Modelling and Simulation of the Supply Chain of Automobile Industry

Jun-yan Sun 1,2, Wei-ping Fu 1, Wen Wang 1, Dan Yao 1

1 School of Mechanical and Precision Instrument Engineering, Xi’an University of Technology Xi’an 710048, China.
2 School of Mechanical and Electrical Engineering, Shaanxi University of Science and Technology, Xi’an, 710021, China.

Abstract - In this work, a model is built to simulate the dynamic evolution of consumption-driving supply chain system of automobile industry on the geographic information system (GIS) map using agent based model (ABM) and discrete event modeling method. Meanwhile, this model is established by using the ANYLOGIC simulation software and a connection mechanism which can independently choose the upstream or downstream Agent. First, the reliability of the model has been verified by comparing the sale volumes of products and the changes of parameters of each Agent with the realistic supply chain. Second, this model is confirmed to be a typical scale-free network by analyzing the network characteristics of the model employing complex network theory. Last, it is found that the model moves at a chaotic state, which reflects that this model has nonlinear typical characteristics of complex adaptive systems (CASs). Apart from the dynamic evolutionary process of complex networks of automobile supply chain in the macroscopic level, this model also presents the operating process within all Agents in the microcosmic level. Modeling and simulating the supply chain by integrating the synthesizing complex network and the CAS theory provide a new approach for the supply chain management (SCM) and a theoretical basis and empirical reference for the SCM of automobile industry.

Keywords - automobile supply chain, hybrid modelling, simulating, ANYLOGIC software, evolution

I. INTRODUCTION

A supply chain, as a complex network, has some characteristics of complex networks, such as small-world property, scale-free property and clustering [1-2]. Traditionally, the macroscopic models for the evolution of supply chains are generally established by designing the node connection and exit mechanism from the perspective of complex networks [3]. As the node enterprises themselves in these models are lack of autonomy, self-organization and self-learning ability, the models fail to reflect the macroscopic and microscopic links of the evolution the supply chain. A supply chain is not only a complex network, but also a complex adaptive system (CAS) [4]. In view of the defect of complex networks that nodes are autonomous without self-learning ability, R Axelrod [5] put forward a modeling method based on intelligent agent, that is, agent based model (ABM). Because ABMs are highly flexible, integrated, and hierarchic, they can adapt to changing conditions so as to present obvious advantages in the supply chain modeling [6-7]. For the establishment of ABMs, a majority of scholars just focus on the supply chain of a core manufacturing enterprise to simulate local problems of the supply chain. While, the detailed information includes the logistics, information flow, supply-demand relationship and behavior rule among multiple agents in the supply chain are not described in detail [8-9]. Therefore, it is impossible to realize the all-around analog simulation of main procedures involved in the operating process of supply chains, including the plan, purchase, production and distribution so that it is hard to reflect the structure of large supply chain systems [10].

As the most complex and professional supply chain widely acknowledged in the world, the supply chain of automobile industry is composed of enormous amounts of suppliers, manufacturers, distributors and consumers. It is a complex system where competition and cooperation co-exist formed under the influence of external environments. The supply chain, which is driven by consumers and applies manufacturers as the core, is an organic unity of logistics, capital flow and information flow. To deal with the increasingly fierce competition in the automobile market and the impact of economic globalization, it is necessary to comprehensively establish a detailed model for the supply chain of the industry from two perspectives, namely, complex network and CAS. Meanwhile, we also need to study the development and evolution laws of the supply chain of automobile industry so as to scientifically and effectively design and manage the supply chain so that endow automobile industry with lasting competitiveness.

II. CONCEPTUAL MODEL

A. Basic principle of model design

In essence, modeling based on agents is a collection of interacting objects, and the whole behavior is the result of the interaction among the individual objects. By regarding each enterprise and consumer in a supply chain as an independent agent, the enterprises and consumers can be classified into 4 categories, namely, supplier, manufacturer, distributor and consumer agents. Based on the geographic information system (GIS), all kinds of Agents in a supply chain are established according to the
corresponding position where survey data are acquired in the GIS map. Moreover, the parameters, behaviors, states and choice mechanism of upstream and downstream of each agent are defined. In addition, the authors also set some auxiliary agents, such as the agent used to express the information and the comprehensive factors affecting consumers buying an automobile. The independent agents in all kinds of agents can dynamically and independently choose the agents in the upstream and downstream according to their business conditions and decision rules. In this way, the authors build a complex network model to simulate the dynamic evolution of supply chains. Then, the rationality and effectiveness of the model are verified by practical examples followed by analyzing the network characteristics of the supply chain of automobile industry through the complex network theory. Furthermore, the authors also analyze the nonlinear characteristics based on the CAS theory.

