International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tprs20

A fractal perspective-based methodological framework for supply chain modelling and distributed simulation with multi-agent system

Hua Dai[ab], Jie Lin[a] & Qingqi Long[c]
[a] School of Economics and Management, Tongji University, Shanghai, China
[b] College of Computer Science, Hunan Institute of Science and Technology, Yueyang, China
[c] College of Information, Zhejiang University of Finance & Economics, Hangzhou, China
Published online: 21 May 2014.

International Journal of Production Research, 2014
Vol. 52, No. 22, 6819–6840, http://dx.doi.org/10.1080/00207543.2014.919414

A fractal perspective-based methodological framework for supply chain modelling and distributed simulation with multi-agent system

Hua Dai[a,b], Jie Lin[a*] and Qingqi Long[c]

[a]*School of Economics and Management, Tongji University, Shanghai, China;* [b]*College of Computer Science, Hunan Institute of Science and Technology, Yueyang, China;* [c]*College of Information, Zhejiang University of Finance & Economics, Hangzhou, China*

(*Received 19 October 2012; accepted 22 April 2014*)

With the development of global economy, supply chain, as a recognised complex system, is becoming more complex for analysis. In this context, it is worth introducing the perspective of complex system in perceiving and modelling of supply chain system to address its dynamic, stochastic and uncertain characteristics. Therefore, this paper proposes a methodological framework of supply chain modelling and simulation based on the fractal perspective, and presents an all-round and systematic exposition of concept modelling and distributed simulation by means of multi-agent technology. In this framework, different supply chain scenarios focusing on manufacturing, inventory and transportation can be easily modelled and simulated at different scales and levels. In addition, a prototype system which implements the methodological framework and the key implementation techniques are presented as well. Finally, a supply chain example, which supposes manufacturer as the core member, is modelled and simulated with the prototype system to illustrate the effectiveness of the proposed framework.

Keywords: supply chain management; fractal perspective; modelling and simulation; multi-agent system

1. Introduction

Nowadays, environment of market is becoming increasingly complex and volatile, and competition among enterprises, to a large extent, is reflected in the competition of supply chains. An efficient and flexible supply chain becomes the critical factor for winning competition and survival in this tough environment. However, as an open complex system, supply chain is difficult to analyse. Bandinelli et al. (2006) point out that supply chain management is a very difficult task because of the following: a supply chain can be a very complex network, usually composed of a large number of actors; different units in the supply chain may have different and conflicting objectives; a supply chain is a dynamic system, not only customer demands and supplier capabilities are changing over time, but also their relationships are continuously evolving. Simangunsong, Hendry, and Stevenson (2012) give a review of supply chain uncertainty, and identify a comprehensive list of 14 sources of uncertainty, such as the bullwhip effect or parallel interaction.

Thus, it is a challenging work to deal with the dynamic, stochastic and uncertain characteristics in real-time supply chain systems. Current studies consider modelling and simulation is an effective way in supply chain analysis. Hung, Samsatli, and Shah (2006) classify modelling approaches of supply chain into two main types: analytical models and simulation models. They point out that analytical models are too simplistic to be of practical use for complex supply chains; on the other hand, simulation models can capture realistic supply chain characteristics. Longo and Mirabelli (2008) consider that modelling and simulation-based approach is a powerful tool for managing the stochastic behaviour of supply chains. Therefore, simulation modelling can provide valuable insights into the operational characteristics of supply chains (Chatfield, Harrison, and Hayya 2006). It is beneficial to have an accurate simulation model to explore and evaluate various supply chain improvement policies before their implementation (Hung, Samsatli, and Shah 2006). However, the structure and scale of supply chain is constantly changing along with rapid economic development, which brings about more complexity accordingly. As a result, supply chain management is becoming a more difficult and challenging work. Under this background, it is worth considering new perspectives in perceiving and modelling of supply chain system, so researchers are also trying to gain new insights into the inherent complexity of supply chains through the complex system perspective.

In natural and social systems, the phenomenon of fractal is widespread (Mandelbrot 1982), and philosophy of fractal reveals that the superficial complexity of things conceals the inner regularity and conciseness. From the fractal

*Corresponding author. Email: linjie.tongji@gmail.com

perspective, supply chain presents an approximate self-similarity; this self-similarity, just like Warnecke (1993) and Ryu and Jung (2003) presented, mainly refers to functional structure, as well as the formulation and pursuance of goals. Hence, fractal is a typical feature of complex systems; it is helpful and valuable to introduce the fractal perspective into supply chain system modelling and analysis for addressing its complexity.

The main purpose of this paper is to provide a preliminary study on developing the inner regularity and conciseness of supply chain system, and to implement effective modelling and simulation based on this study in supporting the design and analysis of supply chains. For this purpose, a methodological framework based on fractal thinking and multi-agent technology for supply chain modelling and distributed simulation is proposed in this paper. The proposed framework abstracts and defines five basic fractal elements (BFE) as the core element of both function and structure to model supply chains, and presents integrated and systematic procedures from concept modelling to simulation modelling with distributed multi-agent system (DMAS). In addition, a prototype system according to the framework and its key techniques are introduced and detailed. Different supply chains with specific strategies of manufacturing, inventory and transportation can be easily generated and simulated by configuring fractal patterns of BFEs via a graphical user interface (GUI) of the prototype system, and it also provides both real-time charts and simulation results for quantitative analysis of operations. So the prototype system can be a potential tool for design and optimisation of supply chains.

The remainder of this paper is organised as follows. Section 2 is the related works. Section 3 analyses the inherent self-similarity of supply chain systems. In section 4, the proposed methodological framework based on the fractal perspective is described in detail. Section 5 introduces the prototype system and its key implementation techniques. An illustrative example of supply chain is provided in section 6. Finally, conclusions are given in section 7.

2. Related work

With respect to supply chain analysis, modelling and simulation-based approaches have been the topic and focus of research in recent years and scholars make many achievements. Chan and Chan (2005) test five common supply chain models by using simulation techniques for comparative evaluation of supply chain management strategies. Hung, Samsatli, and Shah (2006) develop a model of a generic supply chain node to capture the features present in all supply chain entities, and the supply chain model is constructed by linking generic nodes and specifying the physical and business attributes of each supply chain member. Cigolini, Pero, and Rossi (2011) propose an object-oriented simulation meta-model which builds simulation models of supply chains automatically and benefits managers to measure the supply chain performance. Longo and Mirabelli (2008) develop a simulator which is capable of analysing different supply chain scenarios using an approach based on multiple performance measures and user-defined set of input parameters. Umeda and Zhang (2006) propose a simulation model which realises centre-controlled (push) system, buffer-driven (pull) system and their hybrid combined system. Pirard, Iassinovski, and Riane (2011) develop a simulation model for various supply network designs evaluation, through simulation-based approach, their model reproduces the dynamics of the totality of the supply chain activities. Other related works, such as Chatfield, Harrison, and Hayya (2006) develop a simulator for integrated supply chain operations, Chan et al. (2006) present a prototype of knowledge-based simulation platform to predict the performance of suppliers and evaluate risk.

Besides, multi-agent technology is widely adopted for supply chain modelling and simulation. In this respect, many scholars have done valuable works. Swarm is the well-known multi-agent simulation platform and toolkit, and the Swarm paradigm is employed in some works (Lin and Shaw 1998; Strader, Lin, and Shaw 1998; Cañizares and Framiñán 2012) which provide extensive and in-depth discussions about the order fulfilment process in different supply chains. Moreover, Lin, Huang, and Lin (2002) and Lin, Sung, and Lo (2005) also evaluate the effects of information sharing and trust mechanisms, respectively, on supply chain performance with Swarm simulation. Different multi-agent architectures for supply chain integration and management have been presented as well (e.g. Fung and Chen 2005; Dong et al. 2006; Zarandi, Pourakbar, and Turksen 2008; Santa-Eulalia, D'Amours, and Frayret 2012; Li and Chan 2013). In a mass customisation context, Labarthe et al. (2007) develop a multi-agent system (MAS) for the modelling and simulation of supply chains. Kaihara (2003) presents a multi-agent-based supply chain modelling with dynamic environment. Akanle and Zhang (2008) propose an agent-based model for optimising supply chain configurations. Li and Sheng (2011) give a multi-agent model for the reasoning of uncertainty information in supply chains. Moreover, distributed simulation (e.g. Mertins, Rabe, and Jäkel 2005; Lees, Logan, and Theodoropoulos 2007; Long, Lin, and Sun 2011; Mustafee et al. 2012) is a major trend considering time efficiency and extensibility of simulation. Bandinelli et al. (2006) suggest that distributed supply chain simulation can be an extremely effective tool for performance analysis in supply chain planning and optimisation, and they give an overview of distributed simulation frameworks and available technologies, such as inter-process communication (IPC) standards and real-time infrastructures.

In recent years, scholars have tuned to adopt complex system perspectives and related approaches, such as complex adaptive systems, system dynamics and complex networks, to deal with the complexity in supply chain analysis (e.g. Surana et al. 2005; Pathak et al. 2007; Tako and Robinson 2012; Hearnshaw and Wilson 2013; Lehr, Thun, and Milling 2013). By inspiration of fractal philosophy, some scholars introduce the fractal idea into their studies. Warnecke (1993) first presents the concept of fractal company, and defines what the essential features of fractal factory are. Ryu, Son, and Jung (2003) propose a fractal-based framework for the management of e-biz companies and model each member in the supply chain as a self-similar structure. Oh et al. (2010) develop a collaborative fractal-based supply chain management framework, and the relationships between the participants of a supply chain are modelled as a fractal. Considering the core competences and strengths of small and medium enterprises (SMEs), Canavesio and Martinez (2007) present a conceptual model for SMEs networking based on the fractal company approach and concept like projects, resources, goals, specialised actors, plans and relationships thereof.

Through analysing and summarising the literatures, an effective approach for supply chain modelling and simulation should not be too complicated for users to build different models, as well as difficult in modelling the detailed features of entire supply chain. Supply chain is a complex social system; therefore, it is necessary and significant to introduce the perspective of complex systems to build more realistic models that can effectively abstract the most important elements and mechanisms. Some well-known multi-agent architectures for manufacturing control applications like PROSA (Van Brussel et al. 1998), ADACOR (Leitão and Restivo 2006) and ANEMONA (Botti and Giret 2008) introduced holonic paradigms. The holon is an autonomous and cooperative entity and may consist of other holons, which has high flexibility in system adaptation and re-configuration to cope with production changes and disturbances. However, these architectures are mainly aimed at manufacturing control for production systems at shop-floor level. Besides, the Swarm-based approaches for supply chain modelling and simulation are widely employed and can provide multiple layers of abstraction and separation of concerns, but such simulations' capacity and performance may be limited due to the non-distributed computational structure of Swarm platform; moreover, owing to higher requirements of programming, it is not easy for users to model supply chain with a Swarm toolkit.

