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Measuring the efficiency of low-carbon cold chain logistics in the Greater Bay Area: A system dynamics approach

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Abstract

Purpose: To improve the operation of these systems, the SDA can serve as a valuable tool for examining the behavior and interactions within them. This study employs the system dynamics method to investigate how the effectiveness of low-carbon cold chain logistics in the Greater Bay Area's system is impacted by various technologies. Specifically, we examine the influence of LOT technology, large-scale data analysis, optimization of CC network layout, and green supply chain management (GSCM)on the efficiency of LCCCL.

Design/methodology/approach: To streamline and reduce redundancy, here's a concise version of the previous text:The research framework based on System Dynamics identifies core variables (carbon emissions, logistics costs, cold chain efficiency), defines system boundaries (Greater Bay Area's cold chain logistics), outlines system structure (supply chain interactions), and establishes feedback mechanisms.Using Vensim or Stella, a dynamic simulation model is built for low-carbon cold chain logistics, encompassing procurement, processing, storage, transportation, and distribution, while considering factors like emissions, costs, time, and quality.Data is gathered from surveys, interviews, literature, and statistics, then cleaned, organized, and analyzed to inform model construction and parameter setting.Model validation and calibration ensure accuracy using historical data or expert opinions. A case study in a

representative cold chain logistics enterprise validates optimization strategies through model simulations and data analysis.
Findings: Through an analysis of the positive relationship between the extent of LOT technology and big data analytics application and the efficiency of LCCCL, the adoption of these technologies has a favorable impact on the system's efficiency and carbon emissions.
Research limitations/implications: The focus is limited to the cold chain logistics industry, excluding other sectors that also contribute to carbon emissions within the GBA. The theoretical model serves as the basis of this study, but it may not fully capture the complexities of the actual situation in the region.
Practical implications: Provision of scientific basis for evaluating and optimizing low-carbon cold chain logistics in the Greater Bay Area.
Originality/value: This dissertation stands out by applying System Dynamics to analyze the intricate interactions within the low-carbon cold chain logistics system in the Greater Bay Area. It uniquely blends environmental and economic objectives, offering insights into trade-offs between carbon reduction and operational efficiency. By focusing on the specific context of the Greater Bay Area and leveraging empirical data, the study provides tailored recommendations for the region. Its multidimensional evaluation framework considers carbon emissions, costs, time, and quality, enabling a nuanced understanding of system efficiency.The research offers a robust methodology to evaluate and optimize low-carbon cold chain logistics, guiding sustainable decision-making for policymakers, logistics managers, and stakeholders. In summary, it contributes original insights and practical value to the field.
Keywords: *E*fficiency, low-carbon, cold chain logistics, Greater Bay Area, system dynamics approach

Introduction

LCCCL plays a crucial role in addressing global climate change and escalating energy consumption, thereby contributing to the reduction of greenhouse gas emissions(GGE) and attainment of sustainable development(SD). In the GBA, a prominent economic region, the significance of cold chain logistics cannot be underestimated in ensuring the freshness and quality of agricultural products, food, and medicines. Nevertheless, the existing cold chain logistics system in this area encounters numerous challenges. These challenges consist of scattered and disparate cold chain logistics enterprises, leading to both resource wastage and increased carbon emissions. Moreover, conventional cold chain logistics facilities and processes exhibit high energy consumption, low efficiency, and a substantial carbon footprint. Furthermore, information asymmetry, insufficient collaboration, and inadequate transportation efficiency within the supply chain pose additional concerns.

Figure 1 presents a map illustrating the approximate geographic distribution of the GBA. This map provides valuable insights into the economic zones within the GBA, highlighting the locations of each city and showcasing the distances and connections between them.

