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Research Article

Modeling and Simulation for Effectiveness Evaluation of Dynamic Discrete Military Supply Chain Networks

Biao Xiong, Bixin Li, Rong Fan, Qingzhong Zhou, and Wu Li

Department of Oil, Army Logistics University of PLA, Chongqing 401311, China

Correspondence should be addressed to Biao Xiong; xiongb001@126.com

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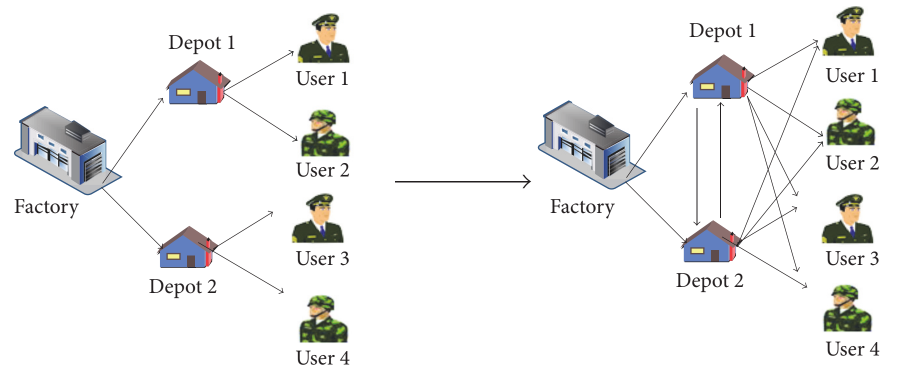
The effectiveness of military supply chain networks is an important reference for logistics decision-making, and it is crucial to evaluate it scientifically and accurately. This paper highlights the problem from the perspective of dynamic and discrete networks. A topological structure model with the characteristics of dynamic and discreteness is used to describe the structure of military supply chain networks (MSCNs). In order to provide a platform for evaluating the effectiveness, simulation algorithms based on topological structure models for MSCNs are presented. Considering military and economic factors, evaluation metrics including supply capability and supply efficiency are proposed. By applying the model and algorithms to a POL supply network in a theater, we obtain the values of supply capability and efficiency metrics in a dynamic environment. We also identify an optimal solution from multiple feasible solutions to help decision-makers to make scientific and rational decisions by using exploratory analysis method. The results show that new evaluation metrics can capture important effectiveness requirements for military supply networks positively. We also find the proposed method in this paper can solve the problem of evaluating the effectiveness of dynamic and discrete network effectiveness evaluation in a feasible and effective manner.

1. Introduction

Networks are ubiquitous in our daily lives, such as the communication networks that we use to contact each other by cell phones, social networks that reflect the connections between people, and molecular structure networks that illustrate the nature of the material [1–3]. An important feature of this type of network is that its topological relationships and structure are constant. In other words, these are continuous networks [4]. The topological structure of continuous networks is one of the most active areas of complex network study at present [5, 6]. In many other real-world networks, the connections between nodes change over time rather than remaining constant. This type of network is called a discrete network [7]. Military supply chain networks (MSCNs) are one of the most common discrete networks. Compared with a traditional supply chain, the MSCN has more entities, and its dynamic feature is more obvious. In a military supply chain network, supply units and battalions rely on supply orders to connect dynamically. At some point, a connection is established when a supply unit places an order of goods to a battalion. Without the order, there is no connection between the two.

The efficiency and effectiveness of MSCNs are the main concerns for logistics decision-makers [8]. However, the connections between supply units and battalions are under constraints of transportation, storage, traffic, labor power, and so forth, which can make MSCNs extremely complicated and unpredictable [9]. Meanwhile, the effectiveness of military supply chain networks often faces disruptions under uncertain conditions [10]. Therefore, a commander is supposed to scientifically evaluate the effectiveness of the entire military logistics support network and to make measured decisions after considering the above factors.

Since traditional research on the effectiveness evaluation of military supply chain normally includes only a few entities [11], when it comes to strategic-level paradigms with hundreds of entities in an MSCN, these methods are no longer satisfactory. But the analytical method of complex networks can solve this problem very well [12]. Some researchers consider the MSCN as a continuous and complex network to analyze the reliability and resilience of its structure [13], while



(a) Military supply chain

(b) Military supply chain network (MSCN)

Figure 1: Structural diagrams of military supply systems.

few strategists study the MSCNs from the perspective of the effectiveness and efficiency evaluation of discrete networks. In this paper, we adopt the complex network view of supply chains and study the effectiveness and efficiency of MSCNs as discrete networks. We consider capability and efficiency as the two most useful parameters for effectiveness evaluation. We then build a dynamic and discrete simulation algorithm to evaluate the effectiveness of MSCNs in order to reach accurate evaluation results by guaranteeing a good agreement between the simulation outcomes and practical situations.