B Behaviours of all agents

B1. Behaviours of consumer agents

Consumer agents mainly behave in the following three manners:

1) Choosing distributors. The behavior that consumers choose and buy products can be measured by the combination of consumer utility with distance. The former mainly includes four parts, namely, price, quality, promotion and reputation. The combination of consumer utility with distance can be expressed by formula 1.

\[
U_i = U_{p_i} + U_{q_i} + U_{w_i} + U_{a_i}
\]

\[
TU_i = U_i + L_i
\]

\[
st. \quad TU_i > TU_{i'}
\]

(1)

Where \(U_i\), \(U_{p_i}\), \(U_{q_i}\), \(U_{w_i}\), and \(U_{a_i}\) represent the total utility, price utility, quality utility, reputation utility and promotion utility of a consumer, respectively. While \(TU_i\), \(L_i\), and \(L_i\) denote the general comment between the consumer utility and distance, distance between consumer \(i\) and a distributor, and interest value of consumer \(i\) for buying products, that is, the critical point of purchase (POP), separately. Consumers choose the maximum \(TU_i\) to order by comparing \(TU_i\) of all distributors.

2) Ordering from distributors. After determining the brand of the automobile to be bought, consumers are supposed to order from the nearest distributor of the brand in the nearest distance. If the distributor has inventory, the consumer directly takes delivery; otherwise, the consumer needs to wait for the distributor to order. If the waiting time exceeds 30 days, then the consumer gives up the purchase of this brand and chooses distributors again.

3) Receiving finished automobiles (taking delivery). After receiving the finished automobile, the consumer is expected to become the customer of the automobile brand. The specific behaviours of consumers are displayed in Fig. (1). (a).

B2. Behaviours of distributor agents

The behaviours of distributors are mainly divided into five types:

1) selecting manufacturers. According to the rule, a distributor can merely sell automobiles of one brand, that is, one distributor only chooses a manufacturer. In this way, the brand sold by each distributor is determined. However, distributors selling automobiles of a same brand not always order from the same manufacturer but order from the nearest factory producing automobiles of this brand according to the principle of proximity;

2) purchasing. The products purchased by distributors are the finished automobiles;

3) managing inventory. Because the inventory of distributors is the finished automobiles, we adopt a strategy of maximum and minimum inventories (S, s);

4) managing orders. According to the first-come-first-served principle, the orders are processed in sequence;

5) selling and transporting. When the inventory is greater than 1, consumers are allowed to take automobiles directly. The order quantity can be calculated by formula 2.

\[
N_{Di} = S_D - (K_{Di} + K_{pi} - N_{Ci})
\]

\[
st. \quad K_{Di} + K_{pi} - N_{Ci} < s_D
\]

(2)

Where \(N_{Di}\), \(N_{Ci}\), \(K_{Di}\) and \(K_{pi}\) signify the order quantity of a distributor \(i\), the order of consumers, the practical inventory of the distributor \(i\) and the in-transit stock of finished goods, respectively. While \(S_{Di}\) and \(S_D\) are the set values of maximum and minimum inventories of the distributor \(i\). The detailed procedure of distributor behaviours is presented in Fig. (1). (b).
B3. Behaviours of Manufacturer Agents

Manufacturers play the key role in the supply chain and are mainly in charge of assembling the automobile products. Manufacturers mainly have the following six behaviors:

1. Choosing suppliers. Manufacturers choose suppliers according to the information including the distance and the service quantity of distributors.
2. Managing inventory. Because the current order rules (including the order time, the order quantity of each time and inventory) of distributors from manufacturers are set by manufacturers, the manufacturers reduce their finished inventory by playing the dominant role in the order of new automobiles. Therefore, manufacturers adopt an order-oriented assembling method to manage inventories, that is, automobiles are assembled after receiving orders from distributors. The parts inventories of manufacturers are managed by using the strategy of maximum and minimum inventories (S, s).
3. Purchasing. Manufacturers check inventories of each kind of needed parts, in-transit inventory, the finished inventory and the number of work in process (WIP). After counting the numbers of each type of needed parts of currently unfilled orders by using bill of material (BOM) tables, manufacturers order from suppliers. The order quantity is calculated using equation 3.

