in [17]. A multi-agent simulation approach was employed to implement and validate the proposed system.

The impact of the trustworthiness of the suppliers for fulfilling the orders and on-time delivery was investigated in [18] using a swarm multi-agent simulation. The performance of such a supply chain in different scenarios was evaluated, and a sensitivity analysis was conducted. The results confirmed that integrating the factor of the trustworthiness of suppliers into the supplier selection process can reduce the average cycle time and can increase the on-time order fulfillment rate. Focusing on the internet based computing and communication in business process fulfillment and the uncertainty and dynamics of real world situations, Wang et al. [19] proposed a multi-agent framework for supply chain coordination and cooperation. The developed distributed multi-agent system can organize itself, and individual agents can explore their own decisions, coordinate with other agents, and evolve toward a global solution state.

Wang et al. [20] investigated the negotiation models in the multi-agent virtual supply chain to simulate the buying/selling behaviors of the simulation agents. Agents can guess the costs of their rivals, determine the relationship between the inputs and the costs using machine learning, and update the estimated costs each time new inputs are received. Additionally, game theory has assisted multi-agent simulations of the supply chain, as it can be used to identify the dominant players who can retain profit stability when prices decrease. Identifying the dominant player among the four studied players (raw material supplier, component supplier, manufacturer, and retailer) helps to determine the leader of the game, which is beneficial for the decision making process in the supply chain [21]. Long [22] reported that the previously reported computational models were inefficient owing to the lack of a methodological framework. He studied agent based virtual supply chain network modeling based on the materials, information, and time flow aspects from a methodological viewpoint rather than an application viewpoint. The framework developed by Long was confirmed to be feasible and correct via computational experiments and is useful for the creation of virtual supply chains, computational experiment modeling, and implementation. Moreover, Long identified research gaps in the field, such as the modeling of the material flow, the development of a time synchronization mechanism for the time flow, and application related studies to test and improve the frameworks. The importance and requirements of the virtual supply chain are discussed in further detail in the next section.

3. Virtualization of Supply Chain

3.1. Role of Virtual Supply Chain

The introduction of the term “supply chain management” by Keith Oliver in 1982 (Stock [23]) marked the beginning of a new era for process management. The enterprises involved in each supply chain do not conduct their processes in isolation. Instead, they cooperate for the realization of a larger system, i.e., the whole supply chain. In supply chain management, information sharing is vital, and total optimization is achieved by adopting an integrated supply chain model from the perspective of the whole system. The various participants in each supply chain, such as suppliers, manufacturers, retailers, and logistics companies, together with the effects of globalization, make local adjustment of each functional unit and reconfiguration of the whole system difficult. This is illustrated in **Fig. 1**: after the total optimization of the supply chain, to improve the efficiency and coordination of the enterprises involved, autonomous optimization must be performed at each functional unit by considering the whole supply chain and exploiting the flexible and dynamic configuration of the supply chain, which is the goal of Industry 4.0.

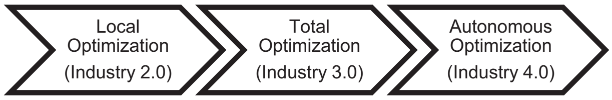

Fig. 1. Proceeding from local optimization to autonomous optimization.

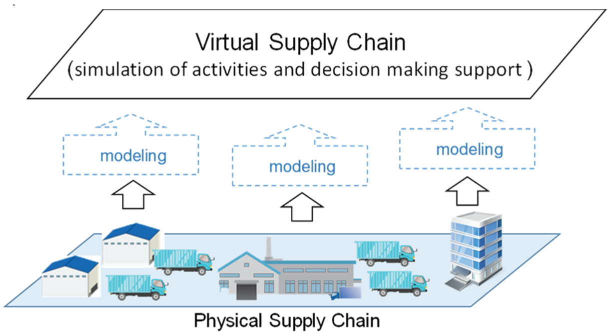

Fig. 2. Virtual and physical supply chains.

