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OPTIMIZATION PROBLEM OF CHINA'S SUPPLY CHAIN TRANSPORTATION ISSUES IN EUROPEAN LOGISTICS

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ABSTRACT: The paper highlights the importance and validity of the research problem: the major consequence for logistics arising from China's logistics market due to its effective short-term and long-term strategies and developing transportation wholesale. The presented viewpoint helps to clearly understand the international perspective of the vastly enlarging China's supply chain market due to its strong links with logistics centres. In recent years, much scientific research and studies have been conducted in China and Europe regarding China's transport evolution era, from the production stage to the physical distribution stage, involving multiple steps until loads are in customers' hands. The article considers the optimisation problem of a supply chain with multiple periods and diverse means of transportation. The considered problem can be formulated as a dynamic multi-criteria decision-making problem, in which the criteria are minimising the total cost, minimising the carbon footprint, and minimising the average transporting time.

KEYWORDS: transport, logistics, supply chain, optimisation, strategy

Introduction

Several scholars have analysed the correlation between the logistics and manufacturing industries; however, these analyses mainly focused on industrial correlation, industrial division, core competitiveness, transaction costs, and industrial chains, as based on the manufacturing of the United States. Feser and Bergman (2000) analysed the degree of industrial clustering and determined industry gaps among different regions to promote cross-regional industrial linkage and to apply cooperation mechanisms more easily and thoroughly. Green supply chain management is an advanced management that considers environmental effects and resource utilisation across the entire supply chain (Yu & Khan, 2022; Khan et al., 2022; Feng et al., 2022; Sheng et al., 2023). The importance of China's economy and its directed logistics interest is gradually growing, guided by efficacious short-term and long-term strategies for its supply chain market. The supply chain dynamics and the effective use of collected data to improve performance require further exploration (Rong et al., 2022). A more applicable method is required to understand the international economics perspective on rapidly extending China's supply chain market. A digital supply chain (DSC) delivers products from their origin to their destination by electronic means (Gezdur & Bhattacharjya, 2017). Owing to their permanently expanding domination in supply chain markets, numerous logistics companies have implemented worldwide supply chain strategies in China and abroad. Thus, centralised and intelligent management is realised for logistics and warehousing data (Anitha et al., 2021). In the post-industrial community logistics era, transport systems contribute to society's economic and financial expansion in industry, agriculture, and even the knowledge economy. More specifically, it is a combination of supply chain management concepts and several green practices, including green purchasing, green design, green logistics, reusing, recycling, and reproducing and environmental technologies with suppliers, manufacturers, distributors, retailers, and customers (Bashar et al., 2023; Ghorbanpour & Azimi, 2022). This is particularly relevant in the context of big data solutions supporting operations and decision-making across various business divisions throughout the product life cycle of a smart factory (Li et al., 2019). Supply chain management is often regarded as a key to promoting growth and developing prosperous technological advancements worldwide. It is an imperative economic tool to avoid chaos in logistics and transportation markets. It plays an essential role in optimising harmful emissions and consumption of resources (Wang et al., 2022). Historical infrastructure construction, such as rail roads, coincided with periods of rapid economic growth in Western Europe, Japan, and the United States; thus, the significance of transportation development grows with social and economic development (Coyle et al., 2000). While this objective received attention from fewer authors (Gao et al., 2020; Rasi, 2022) than reducing carbon emissions, it is nevertheless important to attain overall environmental sustainability. An interesting and rich history of China's civilisation witnessed impressive logistics development and the progress of the social state's economics in the nearest supply chain vision. As multiple-criteria decision analysis (MCDA) is used in various fields and disciplines, such as economics, resource management, production, etc. (Velasquez & Hester, 2013), the article proposes a mathematical model to incorporate cost and environmental variables in the battle between four supply chain echelons and several goods (Rasi, 2022).

Literature overview

The article presents different scientific research based on theoretical and empirical approaches of the East Asian region (China). These objectives include minimising carbon/CO2 and greenhouse gas (GHG) emissions, maximising sustainable development benefits, and minimising energy consumption and waste production (Soleimani et al., 2022; Liu et al., 2022). The objective of minimising carbon/CO2 emissions is essential to decreasing the consequences of climate change (Liu et al., 2022). The main research object is exploring different paradigms in the context of global and international transport markets, including the integration of different elements, from a supplier delivering raw materials to a manufacturer to the delivery of the finished product or service to the end customer in the relationship management process. Handling sensitive supply chain information poses significant risks, including the potential for data breaches, un authorised access, and data misuse (Shahzad et al., 2020).

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Due to the expanding trend of nationalisation and globalisation in recent decades in the transportation market, the importance of modern logistics services management has been growing in various areas. Enterprises in the supply chain can use big data to control products and optimise production processes, which can help reduce internal costs related to production, sales, and products (Xu et al., 2020).

For main industries, logistics helps optimise the existing production and distribution processes based on the same global resources through international transport management techniques to promote the supply chain market efficiency and competitiveness of transportation companies. CO_2 and GHG emissions must be rapidly reduced to limit global warming, aiming to reach net zero CO_2 emissions by 2050 (Becattini et al., 2022).

