

Evolution of Logistics System Driven by Simulation Technology: Multi-Domain Application and Development Trend

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Abstract: Logistics system is the core support of modern economic activities, and its complexity and dynamics require researchers to use efficient tools for modeling and optimization. Simulation technology provides a low-cost, low-risk solution for the planning, design and operation of logistics system by constructing a virtual experiment environment. This paper combs the evolution of simulation technology in logistics research, the application of simulation technology in logistics field, and discusses the development trend of logistics system driven by simulation technology from the dimensions of evolution, application scenarios and methodology integration in logistics system.

Keywords: Logistics system; Simulation technology; Supply chain; System optimization.

1. Introduction

Logistics industry is the pillar industry of the national economy, our country called it "the new economic growth point", Japan called it "the third profit source", and "the sunrise industry in the third industry" "the gold under the feet of enterprises" and so on. With the increasing complexity and dynamic of the global supply chain, logistics has not only been the traditional sense of cargo transportation and storage management, but also its connotation has expanded to the whole life cycle management of resource flow, covering the whole chain optimization from raw material acquisition to product delivery, and even the flow management of energy, information and waste. The deepening of this complexity poses a systematic challenge to traditional logistics management paradigms and optimization methods. As an effective decision support tool, computer simulation technology has been widely concerned and developed in the application of logistics system, especially plays a key role in supply chain, warehouse management, production logistics and multi-level network optimization. For example, when enterprises face a complex logistics system, they build a complex logistics scene model with the help of simulation software, and carry out system optimization and decision support by simulating different strategies and schemes, so as to obtain the optimal solution. The core goal of modern logistics system is to achieve the dynamic balance of efficiency, cost and sustainable development, and the achievement of this goal highly depends on the support of technical innovation. As a key tool for logistics system optimization, simulation technology is providing an indispensable driving force for the rapid development of logistics industry. Aiming at the application of simulation technology in logistics system, this paper combs the evolution of the role of simulation technology in logistics research, introduces and compares the existing widely used logistics simulation tools, summarizes the application of simulation technology in logistics system, and analyzes the development trend of logistics system driven by simulation technology.

2. Evolution of Simulation Technology in Logistics System

The interpretation of logistics in the "Logistics Terminology" (GB/T 18354-2021) is: according to the actual needs, the basic functions of transportation, storage, loading and unloading, handling, packaging, circulation processing, distribution, information processing and other basic functions are organically combined to make the physical flow of goods from the supply place to the receiving place. The logistics system is a complex network composed of multiple interrelated subsystems. It is an organic whole with specific functions, which is composed of a number of mutually restricted dynamic elements such as materials, packaging equipment, loading and unloading handling machinery, transportation tools, storage facilities, personnel and communication links in a certain time and space. With the increasing complexity, dynamics and globalization of modern logistics systems, traditional experientially driven or simplified mathematical models have been unable to adequately solve complex logistics problems.

Logistics simulation technology is based on computer modeling and simulation, which dynamically reproduces the structure, process, resources and behavior of the real logistics system (or the planned logistics system). Through modeling various elements of the logistics system, such as transportation vehicles, warehouse facilities, personnel, goods and so on, it simulates the operation state of the system under different conditions. Thus, it can provide decision support for the planning, design, management and optimization of logistics system. In essence, it constructs a "digital sand table" of logistics system, and replaces "actual investment" by "virtual trial and error" to reduce the cost and risk of system optimization. The evolution of simulation technology in logistics system is accompanied by the development of technology, the change of market demand and the progress of information technology. It has experienced many stages from simple simulation to complex digital modeling and real-time simulation.

At the earliest stage, logistics simulation techniques were based on mathematical modeling and static optimization methods, such as linear programming and integer programming. These methods are usually used to solve single-link logistics problems, such as transportation optimization, inventory management, and warehouse design. In the model constructed by Zihui Yang [1] et al., the idea of "time cost" was cleverly introduced through the connection of "weight coefficient", and "time" was quantified as "cost", so that the multi-objective optimization problem was transformed into a classical linear optimization problem, which was used to solve the transportation optimization problem of actual needs of enterprises. Dingyou Lei [2] et al. established the original model of multimodal transportation path optimization for long cargo by taking the minimum transportation time, mileage and cost as the objective function, and the line limit, bridge bearing capacity and lifting capacity of lifting equipment as the constraint conditions. Considering the transformability of the constraints, the original model is extended and optimized, a two-dimensional sequence coding strategy is designed, and the genetic algorithm is used to solve the extended model. These models usually ignore the dynamics, cannot consider the complex time factors and random events in the logistics system, and are more used for optimization problems in specific static situations.