To fulfill the autonomous optimization, it is necessary to define and construct the virtual supply chain as the cybernetic counterpart of the physical supply chain, as shown in **Fig. 2**. The integrated information sharing flow achieved by the virtual supply chain involves gathering, organizing, selecting, and synthesizing data, followed by distributing the data (Bajgoric [24]), which allows the enterprises to conduct value added activities more efficiently and effectively. Furthermore, the virtual supply chain allows the activities and behaviors of the enterprises to be simulated. The results of the simulation process can be used as an output forecast and a decision making support tool for management of the physical supply chain.

3.2. Requirements for Virtual Supply Chain

Similar to the structure of a physical supply chain, the virtual supply chain is a constitution of different enterprises. The activities of the enterprises are modeled as the retailer model, customer model, manufacturer model, supplier model, and transporter model in the network structure of the virtual supply chain. To fulfill this requirement, each component enterprise model is implemented as a software agent, because an enterprise should be modeled including its dynamic behaviors in the supply chain. A virtual supply chain is modeled as a balancing type multi-agent system. In this type of multi-agent system, there are communications and negotiations among

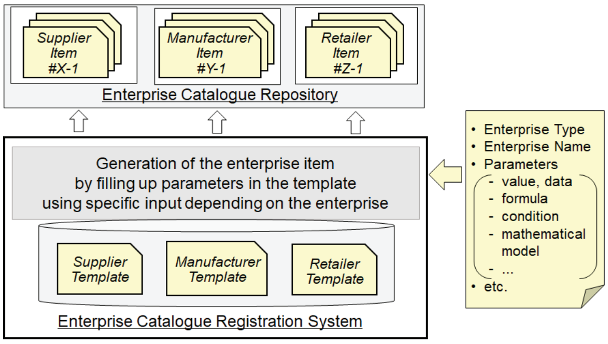

Fig. 3. Structure of an enterprise-catalogue registration system.

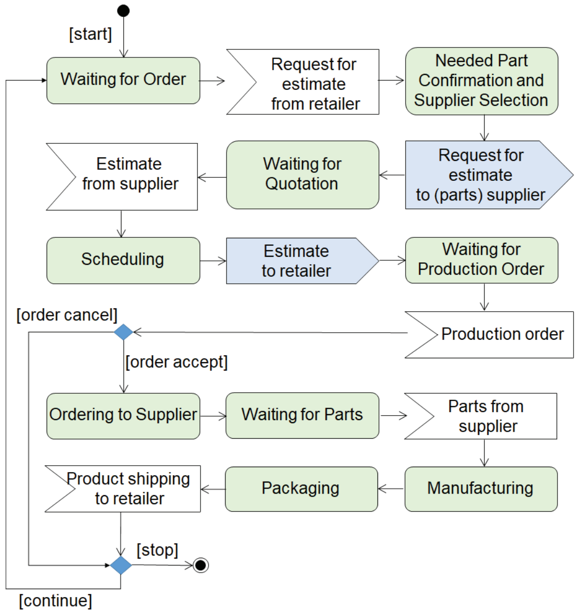

Fig. 4. Manufacturer behavior model.

the component enterprise agents to optimize the performance of the supply chain by balancing profits among the component enterprises. Through the simulation on a multi-agent virtual supply chain, it is possible to achieve autonomous and optimized cooperation among component enterprises in the supply chain.

Each component enterprise agent can be generated from the description of the corresponding component enterprise model. If the descriptions of the enterprise model are standardized and cataloged, a virtual supply chain can be constructed by selecting enterprise models from the e-catalogues. The component enterprises and configurations for a virtual supply chain can be easily changed using the generated enterprise catalogues. Furthermore, adding a new enterprise would be easy too while this is not easy in the physical supply chain. Additionally, the enterprise model can be shared among systems. The enterprise catalogue has various users, e.g., users who review a behavior pattern for determining the most beneficial action for an enterprise, users who conduct public recruitment of a trading partner, and users who search for better trading partners. In the next section, the e-catalogue creation process for each component enterprise is described in detail.