The use of big data in supply chain management has become essential due to the increase in the data flow generated in the supply chain, which motivates companies to accept supply chain analysis to gain a competitive advantage (Yang, 2022). The main key element in a logistics supply chain is a correctly combined transportation system, which joins the separated activities to satisfy the end customer's needs. Engaging in GSCM practices can enhance a company's overall performance, with competitiveness and investment recovery acting as intermediary factors within the organisation's green initiatives (Amjad et al., 2022). A transportation system is required for production services, from the start of manufacturing to product delivery and returns. In a supply chain system, maximum benefits can only be ensured by effective and satisfactory coordination between its components. Supply chain scholars have recognised that inter-organizational networks can furnish resources for benefits, such as increased supply chain capital, inspired firm innovations, and enhanced operational efficiency (e.g., Cousins et al., 2006; Autry & Griffis, 2008; Stolze et al., 2015; Wichmann & Kaufmann, 2016). Therefore, sustainable management of supply chains is vital in addressing sustainability concerns in firms of all sizes and across a broad spectrum of industries. Consequently, many researchers have studied sustainable supply chains (SSC) in recent decades (Beske et al., 2014; Craig & Easton, 2011; Ghadimi et al., 2016; Seuring, 2013). According to Lambert and Cooper (2000), "One of the most significant paradigm shifts of modern business management is that individual businesses no longer compete as solely autonomous entities, but rather as supply chains ... Instead of brand versus brand or store versus store, it is now suppliers – brand – store versus suppliers – brand store, or supply chain versus supply chain". So, different authors focused on this objective and GHG (Boskabadi et al., 2022; Al-Enazi et al., 2022; Hasani et al., 2021). Many logistics companies no longer compete as autonomous entities but as global supply chains, which affects their worldwide operations. The paradigm shift in transposition is most evident in how logistics companies compete in China. Lee and Yang (2003) reported that economic prosperity in the East Asian region was the main driver behind the enormous logistics demands. They highlighted the potential and influences of airports, offering suggestions for their future development. Maximising the benefits of sustainable development comprises a wide variety of techniques that focus on reducing the negative consequences for human health (Agrawal et al., 2022). Acquiring supply chain data from various sources, including customer website visits, social media responses, and evolving contractual ties, has been identified as a critical aspect of big data-driven supply chain capacities (Bansal et al., 2020).

In the global and expanding logistics world, supply and manufacturing issues have gained increasing attention due to the high connectivity of supply chain logistics centres. Supply chains are operating in an increasingly more networked and global environment, where the ability to build and maintain relationships with suppliers is equally critical and challenging for businesses (Hallikas & Lintukangas, 2016). Supply chain (SC) risks are multifaceted and can be classified into operational and disruption risks (Tang, 2006; Tomlin, 2006; Craighead et al., 2007; Sawik, 2011; Govindan et al., 2017; Fahimnia et al., 2018; Ivanov, 2018; Choi et al., 2019; Xu et al., 2020).

The supply chain optimisation transportation management model is presented below (Figure 1). It shows how the loads are transported by air, maritime, rail, and road from Europe to China, using eight manufacturers and four suppliers. It is a prerequisite for the effective operation of the supply chain and distribution management system. Multi-criteria decision-making (MCDM) can be defined as a formal and structured decision-making approach for solving intricate problems with contradictory criteria (Nabeeh et al., 2019). A logistics centre has different tasks to perform in a requested time, e.g., to provide transportation, financial, economic, insurance, IT, telecommunications, adminis-

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tration, and monitoring services. The paper suggests a multi-level, multi-commodity, multi-period, and multi-objective mathematical model to achieve this goal (Mehri Charvadeh et al., 2022).

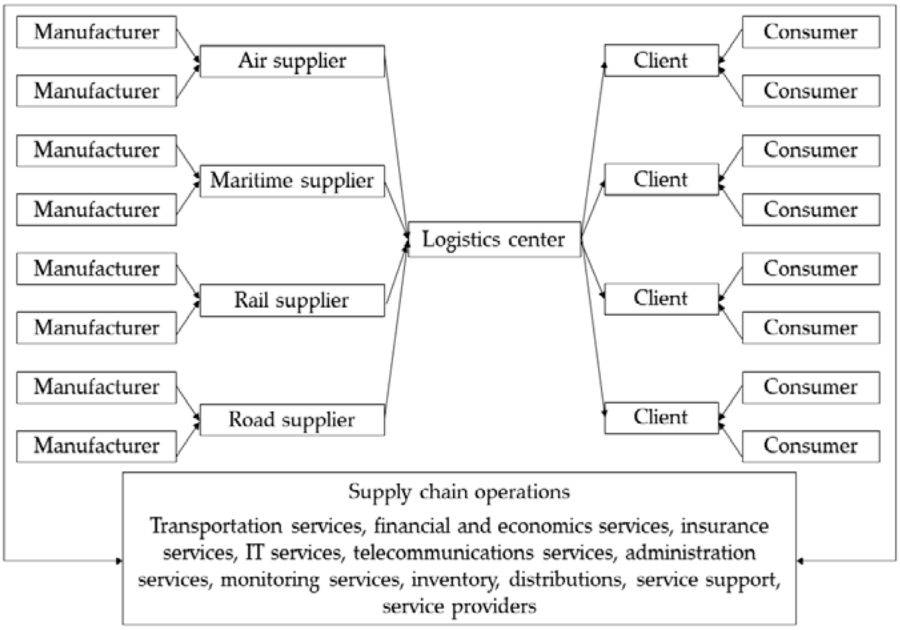

Figure 1. Supply chain logistics management model

Loads are transported from the logistics centre to clients and from clients to consumers. The application of big data analytics has been recognised as an instrument for coordinating and regulating planning, decision-making, and supply chain preparedness, thus enhancing the awareness and flexibility of supply networks (Vincent et al., 2021; Sakib, 2021).