The remainder of the paper is organized as follows. We first briefly review related research. In the second section, we establish the simulation model and effectiveness metrics of MSCN. In the third section, we apply the model and algorithm to evaluate the effectiveness of a special MSCN called the POL support network. Finally, the paper gives a conclusion and discusses possible directions for future research.

2. Review of Related Research

Scholars' research on the structure, resilience, and reliability of supply chain networks can be summarized as a category of effectiveness evaluation of supply networks [14, 15]. Existing literatures contain ways to evaluate and optimize the effectiveness of supply networks [16–20]. However, the supply network optimization problem is NP-hard. Although the traditional methods can evaluate the resilience and reliability of small-scale and static supply chains from the perspective of topological structure, evaluating the effectiveness of MSCNs involves many supply units and has more limitations on resources and other influencing factors, which makes it difficult for the traditional methods to handle it [13, 21].

In order to solve the MSCN evaluation problem with the features of complexity, emergence, and dynamics [22], simulation techniques are applied. Some experts use Monte Carlo Simulation, Bayesian Networks, and System Dynamics Method to build the simulation models [22–25], but these kinds of simulation models, which can simulate static structures, can hardly simulate the dynamic variation process of the military supply chain network's structure. With the development of complex networks, the complex network technology is used to evaluate and optimize structural properties of supply chain networks while regarding them as continuous networks. However, supply chain networks are discrete networks in practice [13, 15]. In effectiveness evaluation, continuous networks and discrete networks have great differences, if the attributes of the network are indiscriminate, wrong conclusions can easily be made. Also, if the evaluation metrics of continuous networks are used to evaluate discrete networks, errors could appear in the evaluation results.

For this purpose, the authors propose a discrete network effectiveness evaluation simulation model, which contains an evaluation algorithm and two metrics. Then we apply a POL supply chain network in a theater as an example and use ARENA to build an evaluation system to assess the effectiveness of the POL supply chain network. The validity and advancement of this method have been proved in this paper.

3. Proposed Approach

With the increasing supply demands of modern warfare, the traditional structure of military supply chain has been evolving into a dynamic and complex MSCN structure. Compared with the traditional logistics chain, MSCNs have two distinct features. The first is the larger size of the network. Since logistics material consumption is becoming larger with the evolution of warfare forms, there is a need for more utilities to be engaged in supply activities. Thus, MSCNs are growing correspondingly larger. The second feature is the complexity of networks. Figures 1(a) and 1(b), respectively, show the supply chain and supply chain network structure diagrams. Because of different attributes like functional localization, geographical location, capacities, and so forth, entities (factory, depots, and users) are mutually independent. The supply relationships between them are indicated by the connections. If there is a connection between two entities, it means that there is a flow of goods between them.

In Figure 1(a), a traditional supply chain can be represented with a chain structure which ensures that the relationships between entities are restricted to upstream