4. E-Catalogues of Component Enterprises

4.1. Preparation of Enterprise Catalogues

To construct a virtual supply chain, each component enterprise should be modeled and cataloged. The enterprise catalogue is a group of a template and its related items. A template is a schema representing a model for each enterprise type including the enterprise behavior. Each template is implemented using a data description language. An item is an instance of a template in which the parameters are filled with values, data, formulas, conditions, etc. An item is a model of a specific enterprise including its behavior. The template and its related items are registered in an open access repository.

The structure of an enterprise catalogue registration system is shown in **Fig. 3**. A manufacturer template, a supplier template, and a retailer template are prepared. Three templates are described by XML. An enterprise item, which is a concrete model of a specific enterprise, is automatically generated by filling parameters in the corresponding template with input values, data, formulas, conditions, etc. The following sections describe the preparation of the enterprise templates for manufacturer, supplier, and retailer.

4.2. Modeling Manufacturing Enterprise

The function of a manufacturing enterprise is a manufacturer of products. The behavior of the manufacturer is modeled as an activity flow, as shown in **Fig. 4**. The activity state is changed to the other state by input from the retailer/supplier or an output to the supplier/retailer. There is an adjustment phase before manufacturing and a production phase after acceptance of a production order from the retailer. In the adjustment phase, the manufacturer designs the supply network of parts by selecting part suppliers, planning and estimating factors such as the cost and delivery date. In the production phase, the manufacturer produces, packages, and ships the product. These activity states are executed in sequence.

Table 1 presents the parameters, which are used to describe a manufacturer behavior model. Parameters are included in activity descriptions of the behavior part of the template. These parameters affect the manufactures' behaviors. The parameters in **Table 2** are about manufacturing product data that are presented in the property part of the template. These parameters in **Table 2** are referred to in activity descriptions of the behavior part. Concrete values for parameters are provided when the manufacturer item is created from the template, as a fixed values, formulas including variables, or conditions with variables. Variables are provided by property parameters and supply chain configuration data when the virtual supply chain is constructed. Furthermore, they are provided by order data, product configuration data and simulation results,

Table 1. Manufacturer template.

Manufacturer Template		
Parameter Name	Type	Example
Manufacturer ID		
Manufacturer Name	String	
Manufacturer Address	String	
Produced Products	List	
Production Quantity (PQ_M)	Formula	$OQ_R - psq_M$
Required Quantity of Parts(RPQ_M)	Formula	$N_P\ PQ_M$
Opportunity Loss (OL_M)	Formula	$OQ_R - isq_M - PQ_M$
Production Cost (PDC_M)	Formula	$pcp_M\ PQ_M$
Stock Cost (SC_M)	Formula	$sc_M\ psq_M$
Opportunity Loss Cost (OLC_M)	Formula	$l_M\ OL_M$
Checking Cost (CC_M)	Formula	$cc_M\ \sum RPQ_M$
Packaging Cost (CC_M)	Formula	$pc_M\ (PQ_M + psq_M)$
Total Cost (TC_M)	Formula	$\sum TC_S + suc_M + IC_M + PDC_M + SC_M + OLC_M + CC_M + PC_M$
Production Time (PDT_M)	Formula	$PQ_M\ ptp_M$
Checking Time (CT_M)	Formula	$ct_M\ \sum RPQ_M$
Packaging Time (PT_M)	Formula	$pt_M\ (PQ_M + psq_M\ )$
Total Production Time (TPT_M)	Formula	$\max\ (TPT_S) + sut_M + IT_M + PDT_M + CT_M + PT_M$
Inspection Time (IT_M)	Formula	$PQ_M\ it_M$
Inspection Cost (IC_M)	Formula	$PQ_M\ ic_M$

Table 2. Manufacturing product data.