One of the main elements of a proper company's functioning is well-organized warehouse management. It is a prerequisite for the effective operation of the supply chain and distribution management system. MCDM provides a systematic methodology that helps decision-makers rank alternatives and make decisions under very complex conditions (Gupta et al., 2012).

In the considered case, the supply chain process management involves partners of cooperating companies in the system comprising a supplier and a recipient. The green objectives represent consumers' and companies' goals for encouraging environmentally friendly behaviours and attaining sustainability (Majeed et al., 2022).

It also enables finding the best possible coordination of the product placement in specific locations considering time criterion. It is possible to pass the distribution problem to analytics for investigation and an optimal solution (Lizbetin et al., 2018).

Implication of the theoretical approach based on the presented supply chain optimisation logistics management model

Supply chain issues can arise during transportation and other stages (Kausar et al., 2023), starting from the flow of raw materials, materials, and semi-finished products to finished products to the distribution stage and the final sale to the end customer (Mansour et al., 2023). Furthermore, implementing privacy protection and data coordination mechanisms based on blockchain can help address privacy and security issues when a large amount of data is exchanged within supply chains (Tang et al., 2006).

The issue has strictly negative effects and influences on the flow of goods and services in all distribution. The issue often occurs when the supply chain structure differs from the known one and from the determined initial value to the last value for delivering. Many risks also have negative and continuous consequences for future transportation. If an issue occurs during the implementation stage of logistics processes or the materialisation of the supply chain transportation, there may be real threats and a dangerous unseen situation for the functioning of the entire transportation system. Logistics Management System (LMS) can transfer suppliers' goods to demanders with the lowest capacity and highest efficiency (Long et al., 2020).

The difference is that the issue has extremely negative consequences for the logistics centre's activities. The crucial risk may be perceived negatively and as an important situation that outlines the logistics centre development opportunities. For the strategic management of supply chains, it is hardly necessary to strongly identify the essential sources of emerging issues and the causes of unexpected global risks. Therefore, it is essential to control the compliance of international logistics for enterprises (Ding & Zhao, 2021).

Issues rarely manifest through adopting an inaccurate strategy or making wrong global transportation decisions. DSCs have many benefits, such as the cost-effectiveness of services and the development of value-creating activities, which are useful to many actors in the ecosystem, including the companies and their employees, customers, and suppliers (Korpela et al., 2017). Countless different conjoint factors affect many issues in the supply chain. They depend on the nature and specificity of the supply chain transportation and the number of relationships and establishments involved in the flow of loads. As each supply chain operation has an environmental and social cost, combining environmental and social problems with economic considerations is becoming more important in increasing awareness about sustainable supply chains (Gupta et al., 2022). The liability of the supply chain for issues or risks depends on the number of mutual communication intersections and the number and types of dissemination modes, i.e., personal resources management, customer cultural relationship management, demand and supply cultural management, order fulfilment process, managing the production process, supply chain procurement cultural management, product culture of development and commercialisation, enhancement in supply chain production. More attention is needed on social aspects to support the triple bottom line's connection and strengthen its theoretical foundation (Tseng et al., 2020).

The optimisation problem of a supply chain with multiple periods and diverse transportation means

In logistics activities, a significant emphasis is placed on actions related to planning the efficient and effective flow of goods in the supply chain. The aspect of planning is also clearly emphasised in various logistics definitions. Logistics planning distinguishes between strategic, tactical, operational, and current planning. Within operational planning, route planning, cargo size, and utilising transportation resources are of particular importance. Transport planning aims to maximise the utilisation of the transport fleet and minimise delivery routes and transport times, thereby reducing the unit transport cost.

In the planning and optimisation of the supply chain, various decision problems are considered, which can generally be divided into the following groups of issues:

- determining the optimal route for transportation vehicles for delivery routes (vehicle routing problems),
- determining the optimal schedule for delivery times (vehicle scheduling problems),
- optimal location of warehouses, production points, or distribution points, along with designing an efficient distribution network (facility location, transportation network design problems),
- determining the optimal (minimum) size of a vehicle fleet (transportation means) necessary for carrying out deliveries, urgent to supply chain realisation (vehicle fleet sizing problems).

Large amounts of organised and unstructured data that are too difficult to manage using a conventional database and scheduling techniques are called ''big data'' (Nath et al., 2022). Logistics companies currently operate in an environment where competitive demands and increasingly complex logistics systems require the use of modern IT tools and quantitative methods to support making optimal logistics decisions. The continuous increase in computing power and the capabilities of modern computers now allow for the widespread use of mathematical optimisation models, used, among other things, for planning transportation processes. This research suggests a novel method for optimising deep learning neural networks using the particle swarm optimisation (PSO) algorithm to increase business decision assessment models' precision and convergence rate (Chen & Du, 2022).

The presented methodology is based on several models: transportation cost minimisation, holding cost minimisation, and warehousing cost minimisation. Different variables and parameters represent models and their values of minimisation and maximisation supply chain. The multimodal load

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transportation by air from Shanghai to Hamburg involves the cities of Hong Kong, Moscow, Minsk, and Warsaw. The multimodal load transportation by sea from Shanghai to Hamburg involves the cities of Surabaya, Cape Town, Abidjan, Dakar, and Lisbon. The multimodal load transportation by road from Shanghai to Hamburg involves the cities of Xian, Urumqi, Astana, Moscow, Minsk, Warsaw, Berlin, Leipzig, Nuremberg, and Frankfurt. The multimodal load transportation by railroad from Shanghai to Hamburg involves the cities of Urumqi, Alma-Ata, Moscow, Minsk, Warsaw, Berlin, Leipzig, Nuremberg, and Frankfurt. In logistics, a lot of emphasis is placed on planning an efficient and effective flow of goods in the supply chain.