With the development of computer technology, discrete event simulation has gradually become the mainstream of logistics system simulation. DES simulates the process of objects changing with time, and advances the simulation process according to the occurrence of discrete events. Discrete event simulation is mainly used to simulate the specific operations in the logistics system, for local bottleneck analysis, such as warehouse management, production line balancing, etc. The early DES simulation models are usually limited to off-line analysis, the simulation process is relatively simple, and the complex system can not be fully

dynamic simulation, and lack of system-level cooperation perspective. Early simulation software such as ARENA and Slimul8 mainly support discrete event simulation, which can help enterprise decision makers in system design and resource allocation by simulating different logistics strategies. However, the functionality of these tools is still relatively simple and mainly applied to process optimization.

With the proposed method of system dynamics, the application of simulation technology in logistics system has entered a new stage. System dynamics reveals the dynamic characteristics of system behavior by simulating the feedback loop and time delay of each part of the system. In logistics systems, system dynamics is widely used in supply chain management, demand forecasting, inventory management and other problems. System dynamics can provide a macroscopic and long-term analysis of logistics systems, and reveal the causal relationships and dynamic feedback mechanisms in complex systems. However, it is usually not suitable for logistics links that need detailed simulation and accurate modeling, especially for physical aspects such as transportation scheduling and warehouse management. In order to overcome the limitations of single modeling method, many simulation systems begin to adopt the strategy of multi-model fusion. For example, when simulating a logistics system, discrete event simulation, system dynamics, and multi-agent techniques are combined to deal with the micro and macro levels of the logistics system respectively. Multi-model fusion can be used to optimize multi-level logistics system, such as material flow optimization in warehouse, global scheduling and risk analysis of supply chain, which can more comprehensively consider the multi-dimensional characteristics and complexity of logistics system, provide more flexible and accurate decision support, and adapt to different logistics links and management needs. This paper lists several common simulation software, see Table 1.

Table 1. Comparison of common simulation software

Software	Main Applications	Advantages	Limitations
Flexsim	Simulation of manufacturing and logistics scenarios, such as factory production lines, logistics warehouse optimization, etc.	It provides intuitive graphical interface and drag-and-drop modeling method, built-in a variety of statistical analysis tools and optimization algorithms, and has a three-dimensional simulation environment, which makes the simulation process more intuitive.	The dynamic optimization ability is weak, the secondary development is difficult, and the multi-system cooperation is insufficient.
Plant Simulation	Factory production line balancing, manufacturing process optimization, equipment maintenance simulation, etc.	Deep integration with Siemens ecosystem, high-precision beat analysis ability, support for multiple interfaces and integration functions, preset part of the industry standard model.	The price is expensive, the learning cost is high, and the visualization and interaction experience is backward.
AnyLogic	Complex supply chain simulation, transportation system simulation, public policy simulation, manufacturing process simulation.	It supports a variety of modeling methods and can be combined according to requirements, supports Java custom coding, can deeply expand the model logic, has powerful 3D visualization and GIS map support, and has built-in optimization algorithms.	The learning threshold is high and the business cost is authorized.
Arena	Manufacturing process optimization, medical system simulation, large-scale system verification.	The powerful discrete event simulation ability can simulate and analyze various complex system behaviors and processes, and the modeling method is flexible.	It only provides 2D attempts, lacks visualization functions, and is difficult to learn.
Simio	Complex logistics system optimization, intelligent manufacturing and production line design, medical system simulation, supply chain risk management.	Intelligent object modeling without programming, built-in OptQuest optimizer, intelligent optimization algorithm embedding, flowchart driven modeling.	Lack of professional libraries, expensive prices, limited learning resources, and low industry adaptability.

3. Simulation Technology in The Field of Logistics Applications

The field of modern logistics is no longer limited to traditional logistics services such as transportation, warehousing and distribution. Its core lies in "system" and "integration", which is a comprehensive system integrating information technology, automation technology and management science. The application of simulation technology in the field of modern logistics has experienced from simple system simulation to the optimization of complex scene flow and the prediction of logistics data. Simulation technology is widely used in the design, optimization and decision support of logistics system. In the logistics field, different types of simulation techniques are suitable for diverse scenarios due to differences in principles and characteristics, and the common types of simulation techniques are shown in Table 2.