The objective of this research is to assess and enhance the effectiveness of low-carbon cold chain logistics（LCCCL)in the Greater Bay Area using a system dynamics method(SDM). We will establish a comprehensive model of the cold chain logistics system, taking into account the different stages and inter dependencies within the supply chain. The model will analyze the key determinants of cold chain logistics efficiency and explore the impact of various decision-making processes and policies on efficiency. Our research outcomes will offer scientific guidance and policy suggestions to enhance and sustainably advance CCL in the GBA. This will involve reducing energy consumption and carbon emissions, as well as improving the efficiency of logistics and the utilization of resources. Furthermore, the insights obtained from this research can serve as a valuable resource for optimizing LCCCL in other geographical regions.

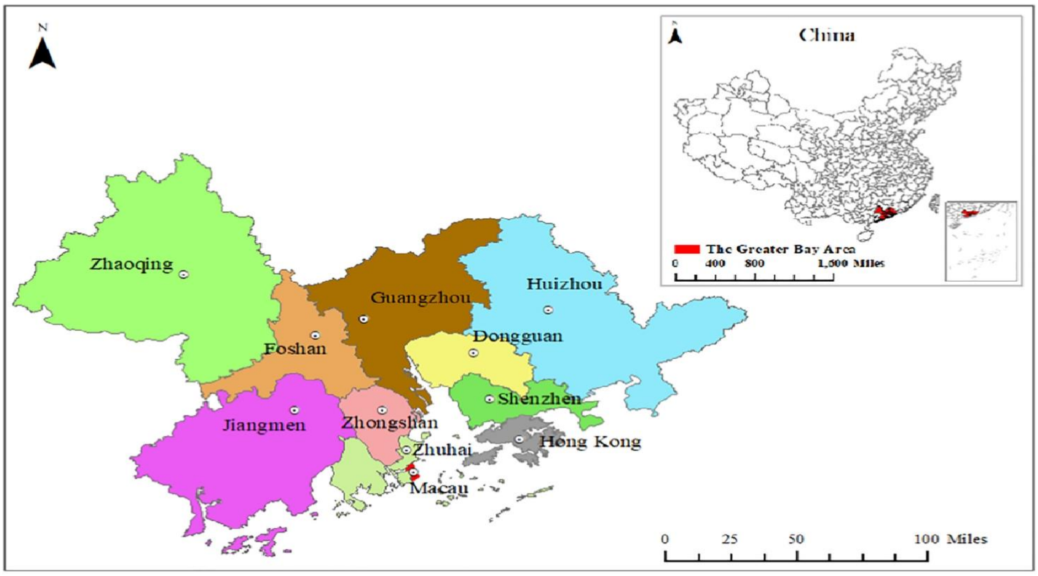

Figure 1:Regional distribution map of GBA

There has been an increasing interest in the concept of LCCCL in recent years, mainly due to concerns about the environment and climate change. This interest has drawn attention to the GBA, a prosperous economic region in China recognized for its carbon emissions and greenhouse gases. Global data indicates that the transportation sector is responsible for around one-third of GGE, with a notable contribution from cold chain logistics. This is particularly applicable to goods that necessitate precise temperature control, like food and pharmaceuticals. Consequently, efficient management of LCCCL has become vital. Additionally, the adoption of LCCCL practices can effectively minimize carbon footprints and promote overall environmental sustainability.

When assessing the effectiveness of LCCCL, it is essential to consider diverse factors, including logistics expenses and the quality of service provided. To guarantee the safe transportation of temperature-sensitive goods and ensure their optimal quality, the integration of state-of-the-art technologies and equipment within CCL is imperative. These tools comprise temperature regulation, humidity control, and adequate ventilation. Logistic companies must also take into account the financial implications associated with establishing and maintaining such facilities.

Assessing the efficacy of low-carbon logistics in the refrigeration supply chain is a intricate undertaking that necessitates the examination of numerous factors. Apart from environmental aspects such as energy consumption and carbon discharges, it is crucial to consider expenses related to logistics, service quality, and the swiftness of logistical activities. Furthermore, the participation and cooperation of diverse stakeholders are imperative in driving the advancement of environmentally sustainable refrigerated logistics.