Methodology of the supply optimisation problem

Multi-criteria model

The considered problem can be formulated as a dynamic multi-criteria decision-making problem. Transportation cost is usually the main criterion taken into account in transportation planning. However, it is worth noting that other issues must also be taken into account by decision makers, e.g. delivery time. Additionally, factors related to climate protection are becoming more and more important. For this reason, we include the following criteria in our model:

- minimising the total cost, including transportation and inventory holding costs (both at the production plants' warehouses and at the distribution centre),
- minimising the carbon footprint resulting from product transportation between production plants and the distribution centre,
- minimising the average time of transporting the product from production plants to the distribution centre.

By introducing a novel way to model network redundancy optimisation, the current study provides a novel methodological approach to fill the gap in the literature (Pavlov et al., 2019). The problem is analysed over an assumed time horizon, with a week as a time unit (period). We assume that the following data is available for each of the considered periods:

- production capacity of each production plant,
- the number of product units that must be available in the distribution centre.

It is also assumed that the product can be transported from production plants to the distribution centre using air, sea, rail, and road transport. For each of these transportation means, the following data is available:

- cost of transporting a unit of product from each production plant to the distribution centre,
- product transportation time expressed in the number of periods after which the product shipped from a particular production plant will be available in the distribution centre,
- carbon footprint resulting from the transportation of a unit of product between a particular production plant and a distribution centre,

Transportation means capacity, which is the number of product units that can be shipped from each production plant in each period.

The dynamic multi-criteria decision-making model is presented below. The following notation is assumed:

- T – number of planning periods (weeks),
- t – period number (t = 0, 1, …, T),
- I – number of production plants,
- i – production plant number (i= 1, …, I),
- J – number of transportation means,
- j – transportation mean number (j = 1, …, J),
- $p_{i,t}$ – production capacity of plant i in period t,
- D_t – the number of product units that must be available at the distribution center in period t,
- $c_{i,j}$ – cost of transporting a unit of product from the production plant i to the logistics center using transportation means j,
- $e_{i,j}$ – carbon footprint resulting from the transportation of a unit of product between production plant I and a distribution center using transportation mean j,

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- $t_{i,j}$ – the time required to transport the product from the production plant i to the logistics center using transportation means j,
- h_i – unit inventory holding cost in production plant i,
- H – unit inventory holding cost in a distribution center,
- B_j – transportation mean capacity – the maximal number of units that can be shipped in each period from all production plants to the distribution center using transportation mean j,
- $y_{i,t}$ – number of units produced in production plant i in period t,
- $x_{i,j,t}$ – number of units shipped from the production plant i to the distribution center in period t using the transportation mean j,
- $z_{i,t}$ – the number of product units stored in inventory at the production plant i at the end of the period t,
- $z_{i,0}$ – initial inventory of the product in the production plant i,
- Z_t – the number of product units stored in inventory at the logistic center at the end of period t,
- Z_0 – initial inventory at the logistic center.

The first objective function represents the total cost, including transportation and inventory holding costs:

$$TC = f_1\left(x_{i,j,t}, z_{i,t}, Z_t\right) = \sum_{i=1}^{I} \sum_{j=1}^{J} c_{i,j} \sum_{t=1}^{T} x_{i,j,t} + \sum_{i=1}^{I} \quad {}_{i} \sum_{t=1}^{T} z_{i,t} + H \sum_{t=1}^{T} Z_t, \tag{1}$$

The objective function f_2 represents the total carbon footprint resulting from the transportation of the product between production plants and the distribution center:

$$TCF = f_2\left(x_{i,j,t}\right) = \sum_{i=1}^{I} \sum_{j=1}^{J} e_{i,j} \sum_{t=1}^{T} x_{i,j,t}, \tag{2}$$

The third objective function represents the average time of transporting the product from production plants to the distribution center:

$$ATT = f_3\left(x_{i,j,t}\right) = \sum_{i=1}^{I} \sum_{j=1}^{J} \tau_{i,j} \sum_{t=1}^{T} x_{i,j,t} / \sum_{t=1}^{T} D_t, \tag{3}$$

The following constraints are considered:

1) constraints on the maximum production volume at production plants in each period:

$$y_{i,t} \leq p_{i,t} \text{ for } i = 1, \dots, I, t = 1, \dots, T, \tag{4}$$

2) equations determining the inventory at production plants at the end of each period:

$$z_{i,t} = z_{i,t-1} + y_{i,t} - \sum_{j=1}^{J} x_{i,j,t} \text{ for } i = 1, \dots, I, t = 1, \dots, T, \tag{5}$$

3) equations determining the inventory at the distribution center at the end of each period:

$$Z_t = Z_{t-1} + \sum_{i=1}^{I} \sum_{j=1}^{J} x_{i,j,t-\tau_{i,j}} - D_t \text{ for } t = 1, \dots, T, \tag{6}$$

4) constraints specifying that the inventories at the end of the last period are to be zero:

$$z_{i,T} = 0 \text{ for } i = 1, \dots, I, \tag{7}$$

$$Z_T = 0, \tag{8}$$

5) constraints on the transportation means' capacity:

$$\sum_{i=1}^{I} x_{i,j,t} \leq B_j \text{for } j = 1, \dots, J, t = 1, \dots, T, \tag{9}$$