Table 2. Common types of simulation techniques in the logistics field

Type of technology	Applicable scenarios	Typical tools
Discrete event simulation (DES)	Event-driven modeling	Flexsim、AnyLogic
	Resource management and scheduling Dynamic process analysis	
System dynamics (SD)	Feedback loop modeling	Stella、Vensim
	Dynamic trend forecasting System structure optimization	
Multi-agent simulation (ABM)	Agent modeling	AnyLogic、NetLogo
	Interactive and collaborative simulation Policy optimization	

The application of simulation technology in the field of logistics mainly focuses on transportation management, warehouse management, inventory control and so on. Transportation is one of the core businesses of logistics and an important function of logistics system. Transportation management involves route selection, vehicle scheduling, volume planning and other issues. Simulation techniques are used to simulate different transportation routes, vehicle scheduling and distribution strategies to help enterprises design optimal transportation networks, thereby reducing transportation time and cost and improving resource utilization. Dianjun Fang [3] et al. used Flexsim to establish a simulation model of logistics transportation in a factory park, and obtained the optimized transportation mode by setting different transportation network parameters. Tianmin Wang [4] et al. explored the container multimodal transportation path optimization problem, established the multimodal transportation simulation model by using AnyLogic simulation software, and solved the optimization model with OptQuest optimization solver. Song Liu [5] used AnyLogic to build a simulation model of material distribution in factories, studied related issues of AGV path planning, and showed the superiority of the improved AGV path planning algorithm through simulation.

Warehousing is the temporary storage of products and items due to the advance of orders or market forecasts in the process of product production and circulation in the logistics system. It is the transfer station connecting production, supply and sales, and the key link to ensure the efficient flow of materials and reduce operating costs. In the field of warehousing, simulation technology analyzes the efficiency and space utilization of different layout schemes by simulating the flow of goods, operation process and equipment operation in the warehouse, and designs the optimal warehouse layout to reduce the cargo handling time and operation cost. In automated warehouses, simulation technology is used to simulate the operation of automation equipment and optimize material handling and access operations. Aiming at the resource allocation problem of AutoStore, a new compact and intensive warehouse system, Xiaojun Wang [6] et al., based on the Petri net model of the system's in-and-out warehouse operation process, established the operation simulation model through Flexsim software, and verified the optimization model based on multiple sets of simulations. The research provided a specific design direction for the determination of resource allocation scheme. Di Guo [7] et al. constructed a discrete event simulation model based on queuing theory in Flexsim for the configuration problem of storage robots in smart warehouses under multiple constraints. The system bottleneck was visualized and the configuration strategy with the minimum system cost was obtained by combining the actual data. Zitao Xu [8] et al. analyzed the logistics system of intelligent factory through simulation technology, built a three-dimensional logistics simulation model based on AnyLogic simulation platform, simulated logistics activities under multiple scenarios, analyzed the number and utilization rate of AGV and the amount of material accumulation in temporary storage area under different scenarios, and showed the feasibility of the optimization scheme.

System dynamics model can capture complex characteristics such as delay, feedback and nonlinearity in supply chain and reveal its dynamic behavior. These properties are difficult to detect in traditional static analysis, while system dynamics helps companies understand the long-term behavior and potential problems of the supply chain by simulating changes in the time dimension. By simulating different supply chain strategies and external environment changes, the key performance indicators of the supply chain are predicted, the inventory fluctuations of the upstream and downstream of the supply chain are simulated, the replenishment strategy and the safety stock level are optimized, the bullwhip effect is reduced, and the upstream and downstream collaboration of the supply chain is enhanced. The effect of different inventory policies (such as safety stock, order point, order quantity, etc.) on inventory level, backorder and cost is simulated. To help enterprises choose the optimal inventory strategy, balance inventory cost and out-of-stock risk, and realize the dynamic optimization of inventory level. BinZhan Yang [9] et al. optimized the inventory fluctuation based on the system dynamics model. The model took the dealer inventory as the object, and obtained measures to optimize the inventory fluctuation and improve the inventory service level by analyzing the influence of the expected inventory coverage time, delay time and replenishment limit on the inventory fluctuation in the system dynamics model.

Distribution is the end link in the logistics system. As the

"last mile" core hub connecting the production end and the consumption end, its operational efficiency and cost control level not only directly determine the service experience of end customers, but also profoundly affect the core competitiveness of enterprises in the fierce market competition. Simulation technology integrates real-time traffic data, order density, vehicle load and other information, constructs a dynamic distribution network model, accurately realizes intelligent resource scheduling, and simulates the distribution effect under different vehicle configurations, departure times, and personnel division schemes. Xiaodong Shi et al. [10] developed a VSP simulation model with a time window by using AnyLogic, and carried out multi-agent modeling and simulation of the material transportation between the material distribution point and the material warehouse in Beijing based on GIS map, and obtained the minimum material reserve amount of the transit warehouse and the optimal number of vehicles with the shortest order processing time of each warehouse. It provides scientific value and reference basis for material distribution research. Canzhu Lin [11] et al. used Flexsim simulation software to simulate the existing layout and functions of different functional areas of A modern logistics distribution center, so as to improve the distribution efficiency of the logistics center.