\[
N_{Mi} = S_{Mi} - (K_{Mi} + K_{hi} + K_{ti} + Z_{Mi} - N_{Di})
\]

\[
st. \quad K_{Mi} + K_{hi} + K_{ti} + Z_{Mi} - N_{Di} < S_{Mi}
\]

\[N_{Mi}, N_{Di}, K_{hi}, K_{ti}, K_{Mi} \text{ and } Z_{Mi}\] represent the order quantity of a manufacturer i, total order quantity of all distributors of the manufacturer i, the inventory of parts, the in-transit inventory of parts, the finished inventory and the number of WIP. \(S_{Mi}\) and \(S_{Mi}\) signify the set values of the maximum and minimum inventories of the manufacturer i.

4. Producing. When the sum of finished inventory and WIP number is less than the total number of unfilled orders and the inventory of parts meets production requirements at the same time, manufacturers start to produce automobiles. Here, the production requirements refer to that the inventory of each kind of parts is at least higher than the number for producing an automobile.
5. Managing orders. According to the first-come-first-served principle, the orders are processed in sequence.
6. Selling and transporting: when the finished inventory is greater than the quantity of the first order, the manufacturer is supposed to deliver automobiles to the distributor placing this order; the transporting time is related to the distance between the manufacturer and the distributor. The detailed procedure of manufacturer behaviors is illustrated in Fig. (1). (c).

B4. Behaviours of Supplier Agents

The behaviors of suppliers are mainly reflected in the following four aspects: (1) Managing orders. Suppliers process orders according to the time of receiving orders, that is, first come, first served. (2) Managing inventory. The inventory of suppliers refers to the finished inventory of parts, and here, we also adopt a strategy of the maximum and minimum inventories (S, s). What differs from manufacturers and distributors, suppliers always have an enough inventory of raw materials, which can meet the production requirements all the time. That is to
say, suppliers don’t need to purchase raw materials at any
time, so there is no inventory of raw materials. (3)
Producing. When the sum of inventory of parts and the
WIP quantity is less than the ordered quantity, suppliers
start to producing. (4) Selling and transporting. When
suppliers receive the purchasing orders from
manufacturers, they need to check whether the inventory
of parts meets production requirements or not. If the
inventory of parts meets the requirements, then suppliers
are supposed to immediately deliver goods; otherwise,
they start to produce the needed parts. The detailed
procedure of supplier behaviours is shown in Fig. (1). (d).

III. CONSTRUCTION OF SIMULATION MODEL

A. Generating GIS map

In order to vividly and effectively describe the
dynamic evolutionary behaviours in the space of the
supply chain of automobile industry, we need to first
generate a simplified GIS map of China mainland first, as
shown in Figure 6. All agents in the model (supplier,
manufacturer, distributor and consumer agents) and the
relationships among them (the connecting line for sending
information between agents) are displayed in the map.
Based on the map, the changing process of the spatial
topology of the supply chain can be observed. In the
process of establishing intelligent agents in the GIS map,
the initial parameters of suppliers, manufacturers,
distributors and consumers are firstly imported from
Excel charts to establish agents at the corresponding
positions in the GIS map. The establishing methods can
be divided into two categories: one is the direct
establishment according to places (such as Beijing and
Tianjin) and the other is to establish agents in the
corresponding provinces without stipulating the specific
sites. According to the quantity and attributes of all
agents, manufacturer and distributor agents are
constructed adopting the first method, while consumer
and supplier agents are established using the second
method.

B. Construction of simulation model

The behaviours of agents are defined using
ANYLOGIC software by means of the state and action
charts. The former focuses on describing the state changes
of entities; while the latter images the entity behaviours of
entities using the structured algorithm to understand and
establish the model more easily. The states of consumers
illustrated in Figure 2 are converted by changes. The
purchase, inventory management, and sale activities of
distributors are displayed by the action diagram, as shown
in Figure 3. The behaviours of agents are mainly realized
by writing and invoking functions using Java. The state
and action diagrams of other agents are similar to that of
distributor agents, so they are not displayed in the paper.

In order to more comprehensively simulate the
operating process of the supply chain, the discrete event
modelling is introduced based on the ABM method.
Discrete event modelling, as a process-centred modelling
method, can preferably simulate the production and
transportation processes of manufacturers. The discrete
event modelling in the production and transportation
processes of manufacturers is displayed in Figures 4 and
5. In addition, to transmit information of order, sale and
geographic position among consumer, distributor,
manufacturer and supplier agents, the “linking to the
agents” tool of ANYLOGIC software is used to carry out
the data interaction among multiple agents.