6) constraints considering that delivery of a product using the transportation mean j takes $t_{i,j}$ units of time, and thus cannot be shipped from the production plant later than in period $T - t_{i,j}$:

$$x_{i,j,t} = 0 \text{ for } i = 1, \dots, I, j = 1, J, t \geq T - \tau_{i,j} + 1, \tag{10}$$

7) non-negativity constraints:

$$x_{i,j,t} \geq 0 \text{ for } i = 1, \dots, I, j = 1, J, t \leq T - \tau_{i,j}, \tag{11}$$

$$y_{i,t} \geq 0 \text{ for } i = 1, \dots, I, t = 1, \dots, T, \tag{12}$$

$$z_{i,t} \geq 0 \text{ for } i = 1, \dots, I, t = 1, \dots, T - 1 \tag{13}$$

$$Z_t \geq 0 \text{ for } t = 1, \dots, T - 1, \tag{14}$$

Problem-solving procedure

The problem considered here is of an operational nature, and therefore, the procedure for solving it should be simple enough to be easily used on an ongoing basis by managers responsible for planning transportation operations between production plants and the distribution centre.

When solving multi-criteria problems, one of the main difficulties lies in extracting preference information. Even when it comes down to simply determining the criteria weights, this is a time-consuming and laborious process. The authors of this article propose a simple interactive procedure that, in a fairly short time, should enable the decision-maker to select a solution that represents a sensible compromise among the three criteria under consideration.

First, the solutions are determined to optimise the value of each criterion separately. For each of these solutions, the values of the other criteria are also determined. Since alternative optimal solutions may exist, a hierarchical approach is used at this stage, employing all possible hierarchical structures of the criteria. This means considering the following lexicographic criteria orders:
1) *TC*, *TCF*, *ATT*,
2) *TC*, *ATT*, *TCF*,
3) *TCF*, *TC*, *ATT*,
4) *TCF*, *ATT*, *TC*,
5) *ATT*, *TC*, *TCF*,
6) *ATT*, *TCF*; *TC*.

For the first hierarchical structure, determining the solution starts by calculating the minimum value of *TC*. Then, assuming that *TC* takes the optimal value, the value of *TCF* is minimised. In the last step, the minimum value of *ATT* is determined, assuming that *TC* and *TCF* are not increased from the values determined previously. For the remaining five hierarchical structures, the calculations are conducted in a similar way. Typically, however, the solutions obtained using structures 1 and 2 are identical, and the same is true for pairs 3–4, and 5–6 are identical, which results in three different solutions.

Additionally, the weighted sum method is used, assuming that the decision-maker considers all three criteria to be equally important. Since each criterion is assessed on a different scale, standardisation is required. Using the solutions determined by the hierarchical method, the minimum (TC^{min},

TCF^{min}, ATT^{min}) and maximum (TC^{max}, TCF^{max}, ATT^{max}) values of the criteria are identified. The objective function of the optimisation problem used for determining an additional solution is as follows:

$$WS = \frac{TC - TC^{\min}}{TC^{\max} - TC^{\min}} + \frac{TCF - TCF^{\min}}{TCF^{\max} - TCF^{\min}} + \frac{ATT - ATT^{\min}}{ATT^{\max} - ATT^{\min}}, \quad (15)$$

The value of WS is minimised, assuming the constraints (4)-(14) are satisfied. The procedure for determining the final solution to the problem is as follows.

Step 1: Identification of problem solutions using the hierarchical method for each lexicographic criteria order and the weighted sum method.

Step 2: Presentation of the solution obtained in Step 1, as well as the values of TC^{min}, TC^{max}, TCF^{min}, TCF^{max}, ATT^{min}, and ATT^{max} to the decision maker.

Step 3: Asking the decision maker to indicate which of the solutions presented in Step 2 they consider the most favourable – this solution is assumed to be the current candidate solution.

Step 4: Asking the decision maker whether they find the candidate solution satisfactory. If the answer is YES, the procedure ends, considering the current candidate solution as the final solution to the problem. Otherwise, the procedure proceeds to Step 5.

Step 5: Asking the decision maker to determine in what way the candidate's solution should be improved. This is formulated by indicating the criterion whose value should be minimised and specifying the maximum acceptable value for the other two criteria, thus defining additional constraints in the optimisation model as follows:

$$TC \leq TC^{\text{acc}}, \quad (16)$$

$$TCF \leq TCF^{\text{acc}}, \quad (17)$$

$$ATT \leq ATT^{\text{acc}}. \quad (18)$$

where:
TC^{acc} – is the acceptable value for total cost,
TCF^{acc} – is the acceptable value for total carbon footprint,
ATT^{acc} – is the acceptable value for average transportation time.

Step 6: Solving the optimisation problem in which the criterion indicated by the decision maker in Step 5 is minimised, assuming that constraints (4)–(14), as well as two additional constraints defined in Step 5, are satisfied. In the case of infeasibility, the decision maker is informed that there is no solution that meets the requirements formulated in Step 5. Otherwise, the newly determined solution becomes a current candidate solution, and the procedure continues by proceeding to Step 4.

