Eng Int Syst (2024) 3: 203–211

Engineering
Intelligent Systems

Building a Low Carbon Supply Chain Energy Conservation and Emission Reduction System for Logistics Enterprises Based on Autonomous Decision Intelligence

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With the development of global economic integration, the number of environmental issues brought about by rapid developments cannot be underestimated. Global climate change is becoming increasingly severe, and governments at all levels around the world are using various means to reduce their own carbon emissions. In a business environment characterized by increasingly fierce competition, the discrepancies and problems existing in traditional logistics enterprises are becoming more acute. At present, information technology is changing rapidly and, consequently, various fields are developing rapidly. Market and customer expectations are also changing, imposing enormous pressure on transportation logistics. Therefore, in the field of logistics, the advantages of a low carbon supply chain (LCSC) energy-saving and emission reduction system based on autonomous decision-making (ADM) intelligence for logistics enterprises stand out among traditional logistics systems. ADM can improve the operational efficiency of the logistics supply chain (LSC) while reducing the impact of logistics-related industries on the environment. However, at present, the research on the energy-saving and emission reduction systems of logistics enterprises is not adequate, making it essential to study these aspects of the logistics industry. Researchers are attempting to improve traditional LSC by upgrading their systems to address issues such as poor efficiency and high emissions. This current study found that ADM can optimize the energy conservation and emission reduction system of LCSCs, and can effectively reduce the impact of the logistics industry on the environment. This study investigated this method of optimization using Petri net decision algorithm and examples. The results of statistical analysis showed that the impact of traditional LSC on the environment increased by 0.5% between 2015 and 2020, indicating an urgent need to reform traditional LSCs. This study investigated the advantages of ADM intelligence that can help to improve the energy conservation and emission reduction systems of LCSCs. The results indicate that with the utilization of ADM intelligence, the energy-saving and emission reduction system is more efficient and reduces emissions the emissions of each link in the supply chain.

Keywords: autonomous decision-making, low carbon, supply chain, reduce emissions

1. INTRODUCTION

The continuous escalation of a series of ecological and environmental issues caused by the global greenhouse effect has attracted a great amount of attention from the international community. A large number of previous studies have shown that global warming trends are caused mainly by excessive emissions of carbon dioxide. Therefore, the reduction of carbon emissions and the achievement of sustainable development have become the focus of global attention. With the continuous development of low carbon technology and low carbon concepts, environmental protection activities with the slogan of "low carbon" would inevitably bring fundamental changes to manufacturing and to people's lifestyles. In order to address a series of environmental problems caused by carbon dioxide, the United Nations Climate Change conference proposed a carbon emissions market trading mechanism. Since then, carbon emissions have become the focus of global economic development. In response to the call for energy conservation and emission reduction, countries have also established carbon emissions trading markets. The logistics industry has always played a crucial role in economic development, and a series of environmental issues caused by logistics enterprises have subsequently come under public scrutiny. Currently, logistics enterprises do not have efficient and effective LCSC energy-saving and emission reduction systems, and there is an urgent need to reform such systems by exploiting the advantages of ADM technology.

The rapid development of information technology (IT) poses enormous challenges to researchers and managers. However, since its emergence, its broader applications have been anticipated; hence, researchers have continuously investigated its potential application and benefits in regard to the logistics industry. Based on a case study conducted by a leading logistics and supply chain organization, Andiyappilai Natesan reviewed the latest technological developments in the implementation of logistics and supply chain systems [1]. Pourader Mehrdokht uses the inductive reasoning method to discuss the emerging themes and applications of blockchain in supply chain, logistics and transportation [2]. Munim Ziaul Haque mentioned that the most urgent aspects of logistics performance are logistics costs and supply chain reliability [3]. Syed Abdul Rehman Khan believed that the use of renewable energy in logistics business can improve the sustainability of the ecological environment [4]. Yanqi Zhang mentioned that in the context of the rapid development of big data and artificial intelligence, knowledge service theory and big data technology can be applied to construct a smart port supply chain knowledge service model [5]. Xue Xiaofang believed that the correct operation of the logistics system is crucial for encouraging supply chain circulation in various industries and has a direct impact on socio-economic development [6]. Chang Liu utilized real-time updates from global positioning systems and big data to calculate the optimal transportation path and quickly and synchronously update and redefine the route of logistics terminals [7]. At present, there has been a preliminary construction of the LSC theoretical system and it has been applied to various processes. However, there is still room for improvement in the practical application of the theoretical system, and the supply chain theoretical system is not yet fully mature.