IV. EMPIRICAL ANALYSIS

The supply chain network is built for 12 automobile
brands ranking in the top ten in the automobile market of
China mainland in the past five years (including price,
quality, reputation, quantity, geographic coordinates).
Suppose that automobiles are composed of 7 parts
including an engine, an automobile body, a transmission
system, a traveling system (such as suspension), a steering
system, a braking system and an electrical equipment,
then suppliers can be divided into 7 categories. Among
them, the transmission system contains a gearbox, a main
reducer and a differential. Manufacturers can be divided
into 12 categories which respectively produce
automobiles of 12 different brands. Manufacturers are not
in charge of the production of these parts but assemble the
parts to finished automobiles, so seven kinds of parts are
all purchased from different suppliers. The initial
conditions of simulation cases are set as follows: there are
total 23 provinces, 5 autonomous regions, and 2 special
administrative regions in China. According to the rules,
there is only one distributor for each brand in a province
or region, so automobiles of each brand are corresponding
to 30 distributors, that is, a total of 360 distributor agents
of the 12 brands. A total of 32 manufacturer agents of 12
brands are set on the basis of the investigation. Each part
has five suppliers, so there are total 35 supplier agents.
That is, totally 427 enterprise agents are contained. The
quantity of consumer agents is set as 13,529 (unit: a
hundred thousand people). Figure 6 presents GIS based
network structure generated in the simulation experiment.

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In Figure 6, the yellow, red and green regions represent suppliers, manufacturers and distributors, respectively. While the scattered dots and their different colours signify consumers and the different states of consumers, separately. There into, the trade behaviours exist among suppliers, manufacturers and distributors, which are connected by lines, while the unconnected dots represent those not contained in the supply chain network. In the simulation experiment, there are total 153 enterprise nodes within the network, among which, there are 27 manufacturers, 26 suppliers and 100 distributors.

A. Model Verification

A1. Sale Verification

Figures 7 and 8 illustrate the occupied market proportions of enterprises and the sale volumes of suppliers, manufacturers and distributors. Table 1 shows the sale volumes.

(1) According to the above figures, the sale volumes of nine suppliers including 1, 6, 8, 10, 17, 18, 19, 20 and 27 are 0, so they do not enter into the supply chain network; the other 26 suppliers all are contained in the supply chain network, which coincides with the basic principle of “survival of the fittest”. (2) Because all the quantities of each type of needed parts in the production of the finished automobiles are 1, although the sale amounts of the 7 parts are different, they are expected to be same in principle. According to the above table, the total sale volumes of the 7 parts are different, but they are all close to 3,000, which is consistent with the order rules.
of manufacturers. (3) It can be seen from the above table that the largest quantity (26,150) of finished automobiles produced by using the parts provided by suppliers is larger than the total sale volume (19,680) of manufacturers, which is more than that of distributors (18,614). The results meet the essential condition of the supply chain, that is, the sale volumes of suppliers need to be higher than those of manufacturers, which is larger than that of distributors.

Fig.(7). The sale volumes of suppliers supplying engines, automobile bodies, electrical equipment, traveling systems and transmission systems

TABLE 1. THE SALE VOLUMES

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Manufacturer</th>
<th>Distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total sale volumes</td>
<td>The maximum quantity of finished automobiles can be produced</td>
</tr>
<tr>
<td>Engine</td>
<td>30938</td>
<td>26150 (26,150)</td>
</tr>
<tr>
<td>Automobile body</td>
<td>26673</td>
<td>26150</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>30058</td>
<td>26150</td>
</tr>
<tr>
<td>Traveling system</td>
<td>26150</td>
<td>19680</td>
</tr>
<tr>
<td>Transmission system</td>
<td>30961</td>
<td>26150</td>
</tr>
<tr>
<td>Steering system</td>
<td>29896</td>
<td>26150</td>
</tr>
<tr>
<td>Braking system</td>
<td>35751</td>
<td>26150</td>
</tr>
</tbody>
</table>

(4) By comparing the sale volumes of manufacturers and distributors in Figure 8, it can be known that the occupied market proportions of manufacturers and distributors of each brand are basically same, but the sale volumes of manufacturers of each brand are always larger than those of distributors, which meets the essential condition of the supply chain.
Figure 9 shows the change trends of the total sale volumes and market shares of automobiles of the twelve brands. According to the figure, the sale volumes of the automobiles of each brand present the rising trend with time on the whole. However, different brand automobiles show different sale volumes and increasing ranges; meanwhile, the market shares and ranks of each brand also constantly change over time. After a certain time, the market share of each brand reaches a relatively stable state, which accords with the same change rules of the sale volumes and market shares of automobiles of different brand in real life. In this way, the validity of the model is verified.