Most of the previous works on supply chain modelling and simulations just propose specific solutions to particular problems, and there exist few generic methodological frameworks in view of complex system perspective. So based on fractal, which is an important feature in complex systems, this paper proposes a methodological framework for modelling and distributed simulation of supply chains. Additionally, a prototype system according to this framework is developed, which is flexible and extensible in modelling and simulating different scenarios of supply chains with specific strategies of manufacturing, inventory and transportation. Meanwhile, the key techniques focusing on distributed time management and synchronisation are introduced and detailed as well. By combining the self-similarity of fractal feature and recognised agent characteristics, the proposed methodological framework has major merits as follows: (1) consistency in scale extending, a whole supply chain is seen as consisting of many sub-chains with similar functional structure and pursuance of goals, and it is easy to extend the system scale both in horizontal and vertical dimensions; (2) flexibility in building models, the defined BFEs being regarded as building blocks provide flexible construction and reconfiguration of different supply chain scenarios; (3) distributed computing structure for simulation, simulated supply chain model can overcome the computational restriction caused by model scale by means of distributed MAS.

3. Perceiving supply chain system from the fractal perspective

A supply chain is an extension and amplification form of internal operations of enterprises, so it has the inherent self-similarity both in structure and function in a sense. Generally, the enterprises of supply chain system are mainly divided into suppliers, manufacturers and distributors. From the fractal perspective, this paper assumes that the boundaries of this division are not strict, in other words, the division of roles is relative from different levels.

3.1 *Self-similarity on the macro level*

Figure 1 describes that supply chain have a form of approximate self-similarity in both structure and function on the macro level. Raw materials and customers are, respectively, at both ends of a supply chain, while different enterprises with various functions, structures and purposes link both the objects in the middle of that complex system. Several enterprises that act as suppliers, manufacturers and distributors can be taken as a whole to be a bigger manufacturer and play this role in a higher vision. So the members' role is flexible and changeable from different perspectives and scales. Meanwhile, the overall function and structure are similar to the part in the whole supply chain, although they are not strictly corresponding. With influence of both demand flows and supply flows, this system is dynamically changing, and also, the members of supply chain as well as its structure will vary accordingly, but the inner self-similar character does not change.

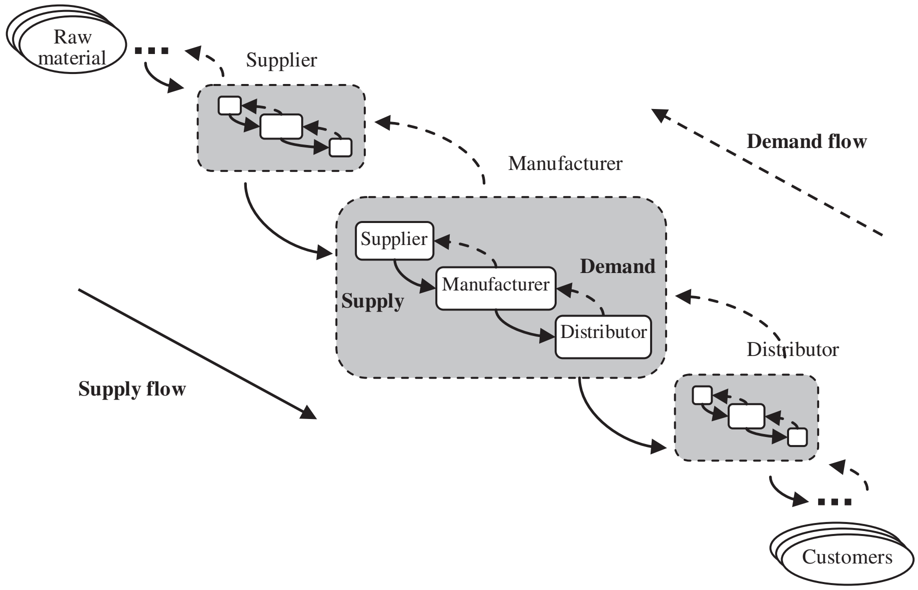


Figure 1. Self-similarity of supply chain system at the macro level.

3.2 *Self-similarity on the micro level*

Besides, the self-similarity also exists on the lower level. Taking manufacturer's inner structure for example, Figure 2 gives a detailed description of this character. The inner structure of manufacturer can be divided into material warehouse, manufacturing units, production warehouse and transportation system for materials. This inner system also has a demand flow and supply flow too, and these components work together to play the similar role as the outer entities of supply chain, respectively.

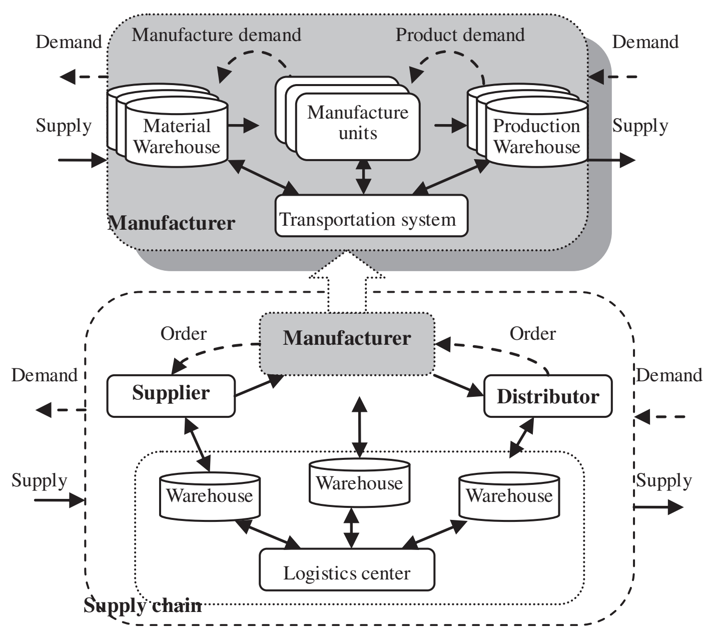


Figure 2. Self-similarity of supply chain at the micro level.

4. Introduction of the proposed methodological framework

This section gives a detailed description of the proposed methodological framework, which includes concept modelling and distributed simulation modelling with multi-agent technology.

4.1 *Overall description of the framework*

The overall flowchart of the framework for modelling and simulation of supply chain is described in Figure 3. Firstly, it abstracts a specific scenario of supply chain in the real world to an aggregation of the BFEs with a certain fractal patterns (namely the logical organisation structure based on fractal perspective). Then, the fractal-based model generator (MG) generates the conceptual model in accordance with the fractal pattern to build the specific scenario. Next, the generated conceptual model is mapped to a DMAS, and implements simulation in computer network. Finally, charts of the simulation results are presented, which provides a visual and quantitative reflection of the real-world supply chain system. This procedure of the framework can be a continuous cycle driven by the need of test on different supply chain scenarios involving manufacturing, inventory and transportation. It is also a useful experimental method for design and optimisation of supply chain systems.

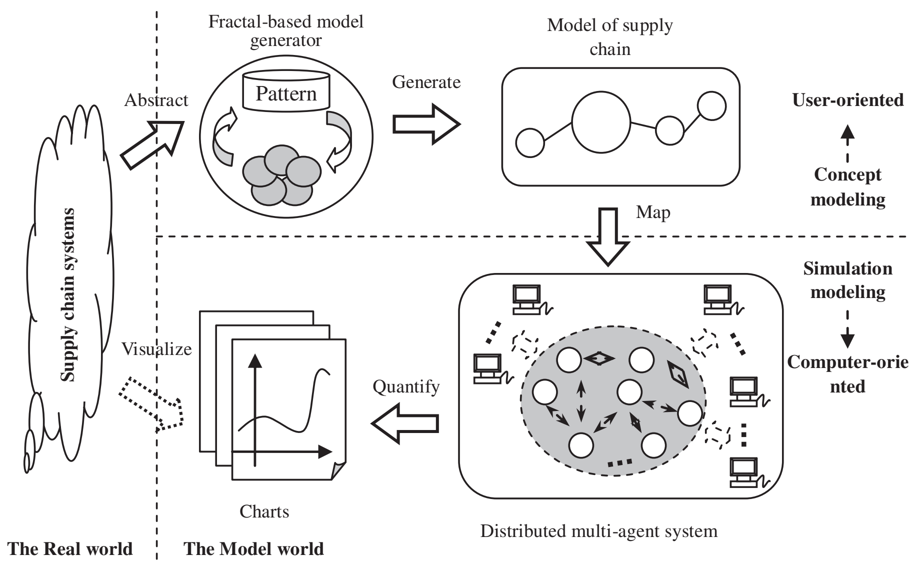


Figure 3. Overall flowchart of the framework.

4.2 *Concept modelling*

Based on above analysis, there are five BFE, which are considered as the core element of both function and structure from the fractal perspective, are abstracted and defined as follow:

- Manufacturing Element (ME): The ME refers to various machines that process materials, or workshops which consist of several machines that have specific process functions at different granularities. For instance, a manufacturer can also be seen as a ME from a higher level perspective.
- Demand Element (DE): The DE stands for the orders from downstream enterprises on the macro level, or the manufacturing demand from the inner MEs of a manufacturer, in this condition, it is in charge of manufacturing planning to arrange all kinds of materials related to MEs. Thus, the DEs of a conceptual model construct the demand flow of a supply chain.
- Storage Element (SE): The SE refers to raw materials warehouses of suppliers, product warehouses of the distributors or manufacturer's temporary warehouses of semi-manufactured products as well as finished products warehouses. It plays the role of cache to supply flows.
- Transportation Element (TE): The TE generally refers to departments, teams or transport equipments which are responsible for delivering all kinds of raw materials semi-manufactured products or finished production between different entities in a supply chain.

- Transportation Planning Element (TPE): The TPE is in charge of providing schemes for TEs, and planning transport of all materials including raw materials, semi-manufactured products and finished products. TPEs and TEs form the supply flow of a supply chain.

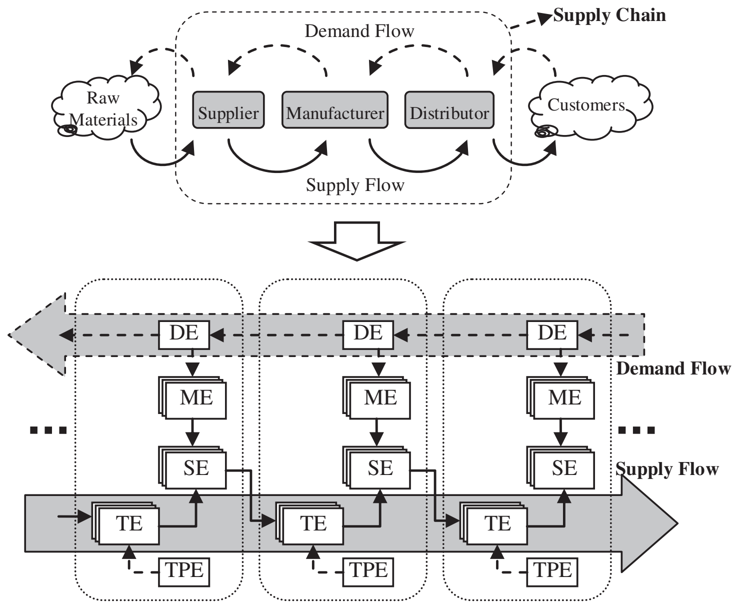


Figure 4. Concept modelling of supply chain with BFEs.