After the United Nations Climate Conference proposed the carbon emissions trading market, global governments began conducting ongoing research in the field of energy conservation and emission reduction. Qi Xiaoyuan mentioned that energy conservation and emission reduction strategies are important to the sustainable development of the manufacturing industry and its green transformation [8]. Xu Xiaodong found that high-level energy conservation and emission reduction have a significant indirect impact on export performance, which is mediated by their signaling of green practices [9]. Cher Arvind believed that the main goal of sustainable design is to reduce the consumption of key resources such as energy, water, and raw materials [10]. Yuyan Wang mentioned that many sustainable management practices are related to the use of low carbon energy and actions to prevent further climate change [11]. Ambekar Sudhir mentioned that the increasing market preference for low carbon products has prompted many companies to incorporate environmental protection and sustainable development into their strategic decisions [12]. Qiang Du stated that improving manufacturing efficiency is considered an effective way to reduce carbon emissions [13]. Das Chiranjit redefined all supply chain functions such as supplier selection, inventory planning, network design, and logistics decision-making by integrating emission-related theoretical achievements [14]. Hence, it is evident that the prospects for the reform of the LSC system are vast and unparalleled.

The research on the LCSC energy conservation and emission reduction system of logistics enterprises in related fields is still at the macro level. In order to better improve the theoretical system of LSC, this study conducted a statistical analysis of LSC and other related fields. The Petri net decision algorithm method was applied to study and scientifically evaluate LSCs under different modes.

2. DEVELOPMENT TREND OF LCSC FOR LOGISTICS ENTERPRISES

The 21st century is an era of informatization and modernization, as well as the transformation and improvement of traditional logistics and warehousing services. The world's logistics industry has undergone two significant changes from quantitative to qualitative. In terms of the depth of control and the breadth of business connections, the supply chain is an extension of logistics. Therefore, supply chain management is an integration of management that connects core businesses and processes within and between enterprises, and then transforms them into an organized and effective business model. It covers not only production operations, but also all related logistics activities, and also facilitates collaboration within and between company departments such as marketing, sales, product design, finance, and information technology.

Therefore, clear definitions are given of the concepts, characteristics, functions, and implementation of "low carbon", "logistics", and "green" supply chains to ensure that they can play an effective role in practical applications. The concept of low carbon logistics and environmentally conscious supply chain (ECSC) can be considered as the combination of environmental protection and low carbon ideas in every process of logistics and supply chain to form a complete ECSC system. ECSC is also defined as the process connecting supplier to manufacturer and service provider to final customer, as well as the management and recovery of raw materials and resources to safeguard the natural environment. ECSC also conforms to the principles of industrial ecology. Industrial ecology is a systematic organizational structure that comprises many elements of environmental management. Industrial ecology regards industry as a natural system, and the local ecosystem is part of the global ecosystem. The industrial system is built on an ecosystem so as to achieve sustainable environmental performance.

ECSC planning applies the green concept to the entire supply chain process of the product lifecycle. From suppliers to incoming logistics, handling, delivery during production, and customer service, environmental protection must be at the core, and environmental pollution must be minimized in order to make the product's lifecycle healthier and more sustainable. In the procurement and supply process, green procurement and green sharing schemes are implemented; in the production process, environmentally friendly design, green production methods, and lean management methods are adopted (in fact, lean extends to the entire supply chain process); in the delivery phase, optimized network design, low carbon transportation and storage, and optimized inventory are adopted to achieve green delivery. In the customer service stage, in order to encourage recycling, enterprises can apply reverse logistics management methods. That is, through the reverse logistics management system, customers' waste can be recycled and treated in order to protect the environment and conserve natural resources. In addition, enterprises can use green marketing and product life cycle management to achieve recycling so as to reduce costs and waste, and improve quality and improve the environment. By improving management efficiency and applying green technologies, ECSC can reduce resource consumption and protect the environment. According to the ECSC model, the main supply chain processes include the green planning process, which designs all supply chain processes based on the principles of minimum consumption, minimum emissions, and optimal performance to achieve the highest environmental benefits, such as optimizing inventory planning and developing a recycling system for reusable raw materials. People have been constantly seeking better logistics to improve the warehouse transportation process in order to avoid excessive costs [15]. The ECSC plan fully considers the need to incorporate low carbon emissions into the supply chain and includes the transport aspect.

The construction of a multi-modal transportation system is also important. The construction of high-speed railways would gradually alleviate the pressure on railway freight transportation. With the continuous improvement of railway transportation capacity and the continuous progress of railway container transportation technology, it would be possible to achieve the development of "sea rail intermodal transportation" and "multi mode" internationally. However, at present, there are still many obstacles to the development of railway container transportation including institutional and institutional reasons, as well as the issues of railway container center stations and dual track container lines. Bridges and tunnels are the "bottlenecks" that affect the transportation of double-decker containers. Therefore, the relevant government departments need to formulate a long-term plan for the transformation of the road freight network to increase investment in this area and innovate the system and mechanisms, so as to promote the development of combined transport [16].