A2. Verifying the Changes of Main Parameters of Agents

(1) Changes of main parameters of supplier agents

Figures 10 and 11 demonstrate the time lines of main parameters of supplier 11 and supplier 22, respectively. The common points of the two figures are: (1) the total sale volumes all show a rising trend; (2) the curve of unfilled orders is similar to that of WIP inventory; and (3) with the reduction of the finished inventory, the total sale volumes increase by corresponding values, while unfilled orders reduce by the corresponding values. The different point lies in that supplier 11 continuously produces products in the simulation; on the contrary, supplier 22 just produces products occasionally. The reason is that the orders received by supplier 11 are more than the production capacity of the supplier so that the unfilled orders are greater than 0 all the time; while supplier 22 receives few orders and does not receive new orders after processing the received orders, leading to the halting production. During the shutdown, the unfilled orders, the finished inventory and the WIP are 0, and the total sale volumes maintain at the original value. This is consistent with the behavior rules set for suppliers in this paper. Moreover, the simulation model is verified to be correct and reasonable.

(2) Changes of main parameters of manufacturer agents
Figures 12 and 13 are the time line graph of main parameters and the time stacking graph of in-transit inventory of manufacturer 2, separately. While Figures 14 and 15 are the time line graph of main parameters and the time stacking graph of in-transit inventory of manufacturer 21. By observing Figures 12-15, we can know that only when the in-transit inventory of all the 7 parts is 0, the quantity of the WIP increases, which indicates that manufacturers do not take production activities until they receive parts from suppliers. According to the rules in this paper, suppliers can produce products according to the order quantity; while for manufacturers, the production of the finished goods is determined by existing parts inventory. Therefore, when the unfilled orders of manufacturers are less than the finished inventory, manufacturers are expected to directly deliver goods; otherwise, while lacking of goods, manufacturers order goods from suppliers to produce the products after receiving the parts. This law can be seen from Figures 12 and 15. This coincides with the behavior rules set for manufacturers in this paper and verifies the correctness of the simulation model.

(3) Variations of main parameters of distributor agents

Figures 16 and 17 present the changes of main parameters of distributor 7 and distributor 32, respectively. It can be seen from the two figures that at the beginning of the simulation, distributor 7 does not receive orders from consumers, while distributor 32 receives orders from consumers. It reflects that consumers enter the simulation model at different moments, which meets the requirement of the conceptual model. Meanwhile, we also find that the relationships among unfilled orders, the finished inventory, the in-transit inventory and the sale volumes also conform with the distributor behaviours set in the conceptual model. The result verifies the correctness and rationality of the simulation model.

Through the above discussions, the model is analyzed from two aspects, namely, sale volumes and the changes of main parameters of agents. By doing so, the model established in this paper is verified to be correct and reasonable.

B. Network characteristics of cases from the perspective of the complex network

The network structure of the model is drawn by using the PAJEK software, which is an annular chart, as shown in Figure 18. In this figure, the red dots represent the enterprise nodes, while the nodes where on the black lines are intensively distributed are the manufacturer enterprise nodes. To more clearly observe the network structure of the supply chain, the spatial distribution of the network is drawn by using the Kamada-Kawai algorithm, as illustrated in Figure 19. Thereinto, nodes 1-27, 28-53 and 54-153 represent manufacturers, suppliers and distributors, separately. The degree distribution of nodes
in the supply chain network can be obtained by counting the node degrees using PAJEK software and carrying out the data statistic and numerical fitting using MATLAB software. The specific condition is shown in Figure 20. According to the figure, the curve obeys the power-law distribution of \( f(x) = x^{-\gamma} \).

According to Figures 18-20, in the network, most nodes are connected by few lines, while a few nodes (manufacturers 1-27 and suppliers 30, 43, 45 and 50) are connected by a large number of lines, indicating that this network belongs to a typical scale-free network. When the high-degree nodes are attacked, the whole network is likely to be paralyzed. As these high-degree nodes play a key role in the smooth running of the network, their maintenance needs to be paid more attention.