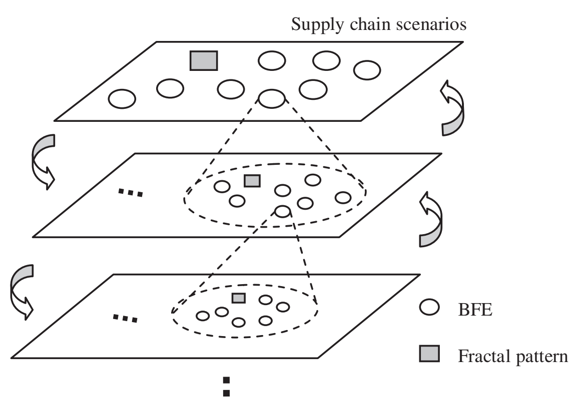


Figure 5. Concept modelling of supply chain at different scales and levels.

In the process of concept modelling, a complex supply chain system is viewed as an aggregate of the five BFEs with a specific fractal pattern. Figure 4 presents the general construction of conceptual model with the five BFEs, in which the BFEs are considered as the basic entities of both function and structure in modelling supply chain scenarios. The main objects of supply chain system and its key operational processes are well abstracted and described as Figure 4 shows. Therefore, the conceptual model gives a sound description of supply chain systems in real world. Furthermore, based on the fractal perspective, the concept modelling grasps the inner regularity and conciseness of supply chain systems. As Figure 5 shows, according to the fractal pattern which is configured for a specific supply chain scenario including manufacturing, inventory and transportation, the conceptual model can easily be generated by means of iteration and combination of BFEs at different scales and levels of detail.

4.3 *Simulation modelling*

Anosike and Zhang (2009) point out that MAS offer an alternative methodology to model and solve problems with a coordinated community of autonomous agents in a distributed and co-operative manner. In addition, high-level architecture (HLA), which is adopted as an IEEE standard (IEEE 2000), is the most important framework for distributed simulation and offers an attractive potential solution to the problems of simulation and simulator reuse, and simulation performance in MAS simulation (Lees, Logan, and Theodoropoulos 2007). Thus, in simulation modelling procedure of the framework, the agent is used to map BFEs in conceptual model and reconstructs the model. In this way, the conceptual model is transformed into MAS (namely a simulation model) which can be easily implemented in computer by agent development toolkit and designed in accordance with HLA. Figure 6 describes the main agents for constructing the MAS in simulation modelling and their correlations with unified modelling language (UML).

As shown in Figure 6, the agents are mainly divided into two types, namely auxiliary agents and BFE agents, and defined as follows:

- Basic Agent: This type of agent is a basic agent class to be extended for constructing the entire DMAS. It is the top class of all agents and has the general features of agent.
- Basic Fractal Element Agent (BFEA): The BFEA is a basic agent to be extended by the agents that map the five BFEs, and defines the general attributes and functions, such as identical attributes, registration, consistency check, message process and so on.
- General Management Agent (GMA): The GMA is responsible for registration of all other agents in the DMAS, maintenance of agent-identity numbers as well as global time management.
- Distributed Management Agent (DMA): The DMA is a middle-management agent between GMA and BFE agents, and has the similar functions and attributes of GMA, but just for distributed management of agents in its own domain.
- Organisation Management Agent (OMA): The OMA is a logical management agent for organising the BFE agents and reflects the fractal pattern in a conceptual model.
- Manufacturing Element Agent (MEA): The MEA maps the ME that is defined in Section 4.2. It acts as either a specific machine or a workshop, and has some attributes like processing capability, failure rate, bill of materials, (BOM) etc.
- Demand Element Agent (DEA): The DEA maps the DE, and it can stand for orders and provide the manufacturing planning for MEAs according to configured strategy.
- Storage Element Agent (SEA): The SEA maps the SE and acts as the role of a temporary storehouse in a workshop or an inventory in an enterprise.

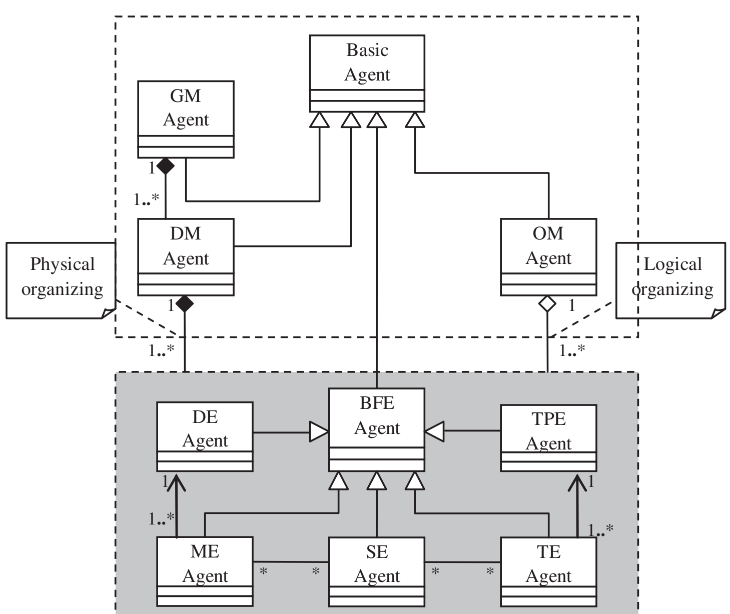


Figure 6. Description of main agents by UML.

- Transportation Element Agent (TEA): The TEA maps the TE, and its main function is delivering raw materials, or semi-manufactured products, or finished products among different SEAs.
- Transportation Planning Element Agent (TPEA): The TPEA maps the TPE, and it provides the schemes of TEAs for planning the transportation of different material based on a specific strategy.

GMA, DMA and OMA are auxiliary agents designed for management in MAS. The GMA and DMA are used for physical organising of BFE agents that are distributed in different domains. Together they construct a distributed hierarchy to manage simulation agents. The function of OMA is for logical organising according to the fractal pattern of the conceptual model. The BFE agents are the main part to construct simulation models and perform the operations of a specific supply chain scenario.

4.4 *Definition of agent behaviour and interaction*

The defined BFEs are regarded as the building blocks with their specific attributes and functions to construct different supply chain scenarios. The BFEs of the constructed concept model are mapped and instantiated to corresponding BFE agents, respectively, for performing their roles in the form of MAS. Figure 7 describes interaction and collaboration among agents in fractal domains. Every defined agent in the MAS communicates and collaborates with each other by means of formatted messages.

As shown in Figure 7, there are five major operations within the fractal domain.

- Organisational structure process: Every fractal domain could be regarded as a sub-chain with consistent structure and functions, which forms a whole supply chain system based on the common goals. In a fractal domain, the OMA has the information about the logical organisation of BFE agents. By message communication with OMA, BFE agents can get their correlation with each other and specific positions in the whole fractal structure. According to different configurations in OMA, a fractal domain may have different number of BFE agents and organisational forms. The OMAs in the MAS hold the organisational structure of the whole simulation model, which determines relationships of BFE agents for their interactions.

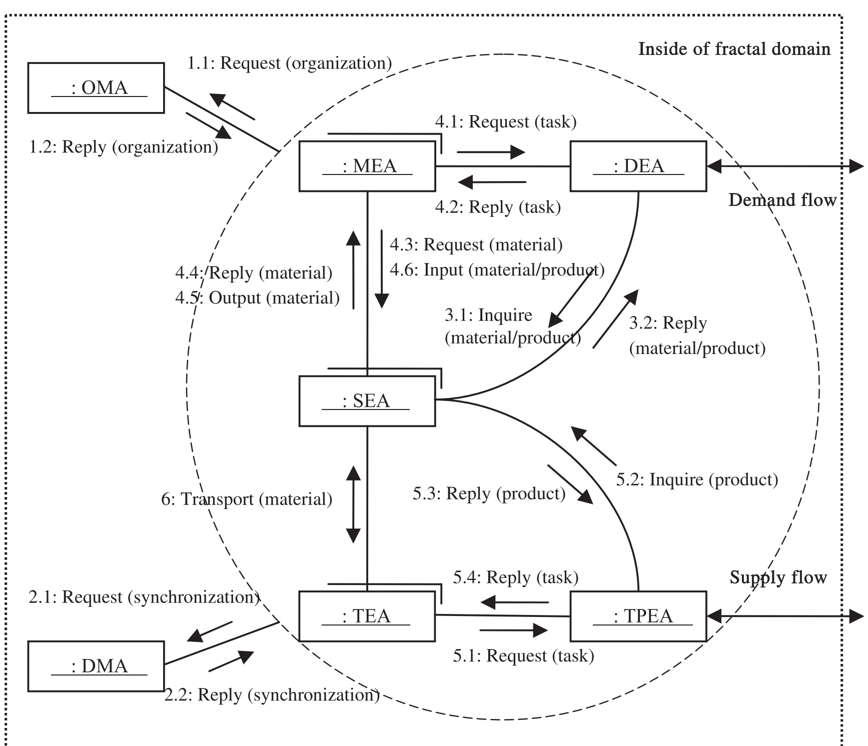


Figure 7. Interaction among agents in the fractal domain.

- Synchronisation of actions: One of the major functions of DMA as defined in the above section is responsible for synchronising actions of distributed BFE agents. Every BFE agent needs request synchronisation before performing its specific action for maintaining the sequence of events in such parallel and distributed environment.
- Demand process: The DEA deals with both internal and external demand information. On the one hand, it accepts the external orders for specific products that are manufactured in its domain; on the other hand, it sends orders to external DEAs for materials required for production. The DEA communicates with internal SEAs to get the inventory of material and product, and on this basis, it schedules the internal manufacture actions of MEAs and communicates demand information with external DEAs. The interaction of this process is detailed in Figure 8.

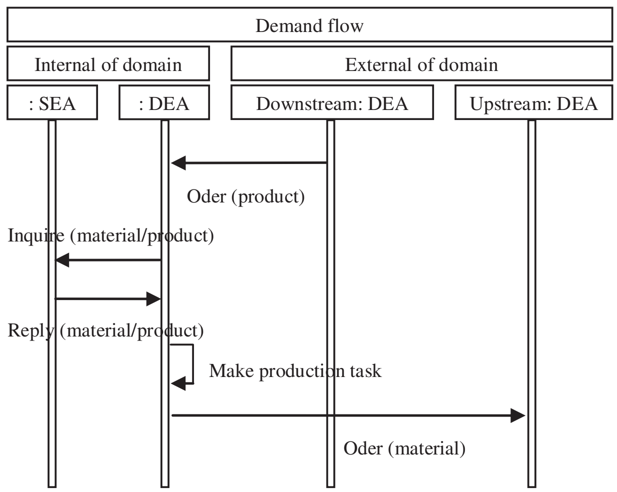


Figure 8. Sequence diagram of demand process.