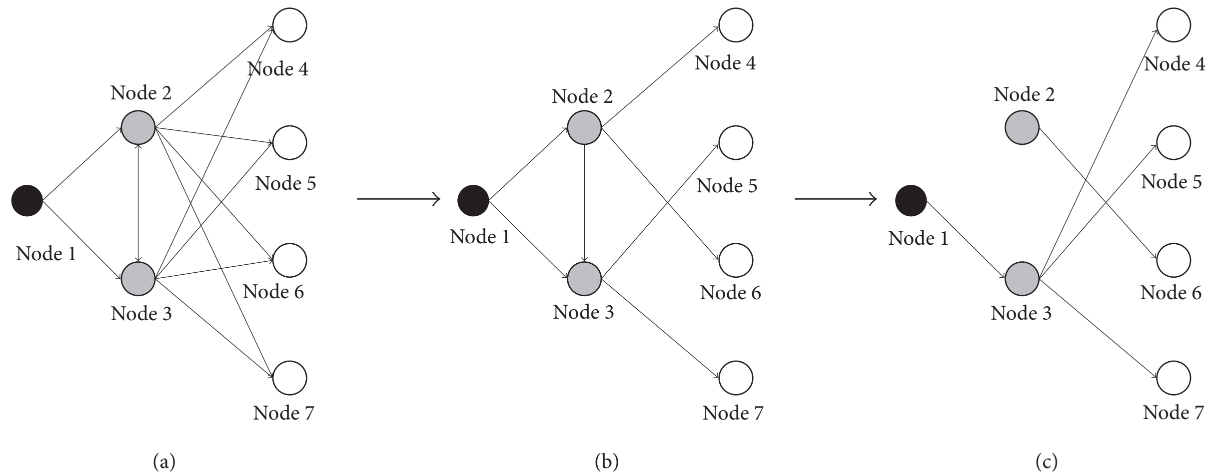


Figure 2: The evolution process of MSCN structure.

and downstream. However, the supply chain networks in Figure 1(b) present a more interactive structure, because changes within the system are closely linked with each other. This close relationship means that any slight move of one point will influence other parts of the network. As a closer relationship exists between each entity of a supply chain network compared with a single supply chain, there has been increasing difficulty to guarantee a concise evaluation of their supply capability and efficiency.

MSCN has become the basic form of the military logistics system. In order to help decision-makers make scientific decisions on logistics support activities, an accurate evaluation of MSCNs' efficiency is needed. In order to solve this problem, this section is organized as follows. First, we present a model of MSCN structure that reflects the characteristics of the networks by using complex networks. Then, we put forward simulation algorithms of network structure for MSCNs based on the MSCN structure model. Finally, we propose two evaluation metrics of MSCN from the aspects of capability and efficiency, which are able to reflect dynamic features of MSCNs in reality.

3.1. The Structure Model of MSCNs. A MSCN can be shown as a directed graph composed of nodes, edges, and attributes, $G = G(V, E, R, \psi)$. In the directed graph G, V stands for the node set representing factories, warehouses, demanded forces, and so forth. E stands for the connection of nodes forming by traffic network and the relationship of supply entities. R represents attributes of supply entities such as physical capacity, location, cargo loading cases, and supply priority; ψ is a relationship function between nodes and edges. Figure 2 shows MSCN structural evolution established by the complex network model.

Figure 2(a) is the relationship diagram of Figure 1(b), which only embodies the supply relationships between entities in the MSCN and does not mean that there are always supply activities between entities. Figures 2(b) and 2(c), respectively, show the MSCN structure at time t and time $t + n$. The actual supply relationships of MSCNs are diverse at different times. For example, node 4 has an established relationship with node 2 at time t, while, at time $t + n$, it has established a relationship with node 3. This kind of structural changes is significantly different from a continuous network.

3.2. Simulation Algorithms for MSCNs. As shown in Figure 3, a simulation algorithm for MSCN can be divided into five steps.

(1) Time Constraints. The algorithm judges whether the time t is within the scheduled time of operations *SumTime*. If so, the simulation enters the second step. Otherwise, simulation ends.

(2) Creating Orders. The algorithm searches for all demand nodes V_j that actual inventory level VD_j^t is less than the preset threshold VDR_j and then creates order OR_j^t.

(3) Order Sorting. The algorithm sorts the orders by importance and urgency and generates the sequence SEQ^t.

(4) Confirming the Relationships between Nodes. According to the sequence SEQ^t and the support rule, the algorithm is assigned from supply nodes to each demand node by supply relationship. At the same time, the algorithm judges if the supply node provides available supplies and vehicles to meet the needs of the supply order or not. If the supply node cannot meet the demand, a later adjustment to other supply nodes will be placed on hold in accordance with supply relationships. The supplies will be provided by the assigned supply node if the node is able to meet the demand.

(5) Executing Tasks. After confirming the relationships, the orders are carried out.

In the process,

t is time of operations;

SumTime is scheduled time of operations;

V_j is the demand node;

V_i is the supply node;