In order to better improve the theoretical system of LSC, this study adopted the statistical analysis method involving the Petri net decision algorithm to objectively evaluate and compare the traditional LSC with one that has adopted the new energy-saving and emission reduction system.

3. INTELLIGENT SUPPLY CHAIN ENERGY-SAVING AND EMISSION REDUCTION SYSTEM WITH INDEPENDENT DECISION-MAKING

3.1 ADM of LCSC Functional Objectives

The goal of an automatic decision-making LCSC function is to provide a new open platform for real-time monitoring of the supply chain system. It requires intelligence, efficiency, energy conservation, and emission reduction, while system upgrades reduce the impact of the supply chain on the ecology. The platform should support dynamic configuration of multifunctional components and auxiliary devices as well as the continuous solution and fault management of the supply chain system. An efficient system should be able to coordinate communication and control multiple units simultaneously in order to address the shortcomings and deficiencies of traditional LSCs and transform them into intelligent supply chains.

3.2 Composition of Intelligent Logistics LCSC Intelligent Emission Reduction System

The emission reduction system includes the controlled components of China Unicom, which can support the heterogeneity of software and hardware, and achieve real-time data exchange and control of components. The simulation of a supply chain environment allows the software to operate in a virtual LSC environment and control the model through data reading and processing. Integrated support tools provide an efficient design tool for transitioning to embedded goals. In terms of design, application programming interfaces provide a user-friendly system interface for software programming on intelligent agent platforms, and each type of stacker is designed according to the actual needs of the supply chain [17]. In terms of offline logistics, the conveying speed, sorting, and merging program can be set according to material size and output frequency, and the working status of the system can also be monitored in real time to achieve a high-speed merging system that adjusts the merging speed according to actual needs. The automatic transmission device of the storage unit is completed by the transmission system and has automatic identification and access functions for the track shuttle.

3.3 Key Technologies in the Independent Decision-making Supply Chain Emission Reduction System

The key technology for the ADM supply chain emission reduction system is middleware technology based on the proxy architecture of the real-time public target request. It is a standard developed by the target management organization, a system specification for target applications, and a solution to the interconnection problem of software and hardware systems in distributed processing environments and adaptive communication environments. The structure of the real-time public target request proxy system written by C++consists of a three-layer structure. It allows designers to focus on the design of control devices, rather than software design that addresses system hardware integration, communication, allocation, portability, execution, and resource management issues. Core layer, reconfigurable control, and hybrid control application programming interfaces

The core layer application programming interface enables asynchronous real-time communication between distributed functional components and priority communication based on event-based dynamic reconstruction. Event channels act as transmitters between components. The event service feature provides a communication extraction function for event channels similar to buses, which supports the interaction between highly decoupled distributed components in the system. This core layer can quickly determine changes in the architecture or construction of the system through the calculation results of distributed targets, and has a relatively high level of reliability.

The middle "reconfigurable controller" layer provides a certain level of abstraction for the control system components, creating a "gap" between the controller area and the distributed components. Designers can design the input or output interfaces and control signals for each functional component on this "gap", and then complete the reconstruction through resource management agencies' decision-making on the redistribution of each functional component. In order to simply define the structure and refactor it with changes in the architecture itself, a reconfigurable application programming interface controller provides an extraction layer. However, in structure management, it is necessary to ensure that the structure is effective and consistent with the overall requirements of the system.

In order to provide flexible and decentralized refactoring performance, refactoring generation algorithms are used to support free coupling between various components of the control system. For example, it can define the efficiency of transitioning from one algorithm to another. When a fault occurs in the LSC system, a discrete approach is generally adopted to shift the control algorithm to the fault handling algorithm in order to achieve stable transformation by mixing the outputs of the calibration controller and the fault controller during the transformation process.

3.4 Integration of Decision Algorithms and Supply Chain Control Systems

In order to achieve the correct invocation of decision algorithms in the LSC mission execution process, it is necessary to integrate them into the supply chain control system. To model the mission control process of the supply chain, it is necessary to use formal language to provide a complete description of the supply chain process.