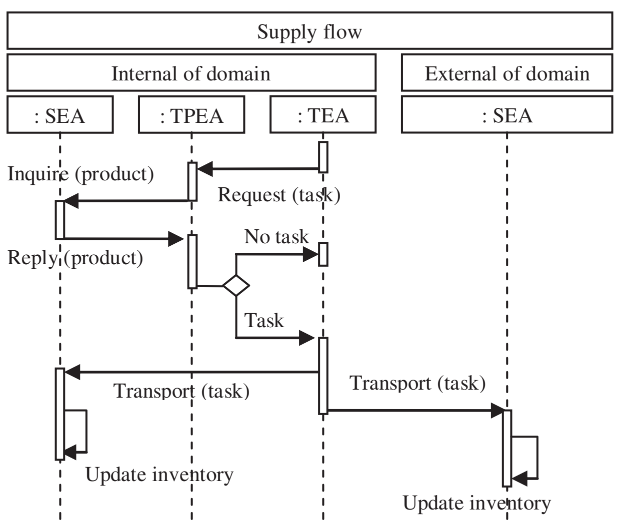


Figure 9. Sequence diagram of transport process.

- Manufacture process: The manufacture behaviour of MEAs is based on the scheme scheduled in DEA. Firstly, an idle MEA requests the task from the DEA, and MEA replies for this request according to scheme. Once a task is scheduled, the corresponding MEA will request the material in BOM of the task from relevant SEAs. The SEA replies this request and provides the current information of material, if the requested material and its volume are satisfied, the MEA will get the material and perform this manufacturing process. And the manufactured products will be stored to corresponding SEA. During this process, the relevant SEAs need to update the inventory.

- Transportation process: The TEAs transport raw materials, or mid-products, or products among different SEAs. An idle TE sends request message to TPEA for transport task, and then TPEA inquires relevant SEAs for material information, the SEAs will reply this inquiry. Next, the TPEA replies to the idle TE, and if there is satisfactory material, the TPEA will schedule a transport task to the TE, and then this TE transports the material from the source SEA to the target SEA. The TPEA could be configured with different transport strategies to schedule the transport action of TEAs. Figure 9 describes the transportation process which forms the supply flow among correlative fractal domains.

Through correlation of demand flows and transport flows, fractal domains as self-similar sub-chain systems are loosely coupled together as a whole at different scales and levels of detail. By this way, it is flexible and scalable to construct different supply chain scenarios for operational analysis, optimisation and design.

5. Introduction of prototype system

According to the proposed methodological framework, this section introduces a prototype system which is developed by Java programme and uses JADE (Java Agent Development Framework) toolkit (Bellifemine, Caire, and Greenwood 2007; Bellifemine et al. 2008) to implement distributed simulation of supply chain with MAS in computers. The prototype system constructs distributed environment in compliance with HLA for modelling and distributed simulation of supply chains, and it can provide both real-time charts and final statistical results of operational analysis. Moreover, the prototype system separates the user-oriented conceptual model from the computer-oriented simulation model, and users just focus on how to characterise the model, but not on how to build it.

5.1 *The prototype system architecture*

The architecture of prototype system is shown in Figure 10. There are four layers in all, and their components and functions are presented as follows:

- User Interface Layer: This layer includes user configuration interface (UCI) and Diagrams Output Interface. The function of the former one is to dispose user's configuration to the fractal pattern (namely the organisational structure of the target supply chain) and relevant attributes, and to access this information to Fractal Pattern Database (FPD), while the latter is to output the charts for analysis during runtime as well as at the end of simulation. According to different granularities of the target supply chain, users abstract the entities in supply chain systems and configure their attributes and relationships.
- Concept Modelling Layer: In this layer, FPD is used to dispose and store the configuration information about the target supply chain from UCI. Through a specific configuration, MG can construct a corresponding concept model of supply chain scenario with BFEs. Simulation Records Database is used to store the results of simulation for subsequent analysis.
- Distributed Multi-agent Simulation Layer: This layer implements the transformation of concept model to simulation model and performs the simulation process. By mapping and instantiating the concept model generated by MG with corresponding BFE agents and other auxiliary agents, a DMAS is constructed as the simulation model. The JADE component, which mainly consists of Agent Management System, Directory Facilitator and Message Transportation System, provides basic bottom-level services and running environment support for the simulation model.
- Physical Network Layer: This layer gives a physical environment for running the model in distributed computers connected by Internet or local networks.

5.2 *Techniques of distributed simulation with MAS*

5.2.1 *Time advance mechanism in simulation*

Time management and synchronisation is important for a distributed simulation process. At present, there are two main time advance mechanisms (e.g. introduced in Jefferson 1985; Fujimoto 2003): conservative time advance and optimistic time advance. Jafer, Liu, and Wainer (2012) discuss the main characteristics of existing synchronisation methods in the above two categories for parallel and distributed discrete event simulations, and they also present the different computational environments for such simulations. Besides, Weyns et al. (2005) provide an overview of the state-of-the-art environments in MASs and discuss the difficulty to synchronise actions of distributed agents. In Weyns and Holvoet's (2003) study, an asynchronous model for situated MASs is proposed that supports simultaneous actions through

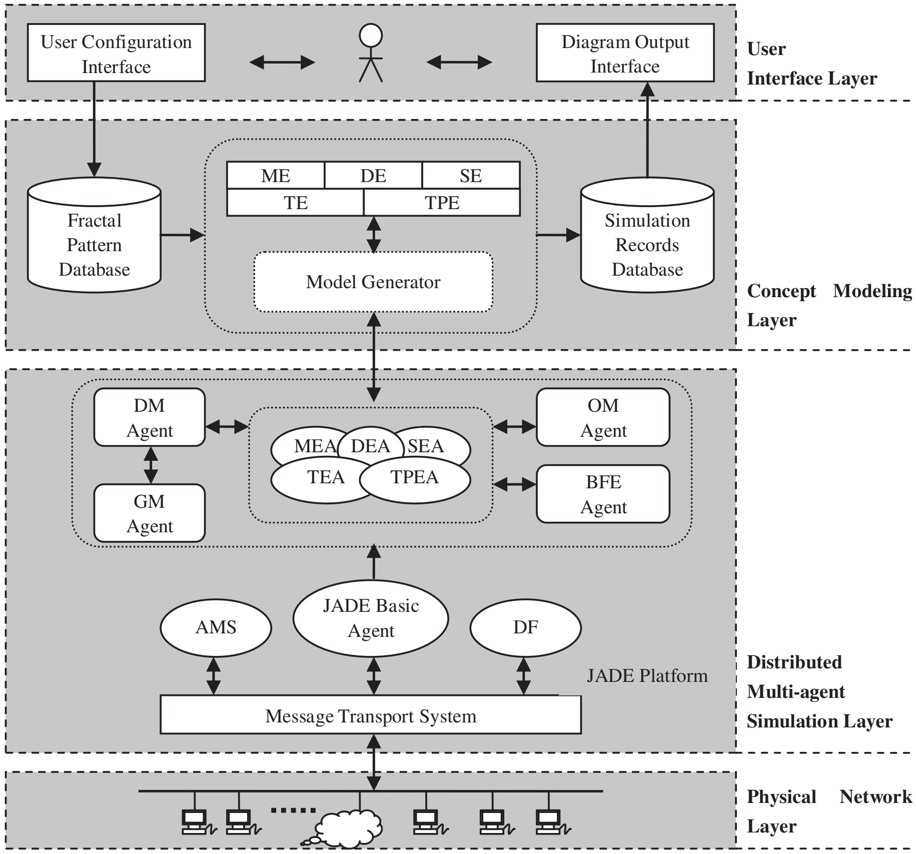


Figure 10. The architecture of prototype system.

'regional synchronisation', which avoids the drawbacks of global synchronisation while preserves the properties for handling simultaneous actions.

With respect to supply chain simulations, the driving mode of simulation time is based on a mass of discrete events. Nevertheless, the complex operations in supply chain system lead to more interactions among simulation agents. To achieve time efficiency of concurrent running while maintaining the causal sequences among activities of agents is a challenge of supply chain simulation based on distributed MAS. Compared with the optimistic strategy, the conservative strategy can better maintain the causal sequence of events and strictly ensure each logical process will be executed according to their time order in distributed environment. Therefore, for supply chain simulations with highly interactive characteristic, the conservative strategy is more suitable for time management and control.

Based on the above consideration, the prototype system designed a hierarchical structure for time management according to conservative strategy, which is composed of central GMA and distributed DMAs. This hierarchical structure can decentralise agent time synchronisation within its distributed fractal domains and effectively eases the global synchronisation as well as reduces message communication over domains. Figure 11 describes the distributed time management structure. GMA is the top time management agent, which is responsible for regulating and controlling the general time advance. And each DMA takes charge of time management of its domain agents to assist global time management.

5.2.2 *Time management*

According to the time management mechanisms of HLA (Fujimoto 1998; IEEE 2000), the prototype system defined three types of time management to agent as follows:

- Time-regulating agent: The time advance of this type of agent can affect other agents, but it will not be affected by others.
- Time-constrained agent: For this type of agent, its time advance is affected by other agents, but will not affect the time advance of others.

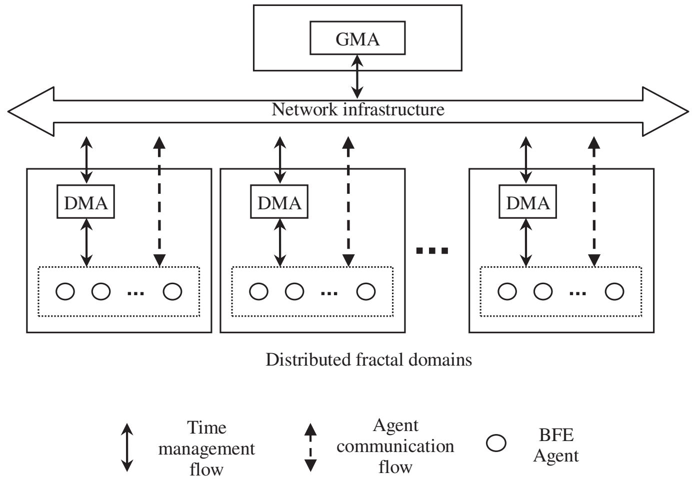


Figure 11. Distributed time management structure.

- Both time-regulating and time-constrained agent: This agent's time advance has characteristics of both time-regulating agent and time-constrained agent. Its time advance affects other agents as well as constrained by others.

In the simulation process, the lower bound on time stamp (LBTS) is introduced based on the conservative time advance strategy, which is the pace for time advance and represents a minimum security value of a time point that can advance to. The global LBTS is defined by GMA according to Equation (1).

$$\mathrm{LBTS} = \min\left(\mathrm{LBTS}_i\right) \tag{1}$$

Here, LBTS_i is any LBTS value of fractal domain, and it is defined by Equation (2) as follows:

$$\mathrm{LBTS}_i = \min\left(\mathrm{LBTS}_j\right) \tag{2}$$

LBTS_j is any LBTS value of BFE agent in the current domain.

For BFE agents, the time-regulating type can foreward its next time point of event by Equation (3).

$$\mathrm{LH}_k = \mathrm{LT}_k + \mathrm{Lookahead}_k \tag{3}$$

Here, LT is the current logical time of simulation, and Lookahead is a value of time interval from current event to the next of a specific BFE agent. With respect to the time-constrained agent, its LBTS value is defined as the following Equation (4).

$$\mathrm{LBTS}_j = \min\left(\mathrm{LH}_k\right) \tag{4}$$

The LH_k is any LH value of the time-regulating agent that affects the time advance of the current agent.