In the first step, a representation of solutions is identified. For this purpose, a hierarchical approach is used. As a result, the decision maker is able to assess the extent to which the values of the criteria will change, assuming that at least one of them reaches the optimal value. The next steps involve a dialogue with the decision maker to identify a solution that he or she finds satisfactory. Numerous studies show that the interactive approach is an effective and acceptable way for decision makers to obtain information about their preferences. If, at certain point, it turns out that the information obtained so far is sufficient to identify a satisfactory solution, the procedure ends. Otherwise, the dialogue with the decision maker continues in order to identify his or her preferences more precisely.

The proposed procedure is flexible enough to take into account other criteria important to both the manufacturer and its customer. However, it should be remembered that by increasing the number of criteria, the number of solutions that the decision maker should evaluate in each iteration is also increased, which makes it difficult to obtain reliable information about his or her preferences.

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Case study

The data used in this study was acquired from a European logistics company. The information collected made it possible to estimate the model parameters. A 40ft container was taken as the transport unit, while a week was taken as the time unit. For each type of transport, the following parameters were estimated: the maximum number of units that can be shipped each week, the cost of transporting a unit of product, the carbon footprint resulting from the transportation of a unit of product, the time required to transport the product from China to the distribution center located in Europe. Shipments from Asia to Europe are usually carried out using multi-modal transport. For example, if goods are delivered to Europe by sea, transportation from the seaport to the logistics center must be carried out by trucks or rail. The estimated parameters of the model take this fact into account when indicating which type of transport is leading, i.e. which is used to transport the goods between China and Europe. The schedule for delivering goods to the logistics center considered below was developed together with a representative of the logistics company.

In our case study, four means of transport are considered: air (j = 1), sea (j = 2), rail (j = 3), and road (j = 4). The transportation schedule is constructed for T = 10 weeks.

The amount of the product that can be transported by each transport channel in each period (from both factories together) is as follows: B_1 = 50 (air), B_2 = 200 (sea), B_3 = 200 (rail), and B_4 = 100 (road).

Table 1 presents the production capacity of each factory, Table 2 shows the amount of the product that must be available at the distribution center in each period, and Table 3 demonstrates transportation costs, carbon footprint, and transportation time for each transportation mean.

Table 1. Production capacity of production plants ($p_{i,t}$)

Production plant (i)	Period (t)									
	1	2	3	4	5	6	7	8	9	10
1	150	150	150	150	150	150	150	150	150	150
2	100	100	100	100	100	100	100	100	100	100

Table 2. Number of product units that must be available at the distribution center (D_t)

Period (t)									
1	2	3	4	5	6	7	8	9	10
0	0	150	150	200	200	300	300	350	350

Table 3. Transportation costs, carbon footprint, and transportation time

Production plant (i)	Transportation mean (j)	Transportation time (ti,j)	Transportation cost (ci,j)	Carbon footprint (ei,j)
1	1	1	190	100
1	2	4	50	60
1	3	2	150	50
1	4	3	110	30
2	1	1	200	120
2	2	5	55	70
2	3	2	140	40
2	4	3	100	25

The solution to the problem was identified as follows.

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Step 1: Problem solutions were identified using the hierarchical method and the weighted sum method; the determined solutions are presented in Table 4.

Table 4. Solutions to the problem obtained by the hierarchical method and the weighted sum method

Solving method	Criteria values		
	TC	*TCF*	*ATT*
hierarchical (TC, TCF, ATT)	152000	96500	3.450
hierarchical (TC, ATT, TCF)	152000	96500	3.450
hierarchical (TCF, TC, ATT)	262500	69500	2.350
hierarchical (TCF, ATT, TC)	262500	69500	2.350
hierarchical (ATT, TC, TCF)	346000	107000	1.775
hierarchical (ATT, TCF, TC)	346000	107000	1.775
weighted sum	262500	69500	2.350

As can be easily seen, three different solutions were really achieved.

Step 2: Three solutions identified in Step 1, as well as the minimum and maximum values of criteria, were presented to the decision maker (Table 5).

Table 5. Solutions presented to the decision-maker

Solution	Criteria values		
	TC	*TCF*	*ATT*
1	152000	96500	3.450
2	262500	69500	2.350
3	346000	107000	1.775
min	152000	69500	1.775
max	346000	107000	3.450

It can be noticed the criteria are dependent. The minimum total cost was obtained for solution no. 1. This is also the solution for which *ATT* is maximised. On the other hand, solution no. 2 is the best in relation to *TCF*, while solution no. 3 minimises the value of *ATT*. The latter is also the worst solution in relation to *TC* and *TCF*. Thus, the relationship between the criteria is not clear enough for a decision maker to make a final decision based on only one of them.

Step 3: When asked to identify the most favourable solution, the decision maker chose solution 2, which became the candidate solution.

Step 4: When asked if they found the candidate's solution fully satisfactory, the decision maker said NO.

Step 5: The decision maker asked to minimise the cost (*TC*) with the following constraints on the value of the carbon footprint and average transportation time:

$$TCF \leq 72{,}000 ATT \leq 2.4$$

Step 6: The solution satisfying the requirements formulated by the decision maker was identified. The values of the criteria in this solution are as follows:

$$TC = 249{,}000 TCF = 72{,}000 ATT = 2.4$$

This solution was assumed to be the new candidate solution. The procedure proceeded to Step 4.

Step 4: When asked if they found the candidate's solution fully satisfactory, the decision maker said NO.

Step 5: The decision maker asked to minimise the cost (*TC*) with the following constraints on the value of the carbon footprint and average transportation time:

$$TCF \leq 75{,}000 ATT \leq 2.5$$

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Step 6: The solution satisfying the requirements formulated by the decision maker was identified. The values of the criteria in this solution are as follows:

$$TC = 238{,}000 \quad TCF = 75{,}000 \quad ATT = 2.5$$

This solution was assumed to be the new candidate solution. The procedure proceeded to Step 4.