Literature Review

Importance of LCCCL in GBA

China released the Development Plan Outline for the GBAon February 18, 2019, after carrying out a comprehensive examination of existing literature. In their analysis of the GBA, LIU

(2020) provides insights into its historical context, its importance in integrating HKM into China, its connection with the OBOR initiative, the MIC2025 plan, and China's broader economic expansion. Additionally, LIU (2020) examines the future of the GBA and brings attention to the obstacles that lie ahead. In the field of blockchain technology, a blockchain-based intelligent logistics platform has been developed by Lai et al. (2020), which could serve as a valuable point of reference for the GBA in facilitating the integration of logistics and promoting the harmonious growth of city clusters. Furthermore, Liu et al. (2021) suggest three important recommendations for cross-border energy collaboration within the GBA, in line with China's ambitious goal of achieving carbon neutrality by 2060. These recommendations encompass the establishment of a shared electricity market, the encouragement of cross-border cooperation in technological innovation, and the formation of a unified carbon trading market.

In this paper section, we analyze the importance and expansion of low-carbon cold chain logistics in the GBA. Initially, we present a general outline of the region's development plan, incorporating its historical context, significance, and organizational arrangements. Next, we propose suggestions for integrating logistics and urban clusters within the area. Furthermore, we highlight the significance of cross-border collaboration in the realm of energy for China's pursuit of carbon neutrality by 2060. This includes the establishment of a shared market for electricity, promotion of collaborative technological innovation, and implementation of a unified market for carbon trading. Moreover, we delve into the utilization and development of subterranean urban space in Shenzhen and the Greater Bay Area.

Regarding the system dynamics my process steps I represent in Figure 2, which may help us to better understand the system dynamics.