5.2.3 *Message definition for time advance*

The implementation of time advance is based on the delivery of message among agents, and the BFE agents can receive the system logical time independently and communicate freely with each other. In the prototype system, there are two types of message defined directly related to time advance of agents:

- LBTS message: LBTS includes local LBTS value generated by every BFE agents, domain LBTS value calculated by each DMA and global LBTS value calculated by GMA. The LBTS message carries the value of LBTS, and this type of message is delivered between GMA and BFE agents via DMA.
- LH message: This type of message is generated by either time-regulating agent or both time-regulating and time-constrained agent; the content carried by LH message is the value of LH that can be calculated by equation (3). This type of message is delivered among relevant BFE agents.

5.2.4 *Description of time advance algorithm*

Through communication of messages defined above, Figure 12 presents the flowchart of time advance algorithm, which includes three levels: the time advancement of GMA, the time advancement of DMA and the time advancement of BFE agents. At the beginning, system logical time is set to zero, and then current value of the system logical time is constantly calculated through designed mechanism step by step during simulation.

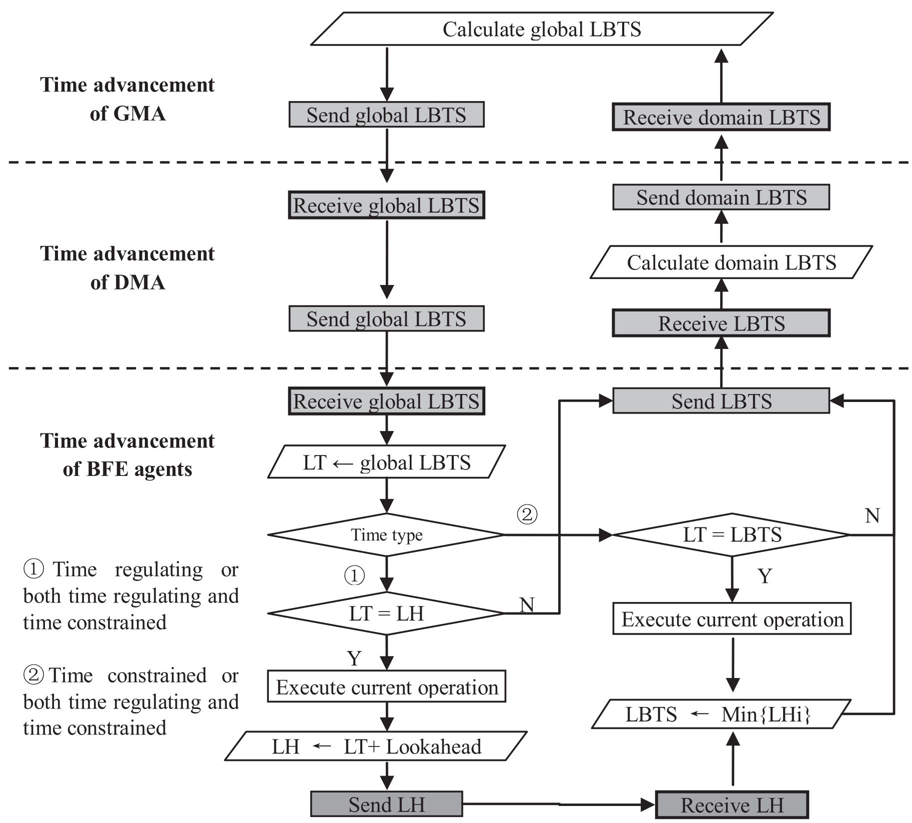


Figure 12. Flowchart of time advance based on messages.

Description of time advance algorithm is detailed as follow:

- Time advancement of GMA:

  (1) Receives domain LBTS messages sent from each DMA;
  (2) Calculates global LBTS which is the minimum value of all domain LBTS;
  (3) Sends global LBTS (namely current system logical time) message to each DMA, and then back to step (1).

- Time advancement of each DMA:

  (1) Receives local LBTS messages of every BFE agents in its domain;
  (2) Calculates domain LBTS which is the minimum value of all local LBTS of BFE agents;
  (3) Sends domain LBTS message to GMA;
  (4) Receives global LBTS messages sent from GMA;
  (5) Sends global LBTS message to its domain BFE agents, and then back to step (1).

- Time advancement of BFE agents:

  (1) Sends local LBTS message to DMA, then waits for global LBTS message;
  (2) Receives local LBTS message, and then sets it as current logical time (LT);
  (3) Identifies time management type:

• Time regulating, if LT equals local LH then executes current operation, and then calculates a new LH value by Equation (3), next, sends its LH to other time-constrained BFE agents, otherwise, moves to step (4);
• Time constrained, if LT equals local LBTS then executes current operation, and then calculates the minimum value of LH_i ($i = 1,2,\ldots\ n$) as a newly local LBTS value according to received LH messages, next, sending the LBTS message, otherwise, moves to step (4);
• Both time-regulating and time-constrained, its time advancement refers to the two types described above.

(4) Move to step (1).

6. Modelling and simulation of an example

This section implements modelling and simulation of a typical supply chain example and proves the effectiveness and feasibility of the proposed framework though analysis of simulation results and corresponding diagrams.

6.1 *The example modelling and description*

As top level of Figure 13 shows, the example is a typical supply chain structure which consists of two suppliers, two distributors and one manufacturer as the core member. In addition, the operation of the whole supply chain system is based on pull mode of orders, and products among all members are transported through a logistics centre.

The model of example can be configured and generated to different supply chain scenarios provided with the GUI of the prototype system. Through the fractal mechanism-based design of BFEs, users can flexibly model the entities of target supply chains to the required level of granularity with BFEs and easily extend the entire model scale. Figure 13 describes the modelling process, in which the example is abstracted and modelled into details of a specific supply chain scenario by BFEs from the top level to the bottom. Besides, according to different requirements, users can easily change the supply chain scenario with different configurations of BFEs. After constructing concept model of the example, the prototype system will map and instantiate BFEs to the corresponding BFE agents, and then together with other defined auxiliary agents, the concept model will be transformed to a DMAS for implementing model simulation in a distributed environment.

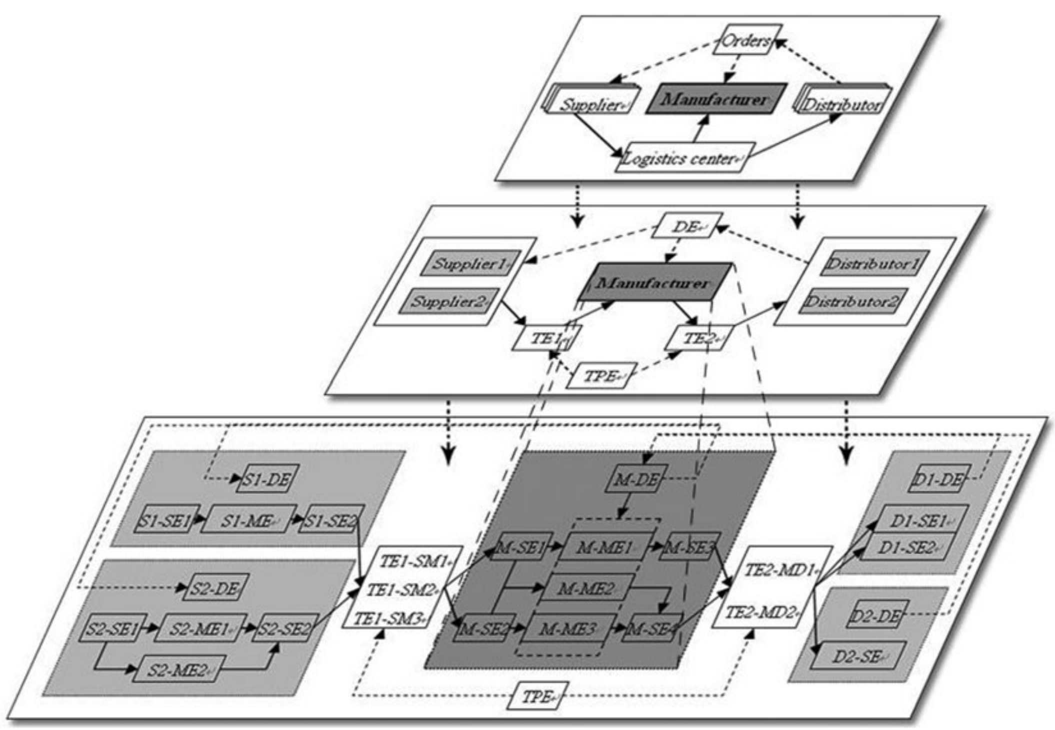


Figure 13. The description of example modelling.

6.1.1 *The construction of example model*

The bottom level of Figure 13 shows that the entire model of the example is modelled and generated by the five types of BFE, and the inner microstructure of core manufacturer as well as other chain members is modelled into a certain extent. The prefix of 'S1-, S2-' stands for the two suppliers, the 'M-' stands for the core manufacturer and 'D1-, D2-' stands for the two distributors. Table 1 details the composition of the modelled example in Figure 13.

D1-DE, M-DE, S1-DE and S2-DE comprise the demand flow of the entire system. TE1 (TE1-SM1, TE1-SM2 and TE1-SM3) and TE2 (TE2-MD1 and TE2-MD2) refer to two transport groups. The former one is responsible for material transport between suppliers and manufacturers, and the other between manufacturers and distributors. Additionally, TPE is in charge of transportation planning of TEs, and all the transport behaviours of TEs are based on TPE's scheme that is configured by users. The manufacturer M has three MEs (M-ME1, M-ME2 and M-ME3) for performing manufacture behaviours and four SEs (M-SE1, M-SE2, M-SE3 and M-SE4) for material store. The supplier S1 has two SEs (S1-SE1 and S1-SE2) as warehouse and a ME (S1-ME) to process raw materials. The S2 has two SEs (S2-SE1 and S2-SE2) and two MEs (S2-ME1 and S2-ME2). The D1 as a distributor is set two SEs (D1-SE1, D1-SE2) as product warehouse, while D2 has one (D2-SE).

6.1.2 *The operation of example model*

The example assumes that inventories of D1-SE1, D1-SE2 and D2-SE order a certain amount of three types of product (P1, P2 and P3) respectively, and the entire system is driven to perform the order fulfilment. Besides, for every event of the simulated example, there is a specific value of generic logical time set, based on which to advance the simulation time. Meanwhile, we also add some randomness to the operations that refer to manufacture and transport.

In the simulated example, we assume the D1-SE1 orders 100 units P1 and 50 units P2, D1-SE2 orders 50 units P2 and 50 units P3 and D2-SE orders 100 units P2 and 50 units P3. Note that the 'unit' in this example is a generic measurement of production, and it can denote a specific measurement in practical use.

Table 2 presents the material information and material processing in the whole supply chain example. Here, identifiers from MT1 to MT7 are raw materials and mid-materials processed by supplier and manufacturer, P1, P2 and P3 are products ordered by distributor. In Table 2, the BOM of different MEs and its production capacity is set, and the production time consumption of each batch is given as well. In addition, Table 3 details the demand information of orders in the example model. By combing the total amount of required products in orders, BOM information, and production capacity of relevant MEs, each DEs in different supply chain members response to manufacture request of MEs dynamically. Here, the manufacturing of all materials is configured with equal priority.