Step 4: When asked if they found the candidate solution fully satisfactory, the decision maker said YES.

As a result, the solution identified in Step 6 was accepted as the final solution. The transportation schedule corresponding to the identified solution is presented in Table 6.

Table 6. Transportation schedule corresponding to the final solution

Production plant (i)	Transportation mean (j)	Period (t)									
		1	2	3	4	5	6	7	8	9	10
1	1	0	0	0	0	0	0	0	0	0	0
1	2	100	0	0	0	50	50	0	0	0	0
1	3	0	0	0	0	0	0	0	0	0	0
1	4	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0
2	3	150	150	0	100	200	200	200	200	0	0
2	4	0	100	100	100	100	100	100	0	0	0

Presenting the above case study, the authors tried to show that the procedure in the paper allows the decision maker to identify a solution that represents a reasonable compromise between three criteria: total cost, total carbon footprint and average transportation time. Even if the criteria are more strongly correlated, its application can be justified. This is because it allows the decision maker to analyse the consequences of the choices made from different perspectives and see how the optimisation of one criterion affects the results obtained for other criteria.

Discussion of the research results

The solution accepted by the decision-maker is a compromise between three criteria whose values are minimised. First, the decision maker was presented with the best solutions for each criterion, and he chose the one with the lowest total carbon footprint as the initial one. However, the decision maker was not fully satisfied with it and asked for a solution to minimise the total cost of transportation while limiting the *TCF* to 72,000, and the *ATT* to 2.4. The new solution again did not satisfy the decision maker, who adjusted the requirements for the *TCF* and *ATT* criteria, specifying that their values should not exceed 75,000 and 2.5, respectively. For the finally accepted solution, the criteria values were as follows: TC = 238,000, TCF = 75,000, and ATT = 2.5. Compared to the solution identified by the decision maker in the first step as the most attractive, the value of *TC* was reduced by 9.33%, while the values of the other criteria increased: *TCF* by 7.91%, *ATT* by 6.38%.

According to the determined solution, the product should be delivered mainly by the second production plant (1800 units). The first factory should supply the product only if the production capacity of the second factory is insufficient. The delivery schedule assumes the use of mainly rail transport (a total of 1,200 units) and, to a lesser extent, road (600 units) and sea transport (200 units).

The problem is dynamic – the delivery plan has been set for several weeks. In such a situation, it is advantageous to use different transportation means, which differ in the speed at which the product is delivered to the recipient. This allows the expedition of the product from the factories to be evenly distributed, even when demand fluctuates significantly from period to period.

The map presents a load transportation itinerary from Shanghai to Hamburg by four transport modes: road, railway, sea, and air (Figure 2). The shortest itinerary to the final city is presented.

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During the forwarding process from the Asian continent to the European continent, it is important to use multimodal transport to reach the final destination in the shortest time.

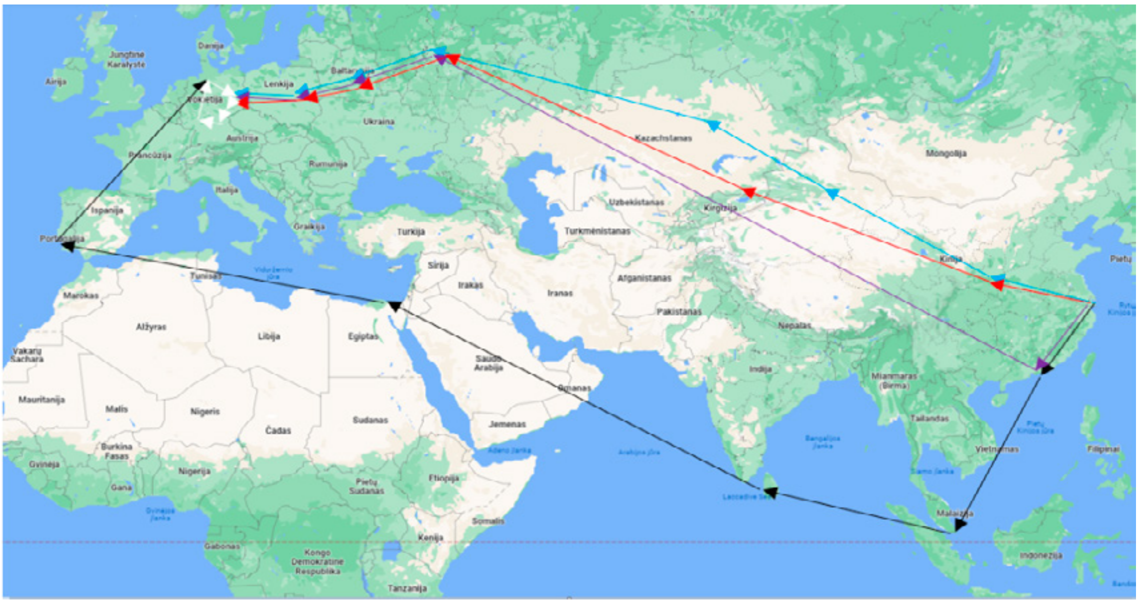

Figure 2. Multimodal transport for the load supply chain model

The presented load transportation model of the multi-criteria multimodal transport supply chain logistics is based on the cargo transportation from Shanghai to Europe with possibly open and closed roads due to some logistics reasons, dealing with optimisation issues by minimising the total cost, the carbon footprint, and the average time for transportation loads.