Manufacturing product Data (Parameter Name)	
Manufacturer	Penalty for Lost Opportunity (l_M)
Produced Product	Inspection Time (it_M)
Production Cost per Piece (pcp_M)	Packaging Time per piece (pt_M)
Production Time per Piece (ptp_M)	Inspection Cost (ic_M)
Setup Cost (suc_M)	Packaging Cost (pc_M)
Setup Time (sut_M)	Number of Component Parts Types (ncp_M)
Inventory Cost per Piece (sc_M)	Maximum Production Capacity (mpc_M)
Provided Stock Quantity (psq_M)	Checking Cost (cc_M)
Initial Stock Quantity (isq_M)	Checking Time (ct_M)

when the simulation is executed. For example, in **Table 1**, the parameters: "Production Quantity" and "Opportunity Loss" refer to a value of OQ_R. OQ_R represents an order quantity whose value is provided by the retailer. Additionally, the retailer obtains the values of TC_M and TPT_M from the manufacturer. Here, the subscript "R" indicates that the value of OQ_R is provided by the retailer when a simulation is executed on the generated virtual supply chain. The subscript "M" indicates that values of TC_M and TPT_M are provided by the manufacturer.

The proposed manufacturer behavior model can be applied to various situations such as make-to-order and make-to-stock. For example, when the manufacturer adopts the make-to-order strategy, the inventory parameter is set at a low level or zero. When the manufacturer adopts the make-to-stock strategy, the inventory parameter is an equation that is kept at an appropriate level based on forecasts and historical data.

The general manufacturer behavior model is provided as the template implemented using XML. **Fig. 5** shows a part of the XML manufacturer template. There are property descriptions and activity descriptions. In the activity descriptions, the activity flow is described as state descriptions including parameters and as relation descriptions among states.

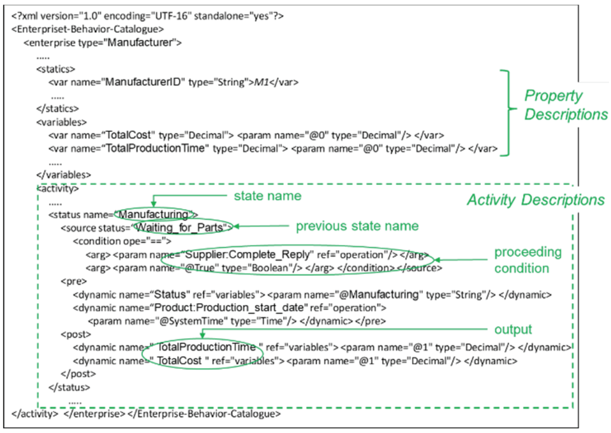

Fig. 5. Part of the XML manufacturer template.

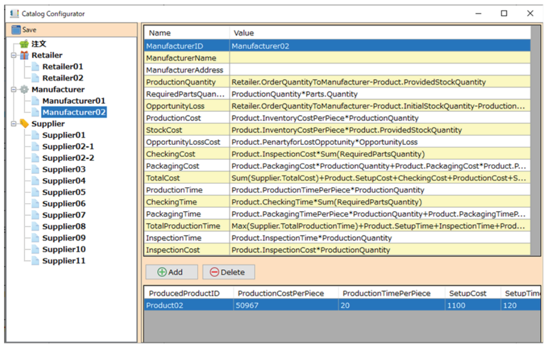

Fig. 6. Example display for making the manufacturer item.

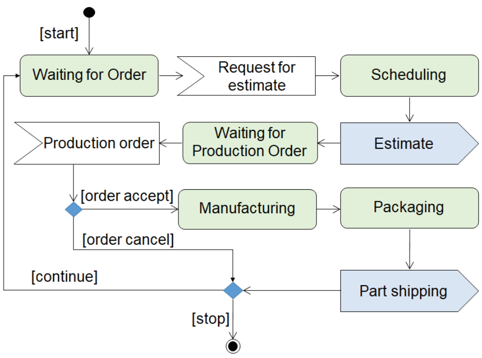

Fig. 7. Part sourcing enterprise model.

Each manufacturer item is created by filling the template with concrete values. **Fig. 6** shows the display for generating the manufacturer item using the enterprise-catalogue registration system.

4.3. Modeling Part Sourcing Enterprise

The function of a parts sourcing enterprise is a supplier of parts and/or material. The behavior of the supplier is modeled as an activity flow, as shown in **Fig. 7**. There is

Table 3. Supplier template.