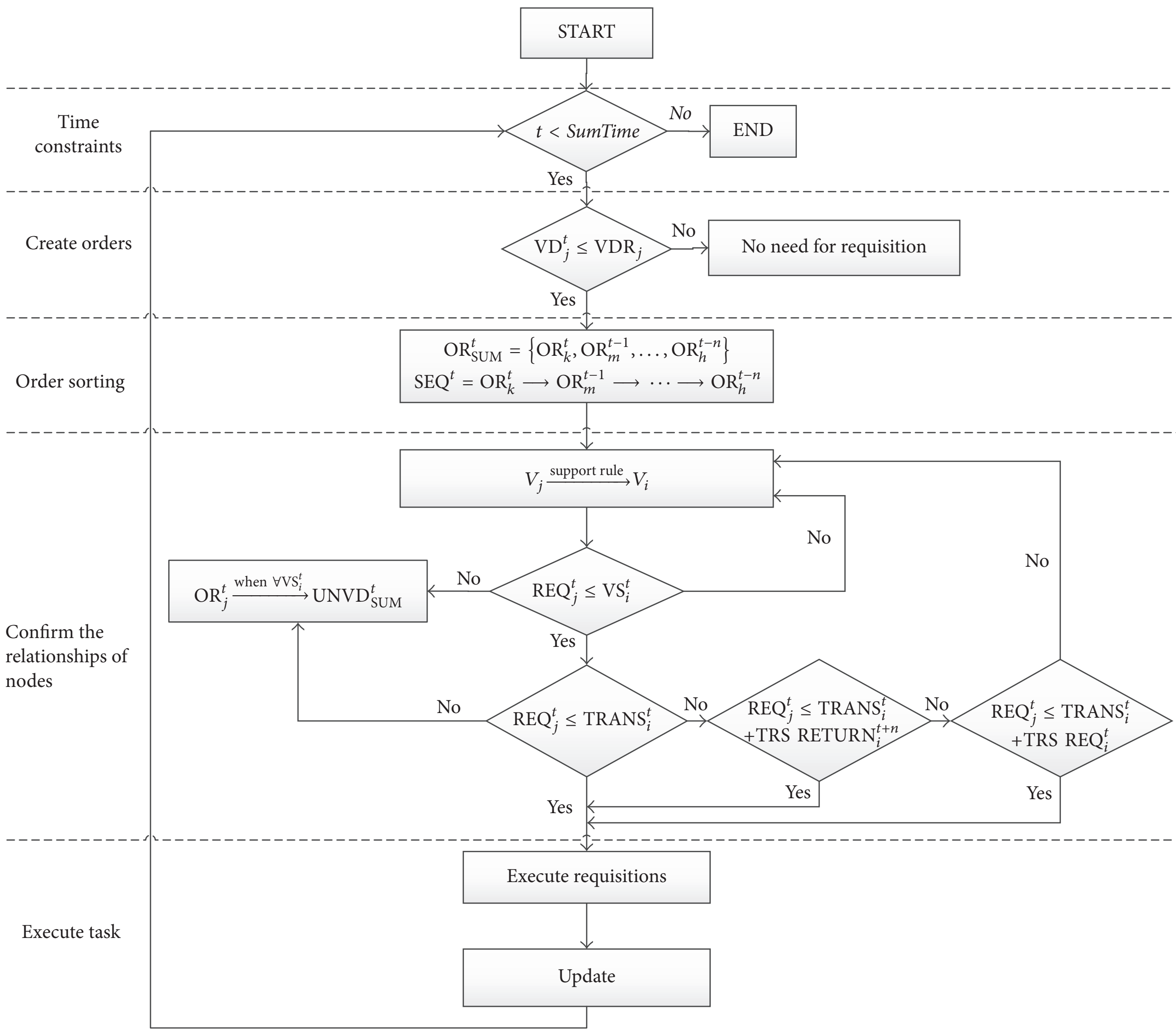


Figure 3: The process of simulation algorithm for MSCN.

VD_j^t is the inventory level of the demand node V_j at time t;

VS_i^t is the inventory level of the supply node V_i at time t;

VDR_j is the application threshold of the demand node V_j;

OR_j^t is the order of the demand node V_j at time t;

VD_{SUM}^t is a collection of all orders at time t;

$UNVD_{SUM}^t$ is a collection of unfinished orders of time t;

SEQ^t is supply orders sorting at time t;

REQ_j^t is applications of the demand node V_j at time t;

$TRANS_i^t$ is the amount of available transportation tools of the supply node V_i at time t;

$TRS\ REURN_i^{t+n}$ is the amount of available transportation tools of the supply node V_i at time $t+n$;

$TRS\ REQ_i^t$ is the amount of available transportation tools of another supply node V_k transferred to supply node V_i at time t;

$VOLUME_j$ is general supplies inventory of the demand node V_j.