As the bottom level of Figure 13 shows, there are three production lines in the manufacturer: (1) M-ME1 acquires mid-raw materials (MT4, MT5 and MT6) from M-SE1 and stocks the finished product to M-SE3; (2) M-ME2 acquires mid-raw materials (MT4, MT5 and MT7) from M-SE1 and M-SE2, and stocks the finished products to M-SE4; (3) M-ME3 acquires mid-raw materials (MT5 and MT7) from M-SE3 and stocks the finished product to M-SE4. The M-ME1, M-ME2 and M-ME3 manufacture P1, P2 and P3, respectively, according to the BOM described in Table 2.

Meanwhile, in the upstream of the manufacturer, the supplier S1 and S2 supply the four types of mid-raw materials. S1 supplies MT4 and MT5 by processing raw materials (MT1 and MT2) with S1-ME, and S2 supplies MT5, MT6 and MT7 by processing raw materials (MT1, MT2 and MT3) with S2-ME1 and S2-ME2.

Table 1. The composition of the modelled example.

Supply chain member	BFE				
	ME	DE	SE	TE	TPE
S1	S1-ME	S1-DE	S1-SE1 S1-SE2	TE1-SM1	TPE
S2	S2-ME1 S2-ME2	S2-DE	S2-SE1 S2-SE2	TE1-SM2	
M	M-ME1 M-ME2 M-ME3	M-DE	M-SE1 M-SE2 M-SE3 M-SE4	TE1-SM3	
D1	Null	D1-DE	D1-SE1 D1-SE2	TE2-MD1	
D2	Null	D2-DE	D2-SE	TE2-MD2	

Table 2. Material information and processing.

Supply chain member	Material	BOM	Production capacity	Production time of each batch	Failure rate
S1	MT1	S1-ME: {MT1 + MT2→MT4,MT5}	5–10	50	0.1
	MT2				
S2	MT1	S2-ME1: {MT1 + MT2→MT5}	5–10	60	0.1
	MT2				
	MT3	S2-ME2: {MT2 + MT3→MT6}	5–15	70	0.1
M	MT4	M-ME1: {MT4 + MT5 + MT6→P1}	2–5	80	0.1
	MT5				
	MT6	M-ME2: {MT4 + MT5 + MT7→P2}	5–10	60	0.1
	MT7	M-ME3: {MT5 + MT7→P3}	2–5	80	0.1
D1	P1	Null	Null	Null	Null
	P2				
	P3				
D2	P2	Null	Null	Null	Null
	P3				

Table 3. Demand information.

Supply chain member	Warehouse and material	Order
S1	S1-SE2: {MT4, MT5}	S1-DE: {MT4: 300, MT5: 200}
S2	S2-SE2: {MT5, MT6, MT7}	S2-DE: {MT5: 200, MT6: 200, MT7: 400}
M	M-SE3: {P1}	M-DE: {P1: 100}
	M-SE4: {P2, P3}	{P2: 200, P3: 100}
D1	D1-SE1: {P1, P2}	D1-DE: {P1: 100, P2: 50}
	D2-SE2: {P2, P3}	{P2: 50, P3: 50}
D2	D2-SE: {P2, P3}	D2-DE: {P2: 100, P3: 50}

With respect to transportation groups of TE1 and TE2, they are responsible for material delivery between SEs according to a specific strategy of TPE. Here, the TPE employs the rule of first come first service for material transportation, and all kinds of materials have equal priority for transportation, i.e. once there is a satisfactory amount of material to be transported, the TPE will schedule the available SE to conduct a transport. Table 4 presents the main transport information in the example.

Table 4. Information of the transportation.

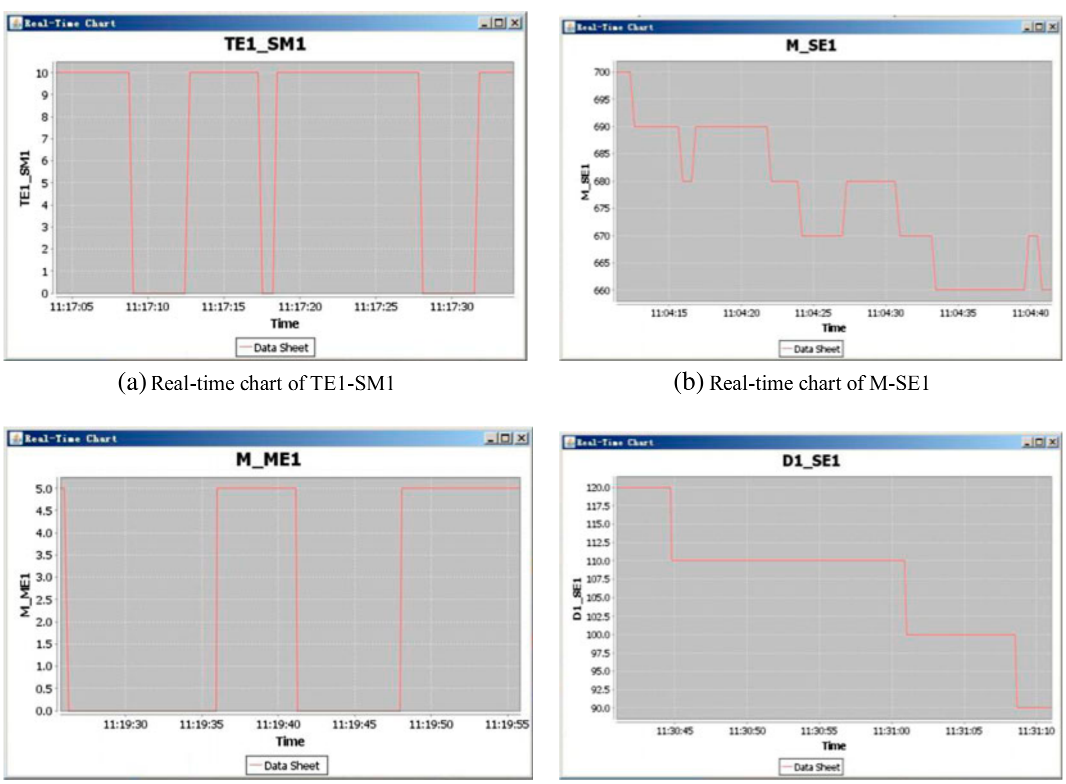
Transport group	Transport unit	From	To	Time-consuming of transport	Transport capacity	Failure rate
TE1	TE1-SM1	S1-SE2	M-SE1	{S1-SE2→M-SE1: 300}	10–20	0.1
		S2-SE2	M-SE2	{S1-SE2→M-SE2: 400}		
	TE1-SM2			{S2-SE2→M-SE1: 300}	10–20	0.1
	TE1-SM3			{S2-SE2→M-SE2: 400}	10–20	0.1
TE2	TE1-MD1	M-SE3	D1-SE1	{M-SE3→D1-SE1: 500}	10–20	0.1
		M-SE4	D1-SE2	{M-SE3→D1-SE2: 500}		
			D2-SE	{M-SE3→D2-SE: 600}		
	TE1-MD2			{M-SE4→D1-SE1: 500}	10–20	0.1
				{M-SE4→D1-SE2: 500}		
				{M-SE4→D2-SE: 600}		

6.2 *Simulation and evaluation*

When the example model is simulated into the prototype system, the operation status of every BFE can be observed through the provided real-time charts by the corresponding agents. Figure 14 presents the real-time operation charts of partial BFEs. Figure 14(a) shows the transport volume of TE1-SM1 changing over time. The change of remaining amount for materials in M-SE1 over time is given in Figure 14(b), and it can be seen from the chart that this value is into a declining trend during that period of time due to constant delivery of raw materials to M-SE1. In Figure 14(c), the chart shows the amount of product manufactured by M-ME1 in the current time frame. Figure 14(d) presents the change of the remaining amount of D1-SE1 for products, with the transport of finished products from manufacturer, this value is gradually reduced. From the provided real-time charts during the simulation, it is easy and intuitive to observe the function of each BFE in the configured model, which provides useful information for users to analyse the whole supply chain on a more subtle level.

After the end of simulation, the prototype system can present a more comprehensive perspective for operations analysis, and reveal detailed information related to the main operations of the modelled supply chain scenario based on the recorded simulation data. In the following figures, some useful statistical diagrams of the simulation results are presented. Figure 15 evaluates the transportation situation and provides the comparison of utilisation rate of TE1-SM1, TE1-SM2, TE1-SM3, TE2-MD1 and TE2-MD2. This chart illuminates that TE1-SM1 and TE1-SM2 have a relatively higher utilisation than other three TEs, and the value of TE2-MD2 is obviously much lower compared with the others. Through information reflected by this chart, it is helpful to develop the targeted planning of transportation in order to improve the overall utilisation rate.

The core manufacturer of the example is modelled into a more detailed level of granularity with BFEs, which facilitates to analyse the manufacturer's operations from whole to parts. In Figure 16, a comparative analysis of utilisation of the core manufacturer's three MEs (M-ME1, M-ME2 and M-ME3) is presented, and the curve indexed with M gives the overall utilisation of the manufacturer. From observation of this chart, because of different requirements of raw materials and the supply conditions during production, there are differences in the start time of manufacturing and utilisation among the three MEs. M-ME1 has an earlier start time, which indicates that the supply of raw materials to M-ME1 is faster, while M-ME2 and M-ME3 get a later time due to certain reasons, such as temporary shortage in the



(a) Real-time chart of TE1-SM1
(b) Real-time chart of M-SE1
(c) Real-time chart of M-ME1
(d) Real-time chart of D1-SE1

Figure 14. Real-time charts of partial BFEs.

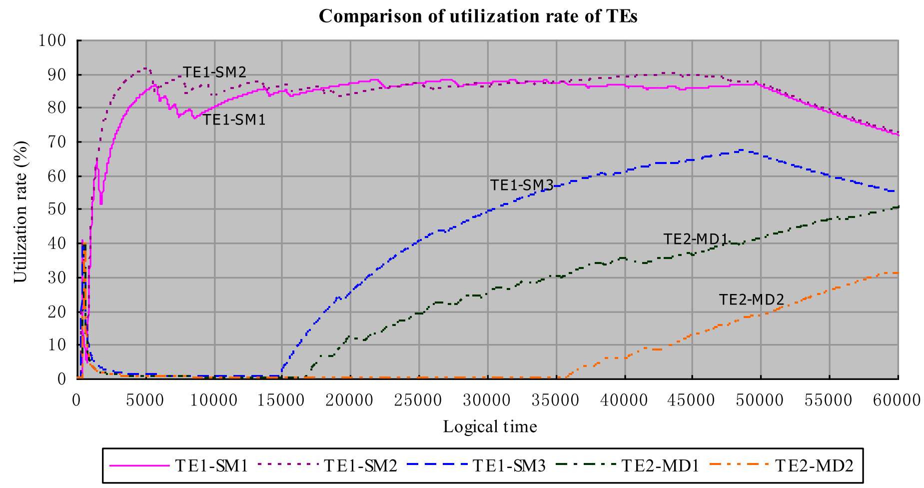


Figure 15. Comparison of utilisation rate of TEs.