Emergency logistics is a special logistics activity that is carried out to ensure the rapid and effective supply of materials when emergencies such as natural disasters and public health events occur. It requires high response speed and accuracy of resource allocation. Simulation technology has become an important tool to improve the efficiency of emergency logistics and reduce disaster losses by virtue of its ability to simulate complex dynamic scenes and the advantage of data-driven decision-making. Simulation technology optimizes the allocation and scheduling of emergency materials such as relief materials and medical supplies by simulating factors such as material demand, transportation capacity and storage capacity. For example, the material transportation scheme between different rescue points can be simulated to determine the optimal resource allocation strategy, so as to improve the rescue efficiency. Peiyu Tian [12] et al. constructed a regional scheduling model of emergency supplies based on scarcity cost in AnyLogic, realized the simulation of regional scheduling of emergency supplies under the three-level material reserve system of "province-city-county", and evaluated the scheduling strategy of emergency supplies from a new perspective.

Simulation technology pushes traditional logistics from "experience-driven" to "intelligent decision-making", and the application in the field of logistics has become an important means to optimize logistics system, improve operational efficiency and reduce costs. Through discrete event simulation, system dynamics, multi-agent simulation and other technologies, simulation can not only help enterprises optimize transportation, warehousing, distribution, inventory and other links, but also can carry out global optimization of supply chain and risk assessment. With the continuous progress of technology, simulation technology will play a more important role in the field of logistics in the future, and promote the development of traditional logistics to the direction of intelligence and automation.

4. The Development Trend of Logistics System Driven by Simulation Technology

In recent years, with the development of Internet of things, big data, artificial intelligence and other technologies, simulation systems are gradually embedded in artificial intelligence to react to the status and changes of logistics systems in real time, which enables enterprises to monitor, predict and optimize the logistics process in real time. Through the synchronous update of real-time data and model, the simulation system can accurately reflect the real-time status of logistics system, and find and solve potential problems in time. Through the combination of big data platform and simulation system, logistics enterprises can dynamically adjust according to real-time data to help enterprises better respond to market demand and emergencies. The application of simulation technology in logistics systems has evolved from a static planning tool at the beginning to a powerful technology supporting real-time decision making and dynamic optimization.

As the core tool of modern logistics system, simulation technology is promoting the evolution of logistics industry to intelligent, efficient and sustainable development. The following are the main development trends of logistics systems driven by simulation technology:

1. Intelligent and data-driven decision-making

The deep integration of simulation technology with the Internet of Things (IoT), big data and artificial intelligence (AI) promotes the development of logistics systems to be intelligent. Through real-time data input, the simulation model can dynamically simulate the running state of the logistics network, predict demand fluctuations, optimize resource allocation and support accurate decision-making. For example, AI-based simulation systems can adjust distribution routes in real time, cope with unexpected traffic conditions, and improve operational efficiency.

2. Real-time dynamic simulation

With the improvement of computing power, cloud simulation platform and real-time simulation technology have gradually become the mainstream. Logistics system can process large-scale data through the cloud, and simulate the dynamic changes of supply chain, warehousing and distribution in real time. This enables companies to quickly respond to market changes or unexpected events such as epidemics or natural disasters, enhancing system resilience.

3. Automation and unmanned logistics

Simulation techniques provide support for emerging scenarios such as automated warehouses, drone delivery, and unmanned vehicles. By testing the performance and collaboration efficiency of automation equipment in a virtual environment, enterprises can optimize the system design and reduce the implementation risk. For example, simulation can simulate UAV delivery paths in urban environments to assess their feasibility and safety.

4. Emergency logistics and resilience

Simulation technology plays an increasingly prominent role in emergency logistics, especially in response to crises such as natural disasters and epidemics. By simulating material distribution, transportation bottlenecks and risk scenarios, enterprises can formulate flexible emergency plans and improve the risk resistance ability of logistics systems.

5. Summary

Simulation technology is the core tool of modern logistics system optimization, and its evolution is always deeply coupled with the complexity and dynamic needs of the logistics industry. From the static optimization based on mathematical modeling in the early stage, to the dynamic simulation of local links by discrete event simulation, and then to the collaborative analysis of the whole chain by system dynamics and multi-model fusion, simulation technology has developed from a single tool to a comprehensive methodology to support the whole life cycle management of logistics systems. At the application level, by constructing a "digital sand table", the "actual investment" is replaced by "virtual trial and error" in scenarios such as transportation network optimization, warehouse layout design, inventory dynamic regulation, distribution path planning and emergency logistics response, which significantly reduces the cost and risk of system optimization. In the future, with the deep integration of Internet of things, big data and artificial intelligence technology, simulation technology will evolve in the direction of intelligent decision-making, real-time dynamic optimization, unmanned scene adaptation and supply chain resilience enhancement, which will promote the transformation of logistics system from "experience-driven" to "data-driven" and "autonomy-driven", and become the key support to realize the balance between logistics efficiency, cost and sustainability.

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