3.3. Effectiveness Metrics. The taxonomy of effectiveness evaluation usually consists of military and economic metrics. These two metrics are interdependent and restrain each other. Military need is based on economic base, and it is meaningless to discuss economic efficiency without considering military need. Furthermore, only considering military need without economic efficiency is not realistic, and a sole focus on economical efficiency excluding military need is unable to cope with all kinds of uncertainty when supply environment and conditions change, which might cause outages in wartime. Therefore, military and economic metrics must both be considered when evaluating the effectiveness of a military supply network.

Several issues occur when constructing MSCN effectiveness metrics using traditional methods. It is difficult to build a metric that can reflect military need comprehensively, so previous attention has been focused on evaluating economic cost. In other words, military need has been ignored. In addition, military metrics usually use static metrics like node degree, average path length, and other characteristic parameters; thus dynamic performance metrics have been missed [15]. The last issue is that the understanding of economic efficiency is relatively simple, and only cost factors are used to represent the economic metrics of MSCN.

As military and economic metrics are affected by many factors, and they are bounded with every part and link of military logistics supply system, it is difficult to describe and evaluate the effectiveness of a MSCN precisely. But through in-depth study, we found that supply capability in MSCNs is the most significant concern of military metrics. Under wartime conditions, supply capability is the degree to which existing logistics resources are used to finish a supply task. When evaluating economic efficiency, cost is not the most critical issue of MSCNs. As long as resources are available, appropriate reserves can enhance the flexibility of a military supply network. Therefore, in terms of economic metrics, it is vital to increase efficient use of critical resources such as transportation. Based on the above discussion, we propose military supply capability and efficiency evaluation metrics. Moreover, we should give priority to supply capability metrics and then apply efficiency metrics when the military need is satisfied.

3.3.1. Supply Capability Evaluation Metrics. Supply capability is an important metric of MSCN effectiveness. This capability refers to the ability to finish the supply task with existing resources. For MSCNs, it can be argued that the supply capability is high if the inventory levels of demand nodes are above a specified threshold (e.g., 0 or more than 10% of inventory levels) continuously throughout the course of the military action. Otherwise, the longer the inventory levels are below the threshold during wartime, the lower the supply capability is. The above arguments can be shown in the following process:

$$\Delta P = \frac{\sum_{j=1}^{M} \sum_{t=1}^{SumTime} \text{Time}\left(\text{VD}_j^t \le \alpha \cdot \text{Volume}_j\right)}{|SumTime|}. \quad (1)$$

In the process,

ΔP is the total value of supply capability for overall demand nodes V_j, and the lower the value, the higher the supply capability;

α is standard threshold ratio;

$\text{Time}(\text{VD}_j^t \le \alpha \cdot \text{Volume}_j)$ is total times of $\text{VD}_j^t < \alpha$.

3.3.2. Supply Efficiency Evaluation Metrics. Supply efficiency counts crucially when supply capability is satisfied. Usually, transmission of supplies is an important element for MSCNs. Hence, it is vital to consider the efficiency of transmissions. This research presents the use of transmission as an indicator of economic efficiency metrics through the following formula:

$$L = \sum^{SumTime} \sum_{k=1}^{Z} \text{Distance}_k^{\Delta t}. \quad (2)$$

In the process,

L is the total distance that all transporting tools traveled during the war;

$\text{Distance}_k^{\Delta t}$ is the transmit distance at time Δt for transport type (e.g., trucks) k.

4. Simulation Examples

4.1. Overview. Petrol oil and lubricants (POL) are the lifeblood of military. Under wartime conditions, POL often account for more than 60% of the entire quantity of material support. As an important reference and basis of decision-making in military logistics departments, it is vital to reasonably evaluate the supply capability and efficiency of POL supply networks during wartime. Nevertheless, constrained by transportation, storage, traffic, human, organization, planning, management, and other factors, a POL supply chain network is formed into a complex military POL supply system containing systematic, complexity, emergence, and dynamic characteristics. In this case study, we will apply the simulation model and algorithm built in Section 3 in order to evaluate the capability and efficiency of POL supply chain networks in a theater (PSCNIT).

As shown in Figure 4, in this theater, there are three supply oil depots (SOD) and sixteen demand petrol stations (DPSs) for PSCNIT. SOD 1 has a fixed pipeline connected to the oil refinery which provides the POL. In addition, SOD 1 provides POL transportation to SOD 2 and SOD 3 through pipelines. SOD 1, SOD 2, and SOD 3 provide fuel to DPSs through POL trucks. The whole process constitutes the POL supply chain network of this theater.