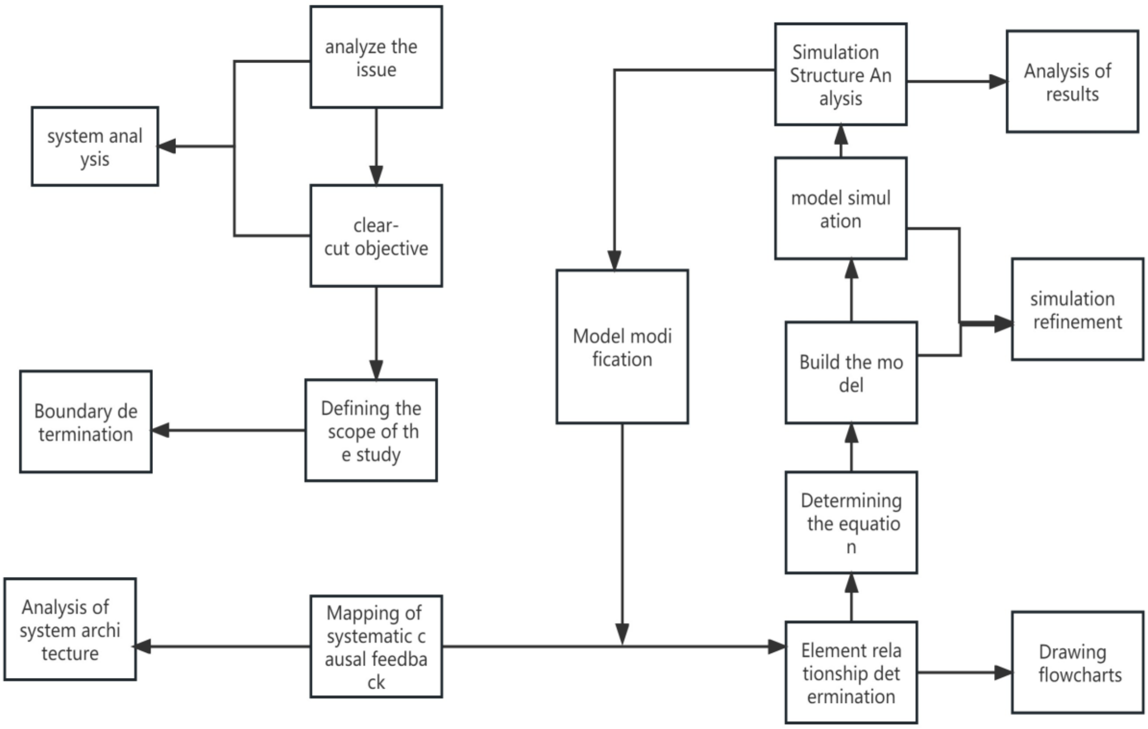

Figure 2:Diagram for building an SD model

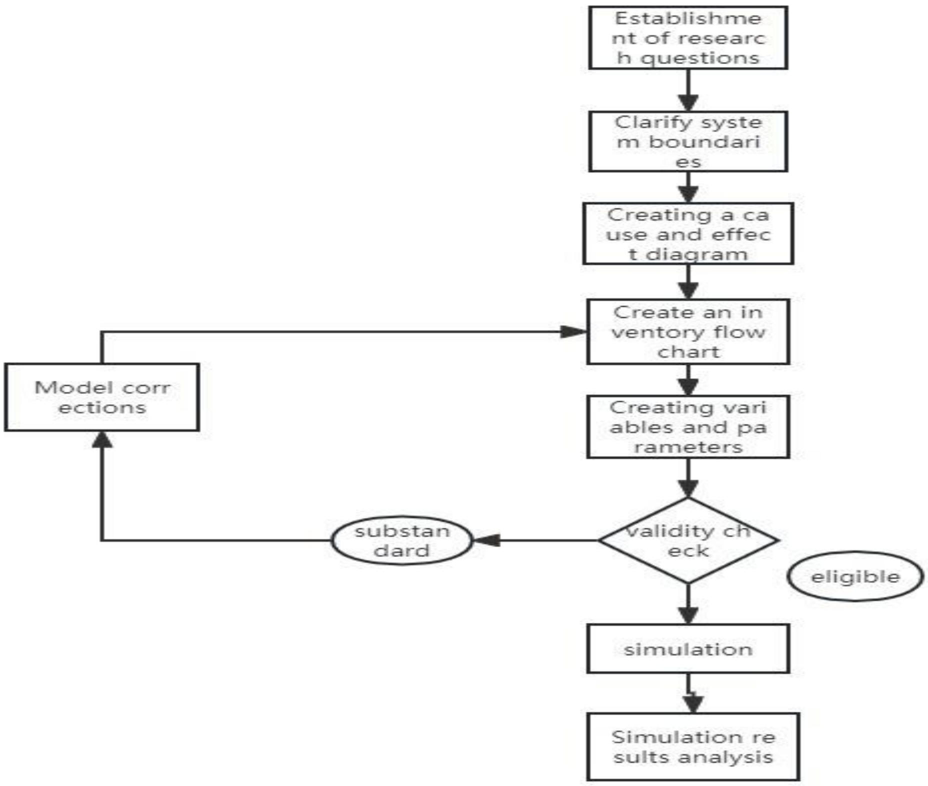

Figure 3:Step-by-step diagram for modeling system dynamics

The logistics performance levels of eleven cities in the GBA were analyzed from a low carbon perspective using principal component analysis (Xu, 2023). Hong Kong attained the highest score, while Zhongshan obtained the lowest score in terms of logistics performance. Other notable contributions in this field include the works of (Yang, 2019).

This research examines the utilization of system dynamics modeling in logistics to attain equilibrium between environmental and economic sustainability. It presents instances of the practical implementation of system dynamics modeling in the logistics field. Additionally, it evaluates the performance of high-tech industries within the GBA, alongside an analysis of the region's economic growth and urban network system.