Conclusions

The effectiveness of the supply chain transportation operation largely affects the level of customer satisfaction and the demand for specific loads at the logistics center. The constant demand for goods and the stabilisation of the supply structure from individual suppliers are demonstrated by efficient cooperation between logistics centers and the need to introduce significant changes in the supply chain to avoid unexpected issues. Planning and delivery are two smooth parts of the supply chain, and the use of advanced solutions is a big plus. The most important aspects of supply chain management may also become its weaknesses and threats due to inadequate adaptation of the logistics centers to the introduced worldwide changes. The most important issues of logistics centers are a combination of speed, time flexibility, and information flow security when using modern technological solutions to solve different unexpected problems. An important effect achieved in a supply chain can enable the development of the logistics center into a market leader and undoubtedly increase the competitiveness of the supply chain system's suppliers and clients. To sum up, the presented structured and systemic process is composed of different transportation system parts: personal resources management, customer technological relationship management, demand and supply technological management, order fulfilment process, managing the technological production process, supply chain procurement technological management, product technological of development and commercialisation, and enhancement in supply chain process strategy. The main issues systematised after a deep analysis of different factors influencing the supply chain's strategic management process aim to improve the whole work process from manufacturers to consumers.

The completed optimisation problem concerned a supply chain with multiple periods and diverse transportation means. The considered problem is formulated as a dynamic multi-criteria decision-making problem with the following criteria:

1) minimising the total cost, including transportation costs and inventory holding costs (both at the production plants' warehouses and at the distribution center),

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2) minimising the carbon footprint resulting from the transportation of the product between production plants and the distribution center,
3) minimising the average time of transporting the product from production plants to the distribution center.

The starting point of the analysis presented in the article was a real logistics problem involving the development of a product delivery schedule from factories in China to a distribution center in Europe. Taking into account data obtained from one of the logistics companies, the model parameters were estimated. To determine the solution, the interactive procedure described in the work was used, involving an expert from a logistics company who acted as a decision-maker. His assessment of the proposed method was positive. The expert appreciated the opportunity to observe the impact of the conditions he formulated on the solutions obtained.

However, it is important to keep in mind the limitations of the proposed procedure. In the problem under consideration, we took into account only three criteria. If it is necessary to consider more criteria, the dialogue with the decision-maker may be more difficult. After all, even a high-level expert in such a situation may have a problem with comparing successively obtained solutions. In turn, the extension of the time horizon may necessitate the use of advanced software due to the high computational complexity of the optimisation problem.

The results of this study show the validity and effectiveness of the created mathematical model. The investigated scientific research topic regarding China supply chain transportation issues in European logistics is essential to demonstrate the created multimodal transport supply chain logistics load transportation model from Shanghai to Beijing based on the mathematical equations of the supply chain load optimisation resolving different transportation issues, such as load transportation in warehouses, the optimisation of terminals and distribution centers, the minimization of transportation costs, the minimization of time, the minimization of the road length, and the maximization of the transportation dimensions. This will improve the planning process from the beginning to the very last delivery site. The study results show the optimal strategies for the transportation of loads by minimising the total cost, the carbon footprint, and the average time of transporting the products. The research problem discussed loads transported from Shanghai to Gdansk. This work is the starting point for further research on multimodal transport and solutions to its problems, as well as the basis for an efficient decision-making support tool in all modes of transport chains.

The contribution of the authors

Introduction, D.B.; Literature overview, D.B. and E.S.; Discussion of the research results, E.S.; Implication of the theoretical approach based on the presented supply chain optimisation logistics management model, V.K.; The optimisation problem of a supply chain with multiple periods and diverse transportation means, V.K.; Case study, V.K.; Case study, V.K.; Methodology of the supply optimisation problem, L.U. and M.N.; Problem-solving procedure, L.U. and M.N.

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PROBLEM OPTYMALIZACJI CHIŃSKIEGO ŁAŃCUCHA DOSTAW ZAGADNIENIA TRANSPORTOWE W LOGISTYCE EUROPEJSKIEJ

STRESZCZENIE: W pracy analizie poddano wpływ, jaki dla rynku europejskiego ma rozwój chińskiego rynku logistycznego, wdrażane na nim krótko- i długoterminowe strategie oraz koncepcja Wholesale Transportation. Celem autorów było wskazanie konsekwencji, jakie dla międzynarodowego rynku transportowego ma powiększający się chiński łańcuch dostaw oraz jego silne powiązania z centrami logistycznymi. W ostatnich latach w Chinach i Europie przeprowadzono wiele badań naukowych dotyczących ewolucji transportu w Chinach, od etapu produkcji do etapu fizycznej dystrybucji, obejmującego wiele faz, aż do momentu, gdy ładunki znajdą się w rękach klientów. W artykule analizie poddano wielookresowy problem optymalizacji łańcucha dostaw przy wykorzystaniu różnych środków transportu. Rozważane zagadnienie sformułowano jako dynamiczny wielokryterialny problem decyzyjny, w którym kryteriami są minimalizacja całkowitego kosztu, minimalizacja śladu węglowego i minimalizacja średniego czasu dostaw produktów z fabryk zlokalizowanych w Chinach do centrum dystrybucyjnego zlokalizowanego w Europie.

SŁOWA KLUCZOWE: transport, logistyka, łańcuch dostaw, optymalizacja, strategia

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