4.1.1. Data Assumptions. Data needed for PSCNIT simulation are shown in Table 1.

Related simulation assumption data shown in Table 1 mainly includes the DPSs' inventory capacity (VOLUME_j), consumption, initial threshold (α), and supply priority.

Consumption refers to consumption and provision of POL from each DPS that supplies other troops. For example, assume that DPS 16 consumes 4 m^3/h. This number indicates that the average consumption per hour is 4 m^3 when it sends POL to the frontier troops.

Initial threshold (α) refers to the following process: when the oil reserves in a DPS decline to its threshold, the station will send a requisition to an SOD. After the SOD receiving supply requisition, they will send the POL to the DPS by POL transportation division.

Table 1: Simulation assumption data.

Number	Filling station	Inventory capacity	Consumption	Initial threshold (α)	Supply priority
(1)	DPS 1	150	1	25	2
(2)	DPS 2	125	1.5	30	3
(3)	DPS 3	880	2	50	2
(4)	DPS 4	245	2	60	1
(5)	DPS 5	480	3	150	1
(6)	DPS 6	560	1	50	3
(7)	DPS 7	260	1	50	2
(8)	DPS 8	250	1	50	3
(9)	DPS 9	320	1	50	2
(10)	DPS 10	1600	1.5	200	2
(11)	DPS 11	100	1	30	2
(12)	DPS 12	850	0.5	100	3
(13)	DPS 13	650	1	100	2
(14)	DPS 14	850	1.5	150	1
(15)	DPS 15	325	2	150	1
(16)	DPS 16	300	4	100	1

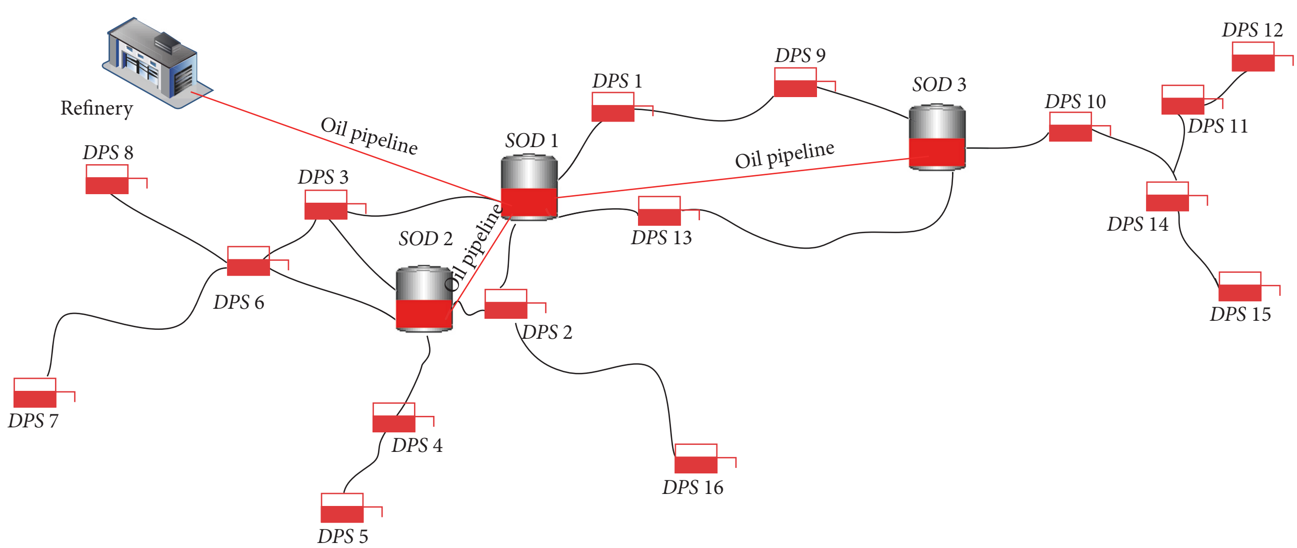


Figure 4: Diagram of POL supply chain network in theater.

Supply priority happens when two DPSs apply for an SOD at the same time. The SOD will guarantee the need of the higher priority first (1 is the highest priority; 3 is the lowest).

4.1.2. Transportation Hypothesis. Suppose that pipeline 1 (from the oil refinery to the SOD 1) has a throughput of 30 m^3/h. SOD 1 provides POL to SOD 2 and SOD 3 through pipelines in 20 m^3/h.