3.4.1 ADM Algorithm

A Petri net is represented as a six tuple, that is:

$$PN = (\mathrm{G}, T, \mathrm{E}, W, M, \mathrm{S}) \tag{1}$$

where G is a finite library set expressed as:

$$\mathrm{G} = \{\mathrm{g}_1, \mathrm{g}_2, \cdots, \mathrm{g}_m\} \tag{2}$$

T is a finite transition set as shown in Formula (3):

$$T = \{t_1, t_2 \cdots t_n\} \tag{3}$$

In addition, $\mathrm{E} \subseteq (\mathrm{G} \times T) \cup (T \times \mathrm{G})$ is the set of directed arcs; $W : \mathrm{E} \rightarrow \{1, 2 \cdots\}$ is the weight function of the directed arc; $M : \mathrm{G} \rightarrow \{0, 1, \cdots\}$ refers to the state identification, which refers to the ability of the object to meet the specified quality requirements during identification. Generally, it has the characteristics of time limit and variability, that is, the identified object can have different states corresponding to different time periods. $\mathrm{S} : \mathrm{G} \rightarrow \{0, 1, 2, \cdots\}$ is the initial identifier, and the identifier configured before a Petri net starts running is called the 'initial identifier'. Petri net diagrams are graphical representations of six tuples. In the network diagram, G represents the "repository" node set, and T represents the "transition" node set; E represents the set of directed arcs between nodes, and W represents a vector composed of the "weights" of the directed arcs as elements.

3.4.2 Integration of Decision Algorithms

By means of three Petri nets, it is possible to correctly call intelligent decision algorithms during mission execution.

3.4.3 Independent Decision-making Process for Energy Conservation and Emission Reduction System in the Supply Chain

The functions, structures, and principles of the bottom, middle, and top layers of the LSC ADM system are different, and the decision-making objectives are also different. However, they all contain a complete ADM process, and the basic steps are the same. The construction of the LSC ADM process lays the foundation for subsequent research on each layer of the ADM system.

3.4.4 Introduction of Autonomous Computing Concept in LSC System

The LSC implements dynamic restructuring and intelligentization through ADM processes. In a certain sense, this process can be understood as the autonomous management of the LSC system, and its basic idea is consistent with autonomous computing. Therefore, this study introduced the ideas and methods of autonomous computing to analyze and design the ADM process of LSC.

The idea of autonomous computing is to construct an information system with autonomous management capabilities by imitating the self-regulation mechanism of the autonomous nervous system, namely the autonomous computing system. A person's autonomic nervous system completes a large

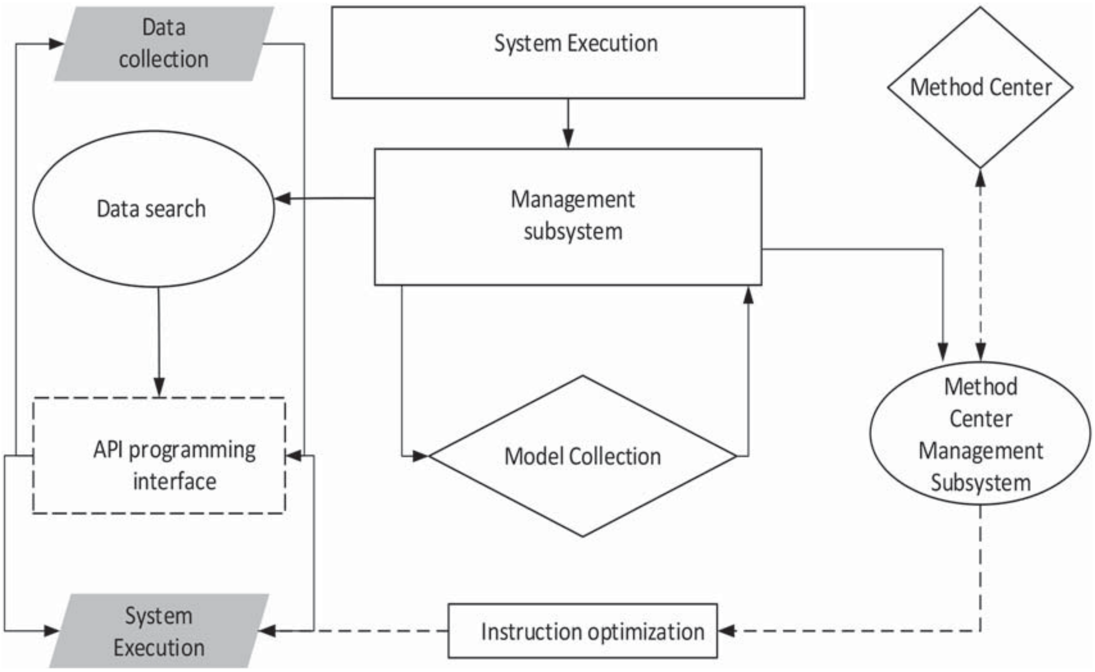


Figure 1 Conceptual architecture diagram of autonomous elements.

number of autonomous management tasks without subjective consciousness. The purpose of autonomous computing is to enable information systems to manage themselves like autonomous neural systems, and achieve overall adaptation, thereby solving the increasingly complex and onerous problem of LSC information system management and reducing the burden on managers.