GBA cold chain logistics based on SD

According to Wu et al. (2020), a study was conducted on the stability of Macao and nine cities in GBA, noting that HK is undergoing complex growth with significant changes. The focus of this research was to examine the relationship between regional economy and logistics coordination, aiming to gain insights into regional economic development. ultimately allowing for prediction based on their findings (Ye et al., 2020). Exploring the technical aspects of blockchain (Lai et al., 2020), the authors designed an intelligent logistics platform using blockchain technology. This development can serve as a valuable reference for the greater bay area, assisting in the realization of logistics integration and facilitating the integration of city clusters. Meanwhile, Yang et al. (2021) conducted a study on the spatiotemporal evolution and underlying factors responsible for forest loss in the GBA at both regional and city levels. Additionally, Jie et al. (2021) focused on establishing an innovative teaching model through the collaboration of educational institutions in GBA. Their efforts emphasized the significance of an integrated practice teaching base that combines production, teaching, and research, serving as a model for promoting innovative practices in various competitions. Highlighting the evaluation of existing energy policies, Zhou et al. (2021) developed a GBA-specific energy technology model called TIMES (The Integrated MARKAL-EFOM System). This model aimed to assess the effectiveness of current policies in optimizing the energy system between 2015 and 2035.

The primary objective of this study is to examine the logistics and the coordination of the regional economy in GBA. It entails an in-depth analysis of the performance of logistics, the transformative nature of the regional economy, and the intricate link between the financial structure and economic growth.

This paper explores the economic progress of the GBA, with a focus on regional logistics coordination and system dynamics modeling, as discussed in existing literature. Findings from exiting literview show that:

Existing system dynamics models lack a comprehensive range of strategies and a broad perspective when examining the decarbonization of freight transport.

The development of the regional economy heavily depends on the coordination between regional logistics and the overall economy.

The integration of logistics and urban agglomerations can be effectively achieved through the use of blockchain smart logistics platforms.

The study assesses the level of economic synergistic development within the city cluster of the GBA, including an analysis of the evolution of the region's economic model and urban network system over the past decade.

From a low-carbon perspective, the logistics performance of eleven cities in the GBA is evaluated, with H K receiving the highest score and ZS achieving the lowest score. 6. The research presents a system dynamics model that compiles CO2 emission inventories of the GBA and neighboring cities. Additionally, the model includes a research framework that investigates the drivers, future trends, and policy implications of CO2 emissions in the region. Furthermore, this paper formulates three propostions.

Propostion 1: The correlation between increased efficiency and reduced carbon emissions is positively influenced by the integration of Internet of Things (IoT) technology and big data analytics in the cold chain logistics system. To validate this hypothesis, we suggest the use of statistical and correlation analyses, utilizing real-life case studies. This entails gathering data on the implementation of IoT technology and big data analytics in the cold chain logistics system and examining their correlation with levels of efficiency and carbon emissions.

Propostion 2: Optimization of the layout of the cold chain logistics network is associated with decreases in transportation distance, time, carbon emissions, and operational costs. To empirically examine this hypothesis, simulation experiments or case studies can be conducted. As an example, data on various network layout options in the CCLS can be collected, enabling a comparative evaluation of their corresponding transportation distance, time, carbon emissions, and operational costs.

Propostion3: To verify this hypothesis, we propose utilizing data analysis and questionnaires as research techniques. By collecting data on the implementation of GSCM techniques in LCCCLS, a comparative analysis and evaluation of the resulting effectiveness levels can be conducted.

Methods

In the following section, I will provide a detailed analysis of the metrics used in the bubble diagram to measure the effectiveness of LCCCL. This analysis will be presented in a tabular format, focusing on the four main factors identified in the bubble diagram: supply chain sustainability, energy efficiency, IoT and big data, and transportation route optimization. Table 1 will provide clear definitions of these factors.