Supplier Template		
Parameter Name	Type	Example
Supplier ID		
Supplier Name	String	
Supplier Address	String	
Handled Parts	List	
Total Ordering Cost (TOC_S)	Formula	$oc_S\ OT_S$
Number of Parts Produced (NP_S)	Formula	$PT_S\ lot_S$
Total Production Cost (TPC_S)	Formula	$pcp_S\ NP_S$
Total Inventory Cost (TIC_S)	Formula	$(NP_S\ lot_S + is_S - RPQ_M)\ sc_S$
Total Cost (TC_S)	Formula	$TOC_S + TSC_S + TPC_S + TIC_S + ic_S\ PT_S + pc_S\ RPQ_M + TMIC_S + cc_S\ OT_S$
Ordering Times (OT_S)	Formula	$(PT_S - is_S)/moq_S$
Total Production Time (TPT_S)	Formula	$PT_S\ ptl_S + TST_S + it_S\ PT_S + pt_S\ RPQ_M + ct_S\ OT_S$
Production Times (PT_S)	Formula	$(RPQ_M - is_S)/lot_S$
Total Material Inventory Cost ($TMIC_S$)	Formula	$(imi_S + OT_S\ moq_S - PT_S)\ msc_S$
Total Setup Cost (TSC_S)	Formula	$PT_S\ suc_S$
Total Setup Time (TST_S)	Formula	$PT_S\ sut_S$
Total Material Cost (TMC_S)	Formula	$PT_S\ mc_S$

Table 4. Supplied parts data.

Supplied Parts Data (Parameter Name)	
Supplied Parts	Packaging Time (pt_S)
Parts Cost per Piece (pcp_S)	Setup Cost (suc_S)
Lot Size (lot_S)	Setup Time (sut_S)
Production Time per Lot (ptl_S)	Material Ordering Quantity (moq_S)
Ordering Cost per Lot (oc_S)	Initial Material Inventory (imi_S)
Inventory Cost (sc_S)	Material Stock Cost (msc_S)
Initial Inventory (is_S)	Material Cost (mc_S)
Inspection Cost (ic_S)	Checking Cost (cc_S)
Packaging Cost (pc_S)	Checking Time (ct_S)
Inspection Time (it_S)	

an adjustment phase before manufacturing and a production phase after acceptance of the production order from the manufacturer. In the adjustment phase, the supplier performs scheduling and estimates factors such as the cost and delivery date. An activity state is changed by an input from the manufacturer or an output to the manufacturer. In the production phase, the supplier produces packages and ships parts.

Table 3 shows the parameters, which are used to describe a supplier behavior model. Parameters in **Table 4** are about supplied parts data.

4.4. Modeling Sales Enterprise

The function of a sales enterprise is a retailer of goods. The behavior of the retailer is modeled as an activity flow, as shown in **Fig. 8**. There is an adjustment phase before the production order and a product selling phase after the production order. In the adjustment phase, the retailer selects a manufacturer according to a customer's order, requests an estimate to the manufacturer, considerers the estimate (including estimated cost and delivery date), and places the production order. An activity state is changed by an input from the customer/manufacturer or an output to the manufacturer. In the product selling phase, the retailer checks and packages product, and delivers it to the customer.

Table 5 presents the parameters that are used to describe a supplier behavior model. The parameters in **Table 6** are about goods data treated by retailer.

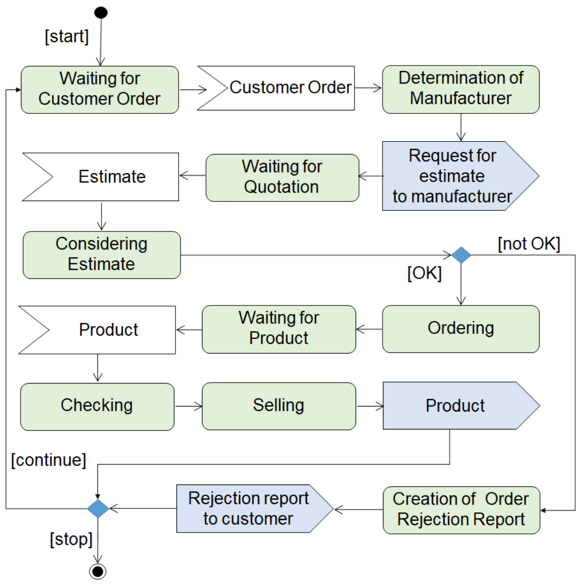

Fig. 8. Sales enterprise model.