The autonomous element can be regarded as a single autonomous management unit, while the autonomous computing system is the autonomous management of each part and branch of the logistics supply chain. Figure 1 shows the conceptual architecture of autonomous elements. An autonomous element covers the entire process of autonomous computing. From Figure 1, it can be seen that autonomous computing is achieved through an intelligent control loop, namely "monitoring, analysis, planning, execution". This cycle collects information from the system and analyzes decisions, then adjusts the system as needed. The autonomous element consists of three parts: autonomous managers, managed resources, and external environment. Among them, resources are managed by autonomous managers, and can also be other autonomous elements. The external environment represents the peripheral environment of autonomous elements. Autonomous managers include components that implement autonomous control loops consisting of five parts: monitoring, analysis, planning, execution, and information. Among them, the "monitoring" component provides a mechanism to collect and preprocess status information from managed elements and the external environment; the "analysis" component is responsible for analyzing status information and determining the situation status; the "planning" component is responsible for organizing corresponding strategies and actions to achieve goals; the "execution" component takes actions corresponding to the plan; "information" is the foundation of this control cycle, and includes historical data information, analytical decision rules, strategies, etc.

3.4.5 Specific Process Design for Logistics LCSC

Based on the four steps comprising "monitoring, analysis, planning, execution" in autonomous computing, a detailed design of the autonomous management process for LCSC in logistics enterprises is presented in Figure 2. The self-management process of logistics LCSC consists of four steps: monitoring, analysis, planning, and execution. The foundation for achieving these four steps is the knowledge base which includes policy library, component library, rule library, and so on. The monitoring component captures environmental information, which refers to the environmental status information of the target supply chain node; the analysis and planning components can be integrated to make strategic decisions based on state information; the execution part refers to the dynamic reconstruction of the LSC system based on the new strategy, and the work is carried out according to the corresponding instructions. For the logistics industry, autonomous management methods can be used to construct an intelligent LSC energy conservation and emission-reduction system for ADM.

4. LOGISTICS ENTERPRISES' LCSC ENERGY-SAVING AND EMISSION REDUCTION SYSTEM INDICATORS

In the context of ADM and intelligent supply chain, the operational performance of supply chain members affects not only their own survival and development, but also affects the interests of other enterprises in the entire supply chain. This requires supply chain member enterprises to adopt effective management measures based on their own actual situation with a responsible attitude and independent decision-making intelligence, in order to improve their operational performance and ensure the interests of other enterprises in the entire supply