C. Analyzing from the perspective of the CAS

Figures 21 and 22 illustrate the power spectra drawn according to the inventories and orders of distributor 7, respectively. It can be seen from the figures that there is no obvious peak in the spectra and the values change continuously; thus it can be identified that the distributor presents chaotic motion. Through the above qualitative analysis, we can know that this system is a nonlinear system and moves at the chaotic state.

Figures 23 and 24 present the three-dimensional (3D) phase space obtained by integrating three variables, namely, the orders, inventories and sale volumes of distributor 7 and manufacturer 21, separately. According to the figures, the 3D phase space charts are open on the whole, containing helical curves distributed irregularly and disorderedly in the morphology, which implies that the motion of the network is shown to be at the chaotic state.
The maximum Lyapunov exponent in this system is calculated by using wolf algorithm, followed by normalization of the maximum values of the data. Therefore, the maximum Lyapunov exponents of orders, inventories and sale volumes are 0.00152, 0.00104 and 0.00086, respectively. Because the maximum exponents of this system are greater than 0, it further explains that the chaos phenomenon occurs in this system. Therefore, we can quantitatively judge that this system is in the chaotic motion under the conditions set above and it is a nonlinear dynamic system with the nonlinear typical characteristics of the CAS.

V. CONCLUSIONS

(1) In the construction of the model: the GIS map is introduced to more vividly reflect the dynamic evolution of the supply chain. By establishing using a hybrid modelling method combining the ABM with the discrete event modelling method, the model reflects the operating processes of all agents in the microcosmic level so as to preferably present the overall procedure of the supply chain. By building the information agents and environment agents, information is exchanged among all agents so as to preferably reflect the information flow and environmental factors of the supply chain. This simulation model lays a foundation for studying the evolutionary and emergence mechanisms of the supply chain.

(2) To verify the model is correct and reasonable, the sale volumes of all agents are analysed, as well as the changes and mutual relationships of main parameters of all agent nodes. These main parameters include the sale volumes, orders, inventories (finished inventory and parts inventory), in-transit inventory and WIP.

(3) As for the simulation analysis, the simulation model is analysed from two perspectives: the complex network and the CAS. Meanwhile, the authors discuss the simulation process in the macrocosmic and microcosmic levels. From the complex network perspective, the supply chain network displays the scale-free and small-world characteristics and the distribution of node degrees coincides with the power-law distribution by analysing the relationships among nodes in the supply chain network. In addition, by analysing the power spectra, the phase spaces and Lyapunov exponents of distributors and manufacturers, it proves that the supply chain is in the chaotic motion. Besides, the supply chain belongs to a nonlinear dynamic system with the typical nonlinear characteristics of CAS.

(4) To overcome the shortcomings of the model, the following works are expected to be carried out in the future: a) the model shows the functions in the departments including sales, purchasing, production and inventory, while it does not establish corresponding agents for the functions. Therefore, it is essential to further improve the interior structure of agents, to build a model based on multi-layer agents with departments such as sales, purchasing, finance, production and inventory being included. By doing so, the research range is supposed to be expanded, accompanying with increasing quantity of subjects (consumers, manufacturers and suppliers); b) furthermore, this model is built merely considering the influence of market factors (reputation, quality and price) on consumers’ purchasing behaviours. Therefore, researchers need to comprehensively consider the influences of macroeconomic and microeconomic environments as well as policy factors in the future; and c) the learning system of the agents needs to be introduced along with the design of an appropriate intelligent algorithm. Furthermore, it is also necessary to study the cluster and emergence characteristics of the supply chain network from the complex networks and the CASs.
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About the authors:
Sun Jun-yan (b. 1978), female, Shaanxi Dali, Associate Professor, PhD, research interests in Logistics Engineering and Industrial Engineering. Tel.: 13772080962; E-mail: tjmsjy2003@sina.com (Corresponding author).
Fu Wei-ping (b. 1957), male, Shanghai, PhD, Professor, research interests in non-linear dynamics, and modern logistics systems engineering and technology.
Wang Wen (b. 1966), female, Xi’an, PhD, Professor, research interests in non-linear dynamics, and modern logistics systems engineering and technology.
Yao Dan (b. 1990), female, Yuncheng, Shanxi, MSc, research interests in hybrid modelling and simulation of supply chain networks.