Table 1: Four main factors of LCCCL efficiency strategies

Efficiency Measurement Factors	define
Green Supply Chain Sustainability (GSCS)	The concept of GSCS involves considering environmental factors throughout the entire supply chain process. This includes everything from sourcing raw materials to distributing final goods to customers. The approach involves implementing strategies and adopting technologies to reduce the environmental impact of the supply chain. The ultimate goal of green supply chain sustainability is to create a system that balances economic and environmental objectives, promoting a sustainable and environmentally conscious supply chain network.
Internet of Things and Big Data(IOT and BD	IoT refers to a network that connects various physical devices, such as vehicles, buildings, and other items. These devices are embedded with sensors, software, and capabilities for connectivity. They can gather and exchange data with each other over the internet, enabling them to interact and complete tasks independently without human-to-human or human-to-computer interaction. On the other hand, the concept of big data involves a significant amount of structured and unstructured data from various sources, including IoT devices, social media platforms, and online transactions. This data is characterized by its large volume, variety, and speed of generation, which present challenges in terms of storage, analysis, and processing. When IoT and big data are combined, they create opportunities for extracting valuable insights and utilizing real-time information to support decision-making processes. IoT devices continuously generate and transmit data, contributing to the production of big data. Big data analytics then helps extract actionable insights from the massive quantities of data generated by IoT devices. By integrating these technologies, organizations can enhance efficiency, optimize operations, improve customer experiences, identify patterns, and make data-driven decisions.
Optimization of transport routes	Optimization of transport routes refers to the process of strategically determining the most efficient and cost-effective routes for transportation. It involves analyzing various factors such as distance, traffic conditions, delivery time, fuel consumption, vehicle capacity, and customer demands to determine the optimal routes for transporting goods, passengers, or services.The primary objective of route optimization is to maximize efficiency and minimize costs in transportation operations. By identifying the most efficient routes, organizations can reduce fuel consumption, vehicle wear and tear, and travel time. This leads to cost savings, improved customer satisfaction, and increased overall operational efficiency.Route optimization typically involves using advanced algorithms and technologies to analyze and process a large amount of data, including historical traffic patterns, real-time traffic updates, vehicle and driver capabilities, and delivery constraints. By considering these factors, organizations can

	make informed decisions on route selection, scheduling, and resource allocation to ensure timely and efficient transportation.
energy efficiency	Energy efficiency refers to the practice of maximizing desired outcomes while minimizing energy consumption and waste in order to achieve optimal energy use. It involves conscious efforts to reduce energy usage without compromising productivity or comfort. The objective of energy efficiency is to optimize energy resources by minimizing losses, reducing waste, and improving overall energy consumption productivity and effectiveness. The implementation of energy-efficient technologies, processes, and practices is crucial across various sectors, including residential, commercial, industrial, and transportation. Energy efficiency measures encompass upgrading insulation in buildings, utilizing energy-efficient appliances, equipment, and lighting, optimizing heating and cooling systems, improving energy management, utilizing renewable energy sources, and adopting behavioral and lifestyle changes to lower energy consumption. Improving energy efficiency offers several benefits, including reducing greenhouse gas emissions, lowering energy costs, enhancing energy security, and mitigating environmental impacts associated with energy production and consumption. Additionally, it provides economic advantages such as job creation, energy savings, improved air quality, and the development of a more sustainable and resilient energy system.

Next I will define in detail the specific metrics for each of the four important measurement factors, the first factor is Green Supply Chain Sustainability, the metrics for judging Green Supply Chain Sustainability are shown in Table 2, and this study will define each metric in detail.