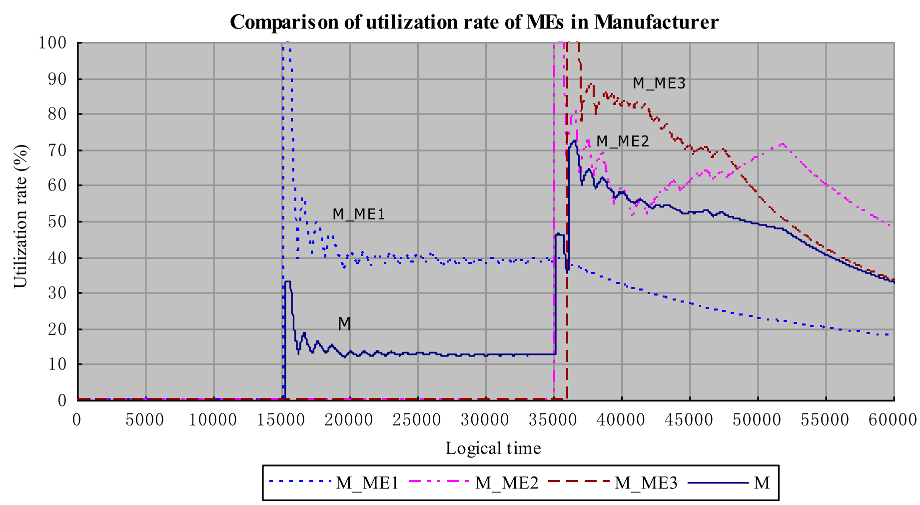


Figure 16. Comparison of utilisation rate of MEs in manufacturer.

amount or type of raw materials. By comparison, the utilisation rate of M-ME3 is higher than the other two MEs, which illustrates a better supply condition of M-ME3 in general.

Then Figure 17 shows the overall inventory information of each SE in the manufacturer during the manufacturing processes and transportation of materials. It is clear to observe the inventory changes during the whole simulation process. As shown in the chart, M-SE1 has a much bigger value of inventory than others in general, while this value of M-SE3 is always kept at a relatively lower level. From the indexed values and the slope of these curves, users can effectively grasp the detailed information about the inventory costs and turns.

From a more micro level, Figure 18 also gives inventory of products (P1, P2 and P3) changing over time with the manufacturer. Compared with product P1 and P2, the inventory of P3 shows larger fluctuation range and value. This chart indicates that P1 and P2 have more smooth process and better performance in manufacturing and transporting the configured supply chain scenario.

Towards the distributors, Figure 19 presents the order fulfilment status of the two distributors, which compares inventory changes of different SEs in the corresponding distributors. It is clear to see the inventory level that changes over time during the whole order fulfilment process. The chart shows D1-SE1 has an earlier start time of inventory increase compared with D1-SE2 and D2-SE, but relatively longer duration in order fulfilment. Besides, it can also get detailed inventory information of the products ordered by different warehouses of distributors, as shown in Figure 20 that shows further details about the inventory changes of product P2 and P3 ordered in D1-SE1. With the analysis of

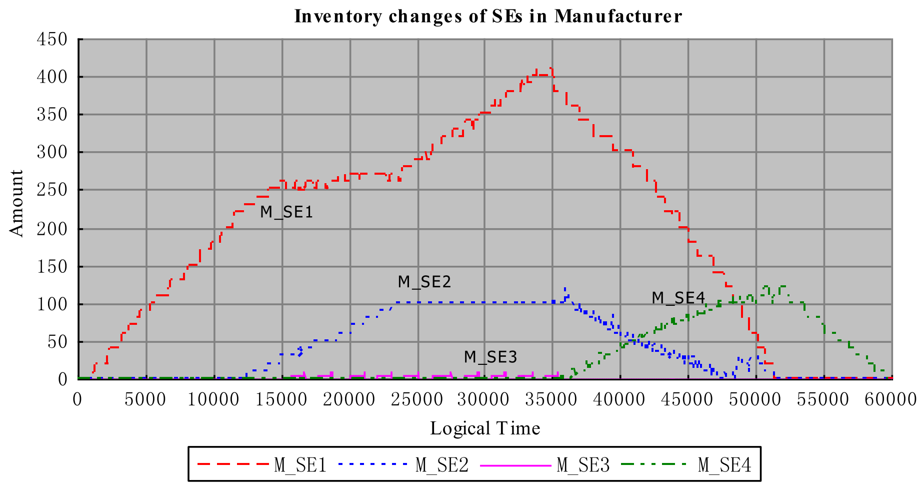


Figure 17. Inventory changes of SEs in manufacturer.

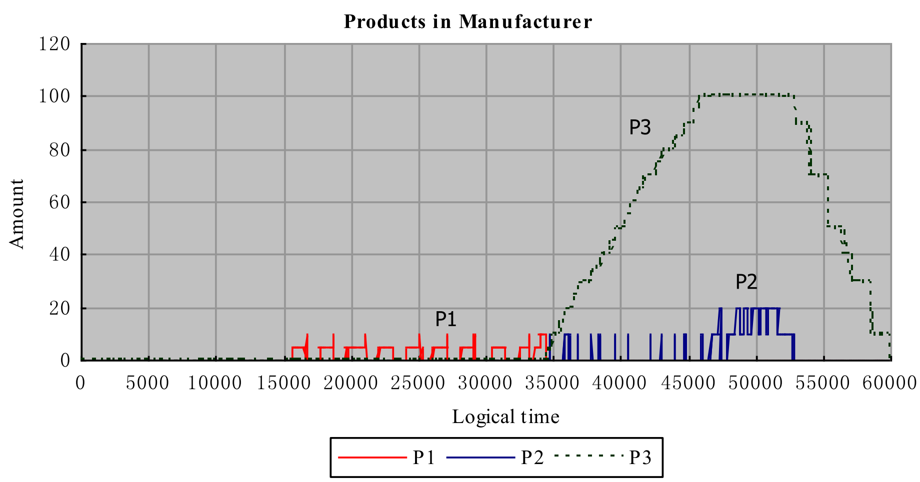


Figure 18. Inventory changes of products in manufacturer.

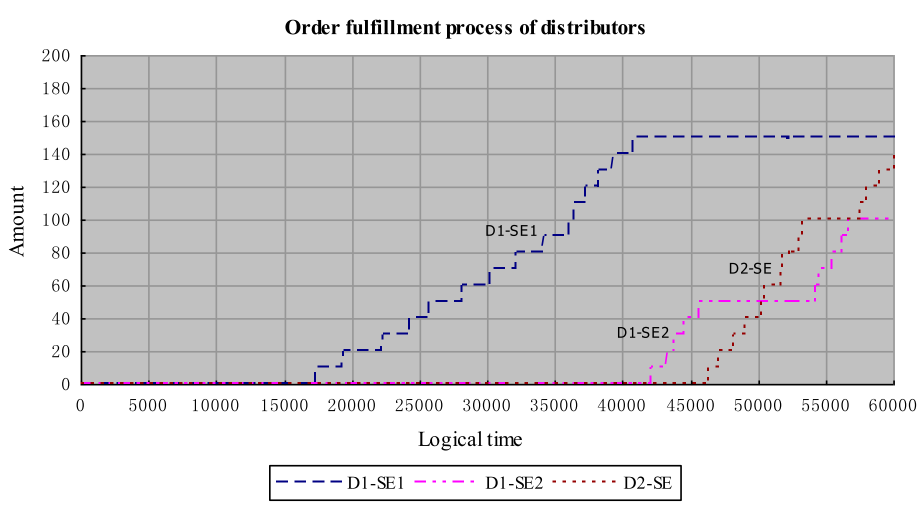


Figure 19. Order fulfilment process of distributors.

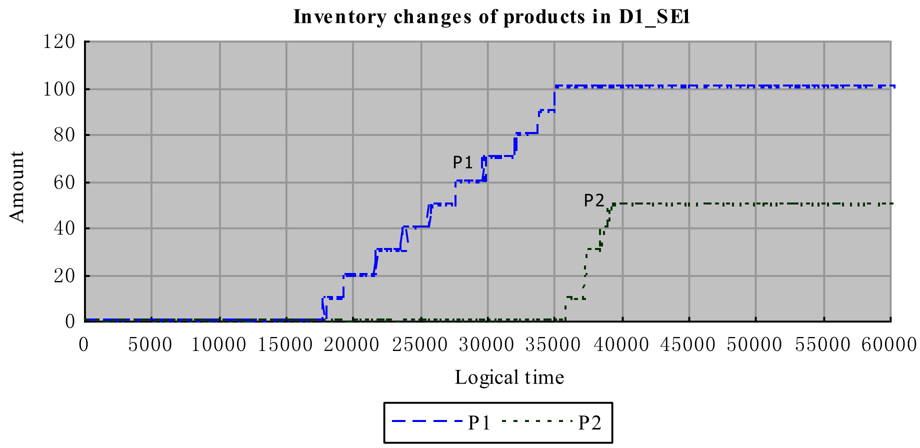


Figure 20. Inventory changes of products in distributors.

the information presented by these charts, it is helpful to reveal subtle inventory changes and draw the decision about whether or not the operations of the configured supply chain scenario are effective to meet the demand of distributors.

7. Conclusions

Modelling and simulation-based approach has great advantages in coping with the dynamically changing characteristics of supply chains in real world, and also has the merits of testability, timeliness and observability. In this paper, we analysed the self-similarity of supply chain systems and proposed a methodological framework for supply chain modelling and simulation based on the fractal perspective. The proposed framework defined five BFEs as the building blocks of models and presented the description of concept modelling and simulation modelling with MAS. In addition, a developed prototype system and its key techniques focusing on the time management and synchronisation for constructing the distributed MAS simulation in compliance with HLA were given detailed introduction. Furthermore, we performed simulation of a typical supply chain example through the prototype system and evaluated the simulation results and corresponding diagrams about manufacturing, inventory and transportation.

The proposed framework introduces fractal perspective for perceiving and modelling of supply chain system, which has the advantages of simplicity, flexibility and extensibility in modelling and simulation at different scales and levels. The developed prototype system based on distributed simulation architecture can effectively simulate and evaluate operations of different supply chain scenarios, which can be a potential tool for design and optimisation of supply chains. However, as a preliminary study, there are some aspects that need to be improved in our further studies: (1) the intelligent self-organisation mechanism of BFEs under the inner and outer environmental effects, which could provide more advantages in supply chain design and optimisation; (2) introducing ontology tool for the top knowledge organisation and retrieval to improve and extend the simulation interactivity among different domains of industry; (3) besides, for the specific environment of supply chain, some further researches related to distributed agent action synchronisation in such situations are significant; (4) with the increasing of simulation scale, the load-balancing problem involving simulation efficiency in distributed environment need to be taken into further consideration; and (5) employing the prototype system for practical applications of supply chains to improve its relevant functions and interfaces.

Acknowledgements

The authors would like to express their gratitude for the reviewers' valuable comments and suggestions that improved the original manuscript.