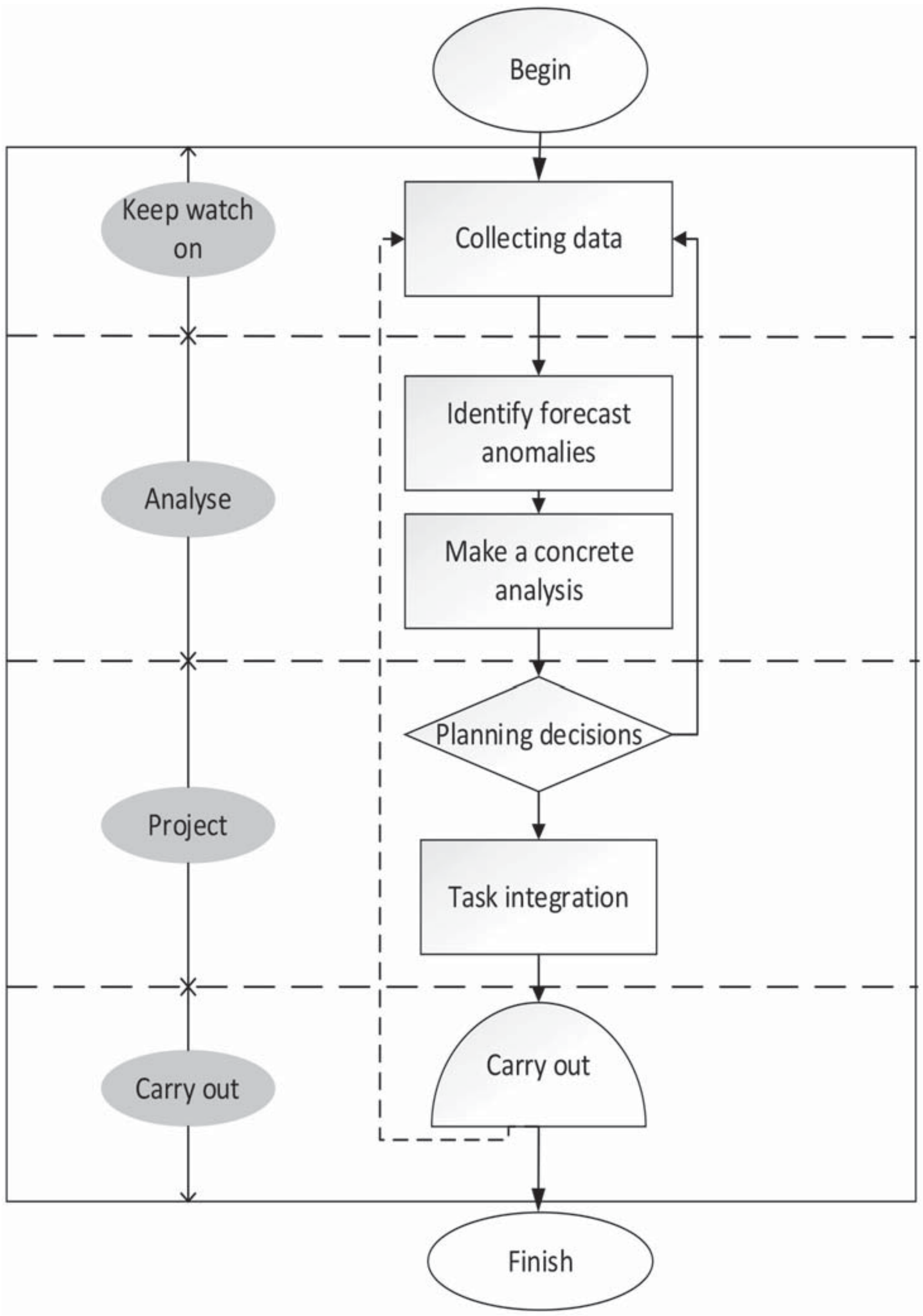


Figure 2 Logistics LCSC independent management flowchart.

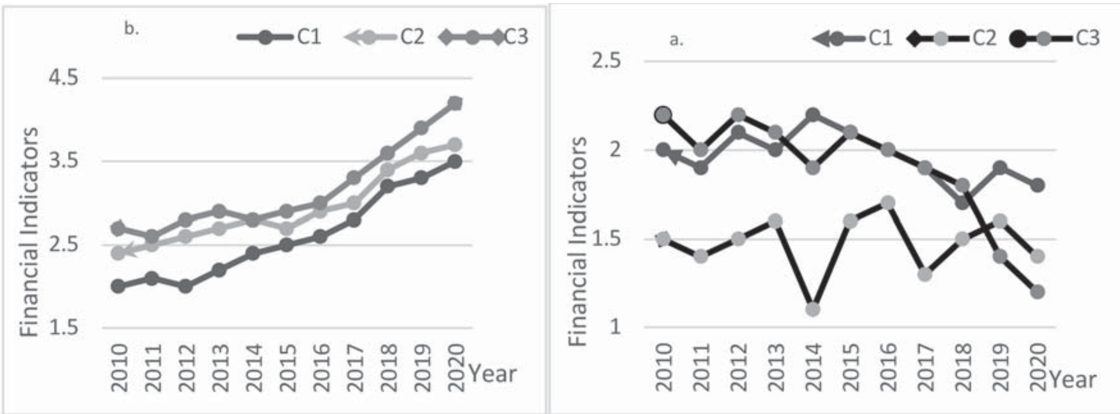
chain. In this study, the performance of LCSC was evaluated under the condition of ADM intelligence. In Table 1, indicators for low carbon performance evaluation have been established according to three dimensions: economic, social, and environmental.

5. SELF-DECISION-MAKING SUPPLY CHAIN ENERGY CONSERVATION AND EMISSION REDUCTION SYSTEM TESTING

Through a survey of traditional and representative logistics enterprises in a certain region of *A* province, as well as representative logistics enterprises with ADM and intelligent new models, data was collected and comparative experiments were conducted. The development status of logistics enterprises under different modes was studied, and the factors influencing the development of logistics enterprises under different modes were determined in order to provide valuable references for the development of logistics enterprises. This study focused on the practical effects of energy-saving and emission reduction in the LCSC system of logistics enterprises based on ADM intelligence, and conducted system analysis and experiments from three perspectives: economic, social, and environmental. The experimental data was recorded and analyzed to determine the advantages, disadvantages, and shortcomings of the LSC under the two modes.