Findings

We propose the following finding：

For Propostion 1. Our analysis of actual case studies and statistical correlations demonstrates a substantial positive connection between the utilization of IoT technology and big data analytics in the cold chain logistics system. This connection leads to increased efficiency and decreased carbon emissions. By integrating IoT devices such as temperature sensors, GPS trackers, and RFID tags and applying advanced analytics to the collected data, logistics operators optimize route planning, real-time monitoring, and inventory management. As a result, transportation delays are reduced, energy efficiency is enhanced, and carbon emissions are minimized in cold chain logistics operations. Regarding

For Propostion 2, we present the outcome as follows. Our hypothesis was confirmed through simulation experiments and case studies, establishing a significant link between the optimization of the CCL network layout and reduced transportation distance, time, carbon emissions, and operational costs. By strategically positioning distribution centers, warehouses, and transportation hubs, logistics operators successfully improve the overall connectivity of the network, reducing the need for long-haul transportation and minimizing the distance covered. This strategic network layout leads to reduced transportation time, lower carbon emissions, and decreased operational costs related to fuel consumption and vehicle maintenance.

Based on the review of real data and surveys, it has been observed that the use of environmentally sustainable techniques in LCCCLS, particularly the implementation of

GSCM practices, significantly improves system efficiency. By employing energy-saving equipment, eco-friendly packaging, and waste reduction strategies.Furthermore, the feedback obtained from industry professionals through questionnaires indicates positive outcomes in terms of effectiveness when incorporating green supply chain management practices in low-carbon cold chain logistics systems.

These results support the hypotheses and demonstrate the potential benefits and positive impacts of integrating IoT technology, optimizing network layout, and adopting GSCM within LCCCLS.