This PSCNIT contains 300 vehicles in total. According to the deployment before the war, SOD 1 is deployed with 50, SOD 2 is deployed with 150, and SOD 3 is deployed with 100 vehicles. The running speed of each vehicle is 30 km/h. We have made hypotheses of mileage, respectively, to each fuel station leaving out the specific numbers. The simulation process does not consider vehicle damage.

4.1.3. Other Hypotheses

(1) The supplying units deal with supply requisitions at a frequency of once per hour.

(2) At the beginning of the combat phase, all oil depots and petrol stations are filled with POL.

(3) The supply relationships between DPSs and SODs are made according to the distance.

4.2. Simulation Model of the PSCNIT Based on ARENA. In order to evaluate the effectiveness of the PSCNIT, this section proposes a simulation model by ARENA which was developed by Rockwell Software Company. We used the PSCNIT as an object and simulated a POL transportation and supply process operating over the course of 30 days using ARENA.

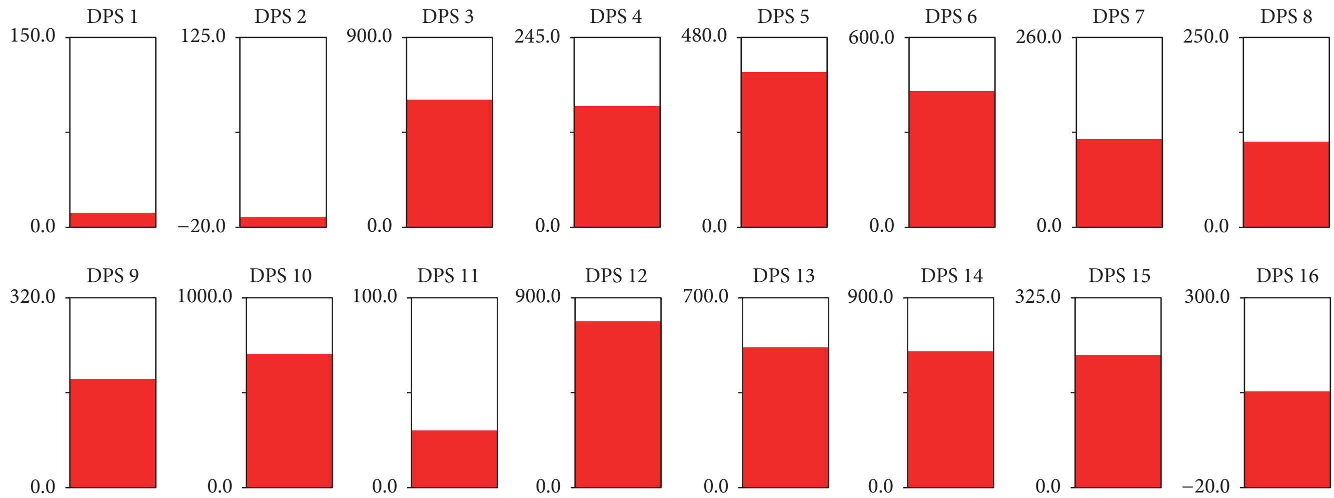


Figure 5: DPSs' inventory levels after 459 hours of operations.

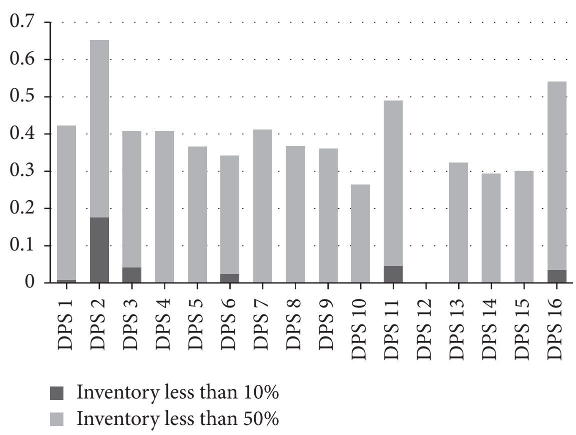


Figure 6: An analysis of supply capability of the PSCNIT.

Using the simulation evaluation system of ARENA, we can evaluate the effectiveness of the PSCNIT by using the statistical data from simulation. As shown in Figure 5, the simulation model provides the POL inventory in 16 DPSs on the 19th day and 3 hours (i.e., the 459th hour) of the battle.