Table 5. Retailer template.

Retailer Template		
Parameter Name	Type	Example
Retailer ID		
Retailer Name	String	
Retailer Address	String	
Handled Goods	List	
Order Quantity to Manufacturer (OQ_R)	Formula	$lim_R + Q_O - sq_R$
Target Delivery Time from Manufacturer (TDT_R)	Formula	$ET_O - lt_R - OQ_R\ it_R - Q_O\ pt_R$
Purchase Price (W_R)	Formula	$w_R\ OQ_R$
Evaluation of Manufacturer Proposed Cost (EPC_R)	Condition	$TC_M \leq W_R$
Evaluation of Manufacturer Proposed Delivery Time (EPT_R)	Condition	$TPT_M \leq TDT_R$
Stock Cost (SC_R)	Formula	$sc_R\ sq_R$
Opportunity Loss (OL_R)	Formula	$Q_O - sq_R - OQ_R$
Opportunity Loss Cost (OLC_R)	Formula	$OL_R\ l_R$
Total Cost (TO_R)	Formula	$oc_R + TC_M + SC_R + OLC_R + ic_R\ OQ_R + pc_R\ Q_O$
Total Delivery Time (TDT_R)	Formula	$TPT_M + lt_R + it_R\ OQ_R + pt_R\ Q_O$

Table 6. Goods data treated by retailer.

Goods Data (Parameter Name)	
Retailer	Penalty for Lost Opportunity (l_R)
Handled Goods	Inspection Time (it_R)
Purchase Price per Piece (w_R)	Packaging Time (pt_R)
Ordering Cost (oc_R)	Inspection Cost (ic_R)
Ordering Lead Time (lt_R)	Packaging Cost (pc_R)
Stock Quantity (sq_R)	Inventory lower Limit (lim_R)
Stock Cost per Piece (sc_R)	

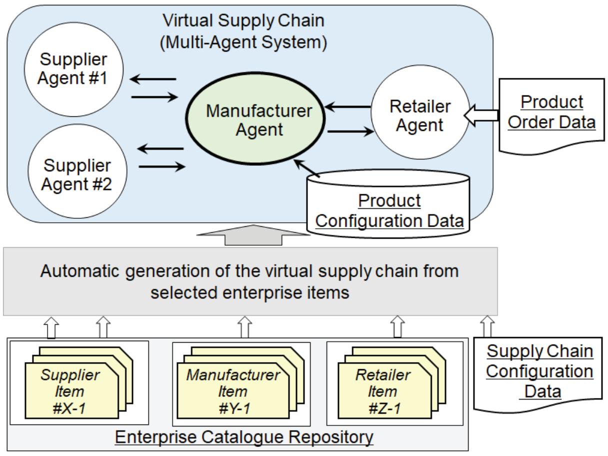

Fig. 9. Construction of a virtual supply chain using component enterprise catalogues.

Table 7. Goods order data.

Goods Order Data (Parameter Name)	
Order ID	Expected Delivery Time (ET_O)
Retailer ID	Ordering Date
Ordering Product ID	Expected Price per Piece (EP_O)
Ordered Quantity (Q_O)	

Table 8. Product configuration data.

Product Configuration Data			
Parameter	ID	Quantity (N_P)	Supplier ID
Product ID			
Component Parts #1		Fixed Value	
Component Parts #2		Fixed Value	
...	...	...	...