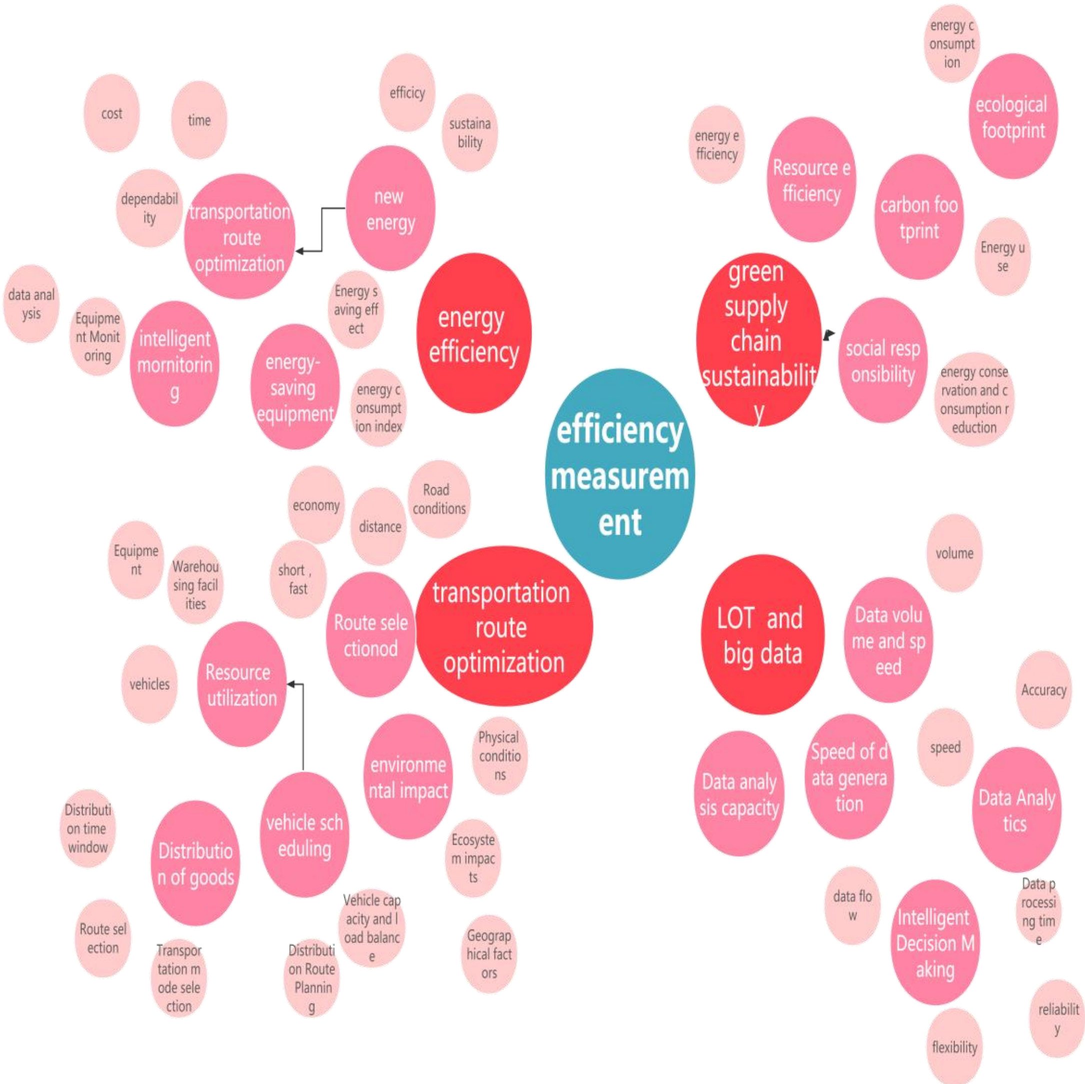

Figure 4: Low-carbon cold-chain logistics efficiency measurement bubble map

Discussion and Conclusion

The efficiency of LCCCLS in the GBA can be greatly enhanced by integrating IoT technology, optimizing network layouts, and implementing green supply chain management. The collaboration in energy utilization across borders within the GBA can be facilitated by establishing a unified market for carbon trading, promoting innovation in cross-border technology, and creating a shared electricity market. Exploring and utilizing the urban underground space can serve as an effective approach to promote the sustainable development of the GBA.

Theoretical Implications

Deepening the Theoretical Research on Low-Carbon Cold Chain Logistics: By employing the system dynamics approach, this study comprehensively analyzes the efficiency of low-carbon cold chain logistics in the Greater Bay Area, providing a new perspective and framework for advancing the theory of low-carbon logistics.

Promoting the Development of Low-Carbon Supply Chain Management Theory: It reveals the potential for low-carbon practices within cold chain logistics in supply chain management, thereby fostering innovation in low-carbon supply chain management theories.

Enriching Methods for Regional Logistics Efficiency Evaluation: This research contributes new tools to the evaluation of regional logistics efficiency, enhancing the scientific rigor and accuracy of such assessments.

Practical and Social Implications

Guiding Low-Carbon Cold Chain Logistics Practices in the Greater Bay Area: By identifying areas for improvement, the study informs the formulation of policies and measures by governments and enterprises, guiding the development of low-carbon cold chain logistics in the region.

Promoting Sustainable Development in the Greater Bay Area: By reducing carbon emissions and protecting the environment, the efficient implementation of low-carbon cold chain logistics contributes to the promotion of green economic development and overall sustainability in the region.

Providing Industry Reference: The study summarizes replicable experiences and practices, offering valuable insights and lessons for the cold chain logistics industry in other regions, stimulating further research and development in this field.

Limitations and Suggestions for Future Research

The focus is limited to the cold chain logistics industry, excluding other sectors that also contribute to carbon emissions within the GBA. The theoretical model serves as the basis of this study, but it may not fully capture the complexities of the actual situation in the region.

This research proposes a comprehensive framework for assessing the effectiveness of LCCCS in the GBA. By integrating IOT technology, optimizing network layout, and adopting green supply chain management practices, the efficiency of these systems can be greatly enhanced. The study highlights the potential benefits and positive outcomes that can be attained through the integration of IoT technology, network optimization, and GSCM in LCCCLS.

Special Note:

In the writing of this article, because the following words appear frequently, they are explained here:The abbreviation for Guangdong, Hong Kong and Macao Greater Bay Area is GBA;The abbreviation for Cold Chain Logistics is CCL;The abbreviation for Cold Chain Logistics System is CCLS;The abbreviation for Low Carbon Cold Chain Logistics is LCCCL;The abbreviation for System Dynamics Model is SDM

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