4.3. Supply Capability Analysis. To evaluate the supply capability of the PSCNIT, we simulated an operation 10 times, setting 30 days for each operation. When inventory threshold is set to 0, there is a total duration of 50 hours of inventory level less than zero for DPS 2 through simulation. When inventory is less than 10% and 50%, the values are shown in Figure 6.

Through analyses, we found that the DPS 2 has less than zero-inventory for a total of 50 hours. That is to say, there is a 50-hour duration that the DPS 2 experiences a supply shortage. We found that the following factors are possibly associated with the shortage of the DPS 2: (1) the inventory capacity is very low, which means that DPS 2 can be easily filled up and used up. This low capacity makes it difficult to meet the consumption needs of the troops. (2) The threshold for supply requisition is too low. Threshold setting is a comprehensive consideration consisting of capacity, distance, and levels of priority. (3) The DPS 2 stands at a low level of supply priority. Low priority means that, under the same conditions, the DPS 2 will always be supported later than other DPSs. (4) There are limited resources for transportation. The DPS 2 has too few vehicles to provide sufficient transport of supply.

We set inventory capacity, the threshold of supply requisition, and supply priority as variables, aiming to reach the highest supply capability. Through simulation and optimization analysis, 25 groups of the local optimal solutions have been calculated. For example, when the DPS 2 has an inventory capacity of 407, its threshold is set to 75, the priority is set to 2, and the total time when the inventory is less than 0 is 0; in other words, there are no outages.

4.4. Supply Efficiency Analysis. The most critical resource is transportation for the PSCNIT in this case. As a result, promoting the efficiency of transportation is the key to improving economic efficiency and the effectiveness of the PSCNIT. Efficiency of transportation is closely linked with two management factors: threshold of supply requisition and supply priority. Therefore, we evaluated the supply efficiency of transportation impacted by these two factors under the conditions of satisfying the basic demands of the war zone. As a result, we obtained 25 sets of feasible solutions. Scatter plots of supply scheme efficiency in these sets are shown in Figure 7. Through analyses, the supply efficiency value of Scheme 6 is the lowest while the supply efficiency is optimal. Hence, according to Scheme 6, when the effectiveness of POL supply network in the theater is optimal, the application threshold should be set to 99 and inventory capacity should be set to 418 while the supply priority should be set to 2.

5. Conclusions and Future Work

In this paper, we simulate a POL network to solve the problem of supply chain network effectiveness evaluation

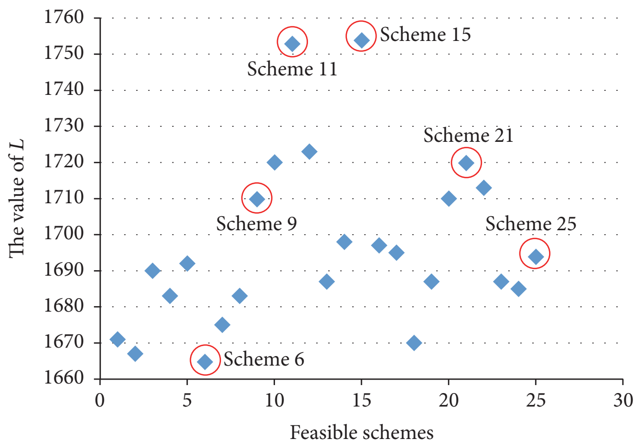


Figure 7: Efficiency value scatter plot of feasible schemes.

from the perspective of dynamic and discrete networks. Although we take MSCNs as an example to analyze the effectiveness evaluation of dynamic and discrete networks, the method is also relevant to other discrete networks. We put forward the simulation ideas and framework of the MSCN, which are based on time series and driven by supply events. These are distinguished from constant network simulations. Following the characteristics of discrete networks, we propose two effectiveness metrics which can better reflect the effectiveness features of supply chain networks, compared to the static metrics of complex networks. The simulation results show that minor adjustment of supply requisition can make the values of effectiveness metrics change dramatically, which proves that MSCNs are typical complex systems and that emergent properties exist in MSCNs. It also shows that the simulation model of effectiveness evaluation established in the paper is feasible and effective in dealing with discrete network effectiveness evaluation problems.

While we have proposed a method of discrete networks simulation and effectiveness evaluation, our future research will address the stability and invulnerability of discrete networks. After all, the purpose of effectiveness evaluation is to optimize the structure and improve the efficiency of networks, so that the overall performance can be maximized.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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