5. Automatic Construction of Virtual Supply Chain

5.1. Construction System for Virtual Supply Chain

Figure 9 shows a conceptual structure of the construction system for a virtual supply chain [10]. Supply chain configuration data is a list of component enterprise names. This data is used to configure a virtual supply chain. Goods order data (as shown in **Table 7**) and product configuration data (as shown in **Table 8**) are used for constructing a virtual supply chain and conducting simulation experiments. First, the system selects the component enterprise items, such as supplier items, retailer item, and manufacturer item from e-catalogues according to the supply chain configuration data. And the system automatically generates manufacturer agent, retailer agent, and supplier agents. All the agents exchange and share information with each other. Then, in the simulation execution stage, the retailer agent places a goods order to the manufacturer agent, the manufacturer agent orders parts to the supplier agents for producing the product according to the product configuration data, and the supplier agent

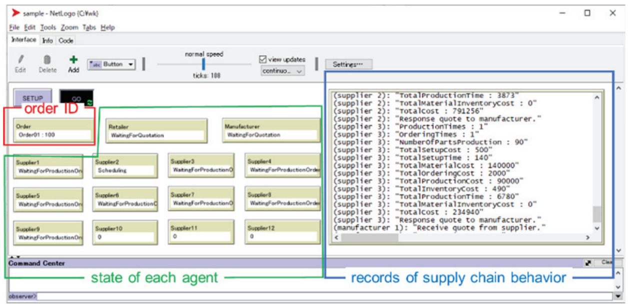

Fig. 10. Example display for executing a simulation.

prepares the parts and provides them to the manufacturer agent. Before the goods order is finalized, a process is conducted for the quotation of the product. Moreover, it is possible to conduct different simulation experiments by changing the data. Adjusting the data set, it may result in different supply chain structure and/or the component enterprises may have different behaviors.

5.2. Trial System for Construction of Virtual Supply Chain

The automatic construction system for a virtual supply chain was implemented to demonstrate its feasibility. This system, which is in the trial operation stage, generated virtual supply chains as outputs that were used for simulation. In this example implementation, the generated virtual supply chain was modeled as multi-agent system on NetLogo [25], which is a multi-agent programmable modeling environment. Agent programs of NetLogo are automatically generated using selected items from the enterprise e-catalogues according to the supply chain configuration data, by referring to the goods order data and product configuration data.

In the NetLogo program developed as a simulation system, the simulation process comprised two phases: the adjustment phase and production phase. In the adjustment phase, a retailer agent requests an order estimation from a manufacturer agent. The manufacturer agent generates a production plan and estimates the costs and delivery time. Then, the retailer agent decides whether to cooperate with the manufacturer. If the customers' demand can be fulfilled, the simulation proceeds to the next phase. In the production phase, a retailer agent places orders to the selected manufacturer. The manufacturer agent orders the parts from the supplier and produces the ordered goods. The supplier agent provides the necessary parts to the manufacturer. An example display for the execution of the simulation is shown in **Fig. 10**.

6. Conclusions

Methods for modeling an enterprise's behaviors and cataloging them for the flexible construction of a virtual supply chain were proposed. The enterprise catalogue consists of a template and its related items. A template is a schema representing a model for a particular enterprise type (including the enterprise behavior), and an item is an instance of a template in which the parameters are filled with values, data, formulas, conditions, etc. A trial implementation of enterprise e-catalogues described by XML for a retailer, a manufacturer, and suppliers was conducted.

Furthermore, using the enterprise e-catalogue, a methodology was developed for automatic construction of a virtual supply chain according to the CPS concept in Industry 4.0. A virtual supply chain was constructed as a cooperative network comprising supplier agents, a manufacturer agent, and a retailer agent. This network was implemented as a balancing type multi-agent system. These enterprise agents were automatically generated from each selected enterprise model, called an enterprise item from the above mentioned e-catalogues.

The effectiveness of the proposed methodology was demonstrated using the developed enterprise-catalogue registration system and the virtual supply chain configuration system. Using a virtual supply chain constructed via the proposed methodology, the behaviors of the different enterprises, the effects of these behaviors, and the total behavior of the supply chain can be simultaneously simulated. It becomes easier to add new agents to the system, to replace an agent, and to change the agent behavior and the network configuration. In addition, the virtual supply chain can be reconfigured dynamically.

In future studies, additional experiments should be performed for applying the proposed methods to practical cases. Moreover, details of technologies for installation of the negotiation process and autonomous optimization process in the generated virtual supply chain network should be determined. Other types of enterprise models, such as transporter and storage models, should be added to the e-catalogues. Furthermore, for using the proposed methodology as a shared technology, the standardization of enterprise e-catalogues should be proposed.

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