Table 1 Evaluation of LCSC performance of logistics enterprises.

Class a index	Secondary indicators		
	Economy	Society	Environment
Indicator layer	Supply costC_1	Service level satisfactionC_4	Resource utilizationC_7
	Finished product qualityC_2	Customer satisfactionC_5	Environmental effectC_8
	Financial indexC_3	Customer ValuesC_6	Comprehensive utilization rate of wasteC_9



(a) Traditional supply chain system (b) Supply chain system with ADM intelligence

Figure 3 A comparison of the two supply chain models in terms of economic benefits.

5.1 Economic Perspective

From an economic perspective, when implementing an ECSC, the total cost includes various operational costs such as procurement, transportation, and supply. Its operation would directly reflect the current development status and future direction of logistics enterprises throughout the entire supply chain.

As seen in Figure 3, the overall economic efficiency of the supply chain system using traditional logistics enterprises was decreasing, while the economic efficiency of the supply chain of logistics enterprises with ADM intelligence was increasing year by year. It can be clearly seen that the financial indicators in Figure 3(a) decreased by 0.9 between 2015 and 2020, while in Figure 3(b), the financial indicators of the supply chain of logistics enterprises with ADM intelligence increased by 1.3, indicating that the economic market of the traditional logistics enterprise supply chain system was not optimistic. Overall, the overall supply chain operation of logistics from 2010 to 2020 did not achieve both technological and scale effectiveness, but from 2010 to 2020, the overall supply chain operation of logistics gradually shifted in the direction of LCSC.

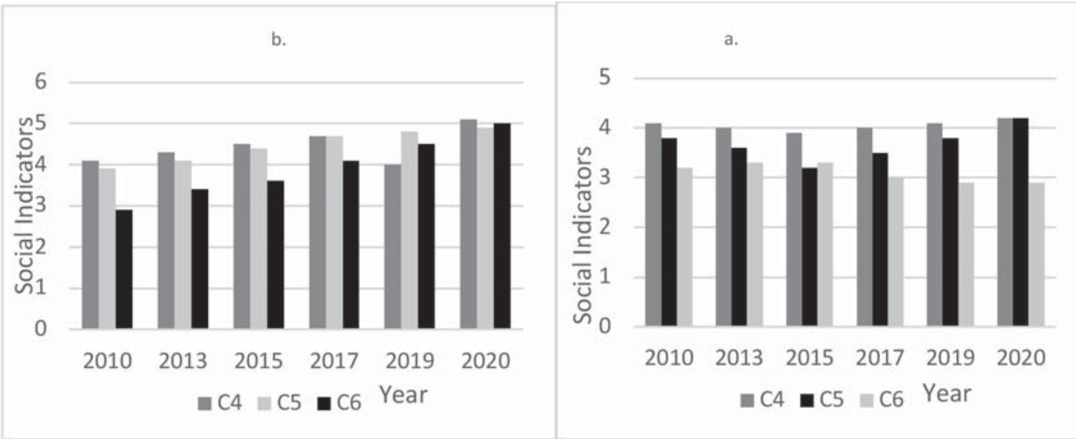
5.2 Social Perspective

From a social perspective, customer satisfaction with services has a significant impact on the economic benefits of logistics enterprises. Therefore, the satisfaction level of customers with the service level provided by an enterprise indirectly determines their return visits to the company, which in turn has an indirect impact on a company's profitability. In addition, customer values to some extent affect customers' willingness to purchase products, which indirectly affects the economic benefits of logistics enterprises. Therefore, customer satisfaction and values are crucial for logistics enterprises, and only through good service can customer satisfaction and values be improved.

Figure 4a shows no significant improvement in customer satisfaction with traditional LSC services from 2010 to 2020. In Figure 4b, the service satisfaction of logistics enterprises with ADM intelligence in the supply chain steadily increased. From 2010 to 2020, customer service satisfaction increased by 1.0%. Logistics enterprises with ADM intelligence in the supply chain scored higher mainly in terms of service level. It can be seen that this supply chain has been successful in reducing production costs, increasing the use of low carbon products, reducing energy consumption per unit output value, and improving environmental efficiency ratios. Other traditional supply chains can learn from this.