Funding

This work was supported by National Natural Science Foundation, China [grant number 71071114], [grant number 71101107]; National Science and Technology Support Program [grant number 2011BAC10B08]; Project of Humanities and Social Sciences of Education Ministry [grant number 11YJC630216]; Zhejiang Provincial Natural Science Foundation of China [grant number LQ13G010003]; and Zhejiang Philosophy and Social Science Planning Project of China [grant number 13NDJC039YB].

References

Akanle, O. M., and D. Z. Zhang. 2008. "Agent-based Model for Optimising Supply-chain Configurations." *International Journal of Production Economics* 115 (2): 444–460.

Anosike, A. I., and D. Z. Zhang. 2009. "An Agent-based Approach for Integrating Manufacturing Operations." *International Journal of Production Economics* 121 (2): 333–352.

Bandinelli, R., M. Rapaccini, M. Tucci, and F. Visintin. 2006. "Using Simulation for Supply Chain Analysis: Reviewing and Proposing Distributed Simulation Frameworks." *Production Planning & Control* 17 (2): 167–175.

Bellifemine, F., G. Caire, and D. Greenwood. 2007. *Developing Multi-agent Systems with JADE*. Chichester: John Wiley & Sons.

Bellifemine, F., G. Caire, A. Poggi, and G. Rimassa. 2008. "JADE: A Software Framework for Developing Multi-agent Applications. Lessons Learned." *Information and Software Technology* 50 (1–2): 10–21.

Botti, V., and A. Giret. 2008. *ANEMONA: A Multi-agent Methodology for Holonic Manufacturing Systems*. London: Springer-Verlag.

Canavesio, M. M., and E. Martinez. 2007. "Enterprise Modeling of a Project-oriented Fractal Company for SMEs Networking." *Computers in Industry* 58 (8–9): 794–813.

Cañizares, R. D., and J. M. Framiñán. 2012. "Development of a Multi-agent Platform for Supply Chain-wide Order Fulfillment." *Proceedings of the 4th International Conference on Agents and Artificial Intelligence*, ICAART 2012, Algarve, Vol. 2, 203–208.

Chan, F. T. S., and H. K. Chan. 2005. "Simulation Modeling for Comparative Evaluation of Supply Chain Management Strategies." *International Journal of Advanced Manufacturing Technology* 25 (9–10): 998–1006.

Chan, Y. L., C. F. Cheung, W. B. Lee, and S. K. Kwok. 2006. "Knowledge-based Simulation and Analysis of Supply Chain Performance." *International Journal of Computer Integrated Manufacturing* 19 (1): 14–23.

Chatfield, D. C., T. P. Harrison, and J. C. Hayya. 2006. "SISCO: An Object-oriented Supply Chain Simulation System." *Decision Support Systems* 42 (1): 422–434.

Cigolini, R., M. Pero, and T. Rossi. 2011. "An Object-oriented Simulation Meta-model to Analyse Supply Chain Performance." *International Journal of Production Research* 49 (19): 5917–5941.

Dong, S.-H., B. Xi, L.-N. Tian, Q.-G. Huang, and H.-X. Chen. 2006. "An Agent-based Architecture for Supply Chain Management." *Proceedings of the 2006 International Conference on Machine Learning and Cybernetics*, Dalian, art. No. 4028046, 137–141.

Fujimoto, R. M. 1998. "Time Management in the High Level Architecture." *Simulation* 71 (6): 388–400.

Fujimoto, R. M. 2003. Parallel Simulation: Distributed Simulation Systems. *Proceedings of the 35th Conference on Winter Simulation: Driving Innovation*, WSC '03, New Orleans, LA, IEEE, 124–134.

Fung, R. Y. K., and T. S. Chen. 2005. "A Multiagent Supply Chain Planning and Coordination Architecture." *The International Journal of Advanced Manufacturing Technology* 25 (7–8): 811–819.

Hearnshaw, E. J., and M. M. Wilson. 2013. "A Complex Network Approach to Supply Chain Network Theory." *International Journal of Operations & Production Management* 33 (4): 442–469.

Hung, W. Y., N. J. Samsatli, and N. Shah. 2006. "Object-oriented Dynamic Supply-chain Modelling Incorporated with Production Scheduling." *European Journal of Operational Research* 169 (3): 1064–1076.

IEEE. 2000. *IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)-Framework and Rules*. IEEE Standard No.: 1516–2000. New York: IEEE.

Jafer, S., Q. Liu, and G. Wainer. 2012. "Synchronization Methods in Parallel and Distributed Discrete-event Simulation." *Simulation Modelling Practice and Theory* 30: 54–73.

Jefferson, D. 1985. "Virtual Time." *ACM Transactions on Programming Languages and Systems* 7 (3): 404–425.

Kaihara, T. 2003. "Multi-agent Based Supply Chain Modelling with Dynamic Environment." *International Journal of Production Economics* 85 (2): 263–269.

Labarthe, O., B. Espinasse, A. Ferrarini, and B. Montreuil. 2007. "Toward a Methodological Framework for Agent-based Modelling and Simulation of Supply Chains in a Mass Customization Context." *Simulation Modelling Practice and Theory* 15 (2): 113–136.

Lees, M., B. Logan, and G. Theodoropoulos. 2007. "Distributed Simulation of Agent-based Systems with HLA." *ACM Transactions on Modeling and Computer Simulation* 17 (3–11): 1–25.

Lehr, C. B., J. H. Thun, and P. M. Milling. 2013. "From Waste to Value – A System Dynamics Model for Strategic Decision-making in Closed-loop Supply Chains." *International Journal of Production Research* 51 (13): 4105–4116.

Leitão, P., and F. Restivo. 2006. "ADACOR: A Holonic Architecture for Agile and Adaptive Manufacturing Control." *Computers in Industry* 57 (2): 121–130.

Li, J., and F. T. Chan. 2013. "An Agent-based Model of Supply Chains with Dynamic Structures." *Applied Mathematical Modelling* 37 (7): 5403–5413.

Li, J., and Z. H. Sheng. 2011. "A Multi-agent Model for the Reasoning of Uncertainty Information in Supply Chains." *International Journal of Production Research* 49 (19): 5737–5753.

Lin, F.-R., and M. Shaw. 1998. "Reengineering the Order Fulfillment Process in Supply Chain Networks." *International Journal of Flexible Manufacturing Systems* 10 (3): 197–229.

Lin, F.-R., S.-H. Huang, and S.-C. Lin. 2002. "Effects of Information Sharing on Supply Chain Performance in Electronic Commerce." *IEEE Transactions on Engineering Management* 49 (3): 258–268.

Lin, F.-R., Y.-W. Sung, and Y.-P. Lo. 2005. "Effects of Trust Mechanisms on Supply-chain Performance: A Multi-agent Simulation Study." *International Journal of Electronic Commerce* 9 (4): 91–112.

Long, Q. Q., J. Lin, and Z. X. Sun. 2011. "Modeling and Distributed Simulation of Supply Chain with a Multi-agent Platform." *The International Journal of Advanced Manufacturing Technology* 55 (9–12): 1241–1252.

Longo, F., and G. Mirabelli. 2008. "An Advanced Supply Chain Management Tool Based on Modeling and Simulation." *Computers & Industrial Engineering* 54 (3): 570–588.

Mandelbrot, B. B. 1982. *The Fractal Geometry of Nature*. New York: W. H. Freeman.

Mertins, K., M. Rabe, and F.-W. Jäkel. 2005. "Distributed Modelling and Simulation of Supply Chains." *International Journal of Computer Integrated Manufacturing* 18 (5): 342–349.

Mustafee, N., S. Taylor, K. Katsaliaki, Y. Dwivedi, and M. Williams. 2012. "Motivations and Barriers in Using Distributed Supply Chain Simulation." *International Transactions in Operational Research* 19 (5): 733–751.

Oh, S., K. Ryu, I. Moon, H. Cho, and M. Jung. 2010. "Collaborative Fractal-based Supply Chain Management Based on a Trust Model for the Automotive Industry." *Flexible Services and Manufacturing Journal* 22 (3–4): 183–213.

Pathak, S. D., J. M. Day, A. Nair, W. J. Sawaya, and M. M. Kristal. 2007. "Complexity and Adaptivity in Supply Networks: Building Supply Network Theory Using a Complex Adaptive Systems Perspective." *Decision Sciences* 38 (4): 547–580.

Pirard, F., S. Iassinovski, and F. Riane. 2011. "A Simulation Based Approach for Supply Network Control." *International Journal of Production Research* 49 (24): 7205–7226.

Ryu, K., and M. Jung. 2003. "Agent-based Fractal Architecture and Modelling for Developing Distributed Manufacturing Systems." *International Journal of Production Research* 41 (17): 4233–4255.

Ryu, K., Y. J. Son, and M. Jung. 2003. "Framework for Fractal-based Supply Chain Management of E-biz Companies." *Production Planning & Control* 14 (8): 720–733.

Santa-Eulalia, L. A., S. D'Amours, and J. M. Frayret. 2012. "Agent-based Simulations for Advanced Supply Chain Planning and Scheduling: The FAMASS Methodological Framework for Requirements Analysis." *International Journal of Computer Integrated Manufacturing* 25 (10): 963–980.

Simangunsong, E., L. C. Hendry, and M. Stevenson. 2012. "Supply-chain Uncertainty: A Review and Theoretical Foundation for Future Research." *International Journal of Production Research* 50 (16): 4493–4523.

Strader, T., F.-R. Lin, and M. Shaw. 1998. "Simulation of Order Fulfilment in Divergent Assembly Supply Chains." *Journal of Artificial Societies and Social Simulation* 1 (2): 1–20.

Surana, A., S. Kumara, M. Greaves, and U. N. Raghavan. 2005. "Supply-chain Networks: A Complex Adaptive Systems Perspective." *International Journal of Production Research* 43 (20): 4235–4265.

Tako, A. A., and S. Robinson. 2012. "The Application of Discrete Event Simulation and System Dynamics in the Logistics and Supply Chain Context." *Decision Support Systems* 52 (4): 802–815.

Umeda, S., and F. Zhang. 2006. "Supply Chain Simulation: Generic Models and Application Examples." *Production Planning & Control* 17 (2): 155–166.

Van Brussel, H., J. Wyns, P. Valckenaers, L. Bongaerts, and P. Peeters. 1998. "Reference Architecture for Holonic Manufacturing Systems: PROSA." *Computers in Industry* 37 (3): 255–274.

Warnecke, H. J. 1993. *The Fractal Company.* Berlin: Springer-Verlag.

Weyns, D., and T. Holvoet. 2003. "Model for Situated Multi-agent Systems with Regional Synchronization." *Proceedings of the 10th International Conference on Concurrent Engineering, Agent and Multi-agent Systems*, CE'03, Madeira, Springer-Verlag, 177–188.

Weyns, D., H. V. D. Parunak, F. Michel, T. Holvoet, and J. Ferber. 2005. "Environments for Multiagent Systems State-of-the-art and Research Challenges." *Environments for Multi-agent Systems, Lecture Notes in Computer Science* 3374: 1–47.

Zarandi, M. H., M. Pourakbar, and I. B. Turksen. 2008. "A Fuzzy Agent-based Model for Reduction of Bullwhip Effect in Supply Chain Systems." *Expert Systems with Applications* 34 (3): 1680–1691.