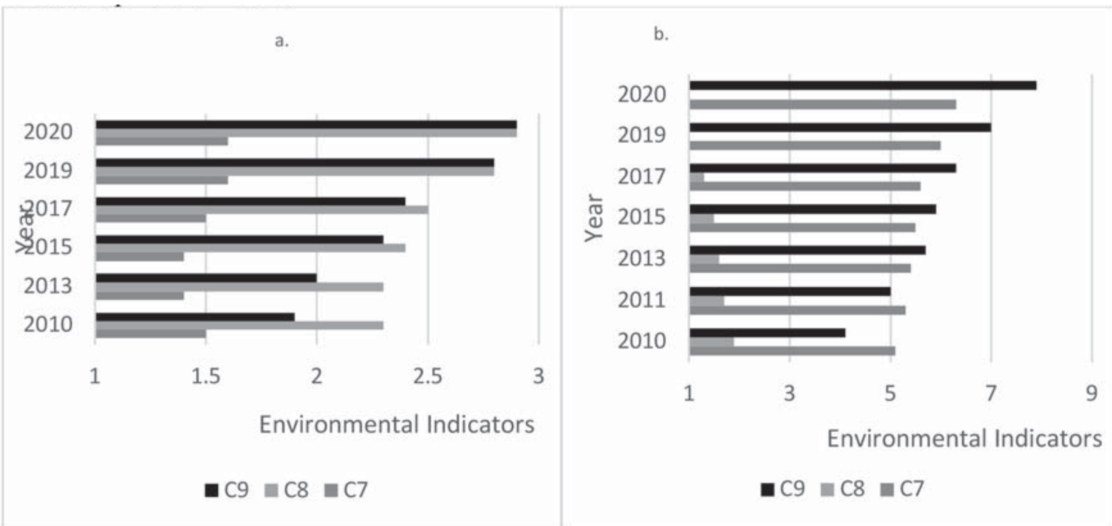
5.3 Environmental Perspective

The utilization rate of resources is an important issue that enterprises and society in general must consider in the ECSC. In such a shortage environment, enterprises or society must reduce their impact on the environment by considering how to better utilize resources. For socially responsible individuals, logistics companies should fully consider whether it would have a certain impact on the environment and make every effort to reduce pollution and damage to the environment. In addition, the recycling and reuse of resources are also essential, which not only reduces the consumption of resources, but also ensures that enterprises can obtain the maximum benefits at the lowest cost while protecting the environment and conserving resources. By improving



(a) Traditional supply chain system (b) Supply chain system with ADM intelligence

Figure 4 A comparison of the social aspects of the two supply chain models.



(a) Traditional supply chain system (b) Supply chain system with ADM intelligence

Figure 5 Comparison of two supply chain models in terms of environmental impact.

the management and efficiency of resources, energy consumption, pollution emissions, raw materials and demand for resources can be effectively reduced, while strengthening market competitiveness. This approach can effectively promote the sustainable development of corporate and society.

As shown below in Figure 5, there is a significant discrepancy between the statistics presented in Figure 5a and Figure 5b. The supply chain of logistics enterprises with ADM intelligence has obvious advantages in terms of waste management, but there are still many areas that need improvement. In traditional logistics and supply chain structures, problems such as singularity, primacy, and heaviness still exist. Therefore, in regard to economic development, there are still relatively extensive problems, and there are also shortcomings in technological innovation. There is still enormous pressure in terms of energy conservation and emission reduction. In Figure 5a, the impact of traditional LSC on the environment increased by 0.5 between 2015 and 2020. Figure 5b shows that the impact of ADM and intelligent logistics enterprise supply chains on the environment decreased by 0.8 between 2015 and 2020. The independent decision-making and intelligent supply chain development model of logistics enterprises is an improvement on the current supply chain development model, as its goal is to reduce greenhouse gas emissions at all points along the supply chain. Therefore, environmental indicators have a significant impact on the development of LCSC.

6. CONCLUSIONS

With the development of global economic integration, the competition faced by the global logistics industry is becoming increasingly fierce. Within this environment, existing problems continue to plague the industry, such as inefficient resource utilization, low-level informatization, outdated management methods, and decentralized organizations. To resolve these problems, researchers need to apply new technologies and concepts. By utilizing the Petri net decision algorithm and combining the characteristics of the LCSC energy conservation and emission reduction system of logistics enterprises with ADM intelligence, this study constructed a LCSC performance evaluation system for logistics enterprises. Empirical analysis was conducted from three perspectives: economy, society, and environment; moreover, numerical analysis was used to scientifically and reasonably evaluate the performance of LCSC. Combined with examples, suggestions were proposed for the optimization of traditional supply chains and the building of a logistics LCSC energy conservation and emission reduction system that achieves ADM intelligence. However, there are still some shortcomings in the existing research, which require ongoing research and improvement in terms of practical application. At many practical levels, more exploration and development are needed.

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