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Value chain design through synergistic optimisation of configuration and operation of value activities: an application case of cold chain logistics

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Synergistic Optimisation of the Configuration and Operation of Value Activities in Cold Chain Logistics

Abstract. The 'no breakage chain' characteristics of cold chain logistics makes it important to study the synergistic optimisation between its activities. This study analyses the value chain of cold/frozen goods logistics businesses and proposes a value chain-based synergistic framework: intra-enterprise synergy, and synergy of internal and external enterprise. Based on this framework, a cost optimisation model for intra-enterprise synergy of value activities is established; then with consideration of the market-oriented value activity configuration, a synergistic optimisation model for internal and external enterprise between customer utility and enterprise cost through value activity configuration and operations is established. The synergistic optimisation model is a 0-1 nonlinear bilevel programming (BLP) problem, which is solved by using a bilevel nested genetic algorithm (BNGA). Finally, the established synergistic optimisation model is applied to a case analysis of a cold chain logistics company as a computational example to demonstrate the effectiveness of the model.

Keywords: cold chain logistics; value chain; value activities; configuration; bilevel programming; bilevel nested genetic algorithm

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1 Introduction

1.1 Value-chain-based synergistic optimisation of cold chain logistics operation

Cold chain logistics refers to an operational process in which goods are transported and delivered from suppliers to customers, either directly or through storage and processing stages, under low-temperature operating conditions (Chaudhuri et al. 2018). The goods transported are mainly foods, medicines, and other products requiring cold storage and shipment. In recent years, with consumer requirements regarding food safety growing more stringent for fresh products and with greater convenience of online shopping platforms established by internet-based commerce, the market demand for cold chain logistics has been steadily increasing and this has promoted the rapid development of the cold chain logistics industry (Cerchione et al. 2018).

Compared with general logistics, cold chain logistics requires not only more investments in technology and equipment, but also ‘no breakage chain’ to maintain a low-temperature environment in the logistics process. The latter requirement makes the synergistic operations between logistics activities more important. Therefore, a research question arises: from what perspective should the synergy of cold chain logistics operations be investigated? Since the cold chain is composed of the main value activities of the cold chain logistics business (Singh, Sikka, and Singh 2012), the ‘chain’ in terms of value chain implies the relationship and coordination, i.e. synergy, among participants of the chain. Thus, it is desirable to explore the synergy of cold chain logistics operations by employing the value chain perspective. Although Porter’s theory (Porter 1985, 33–61) is popular in value chain management, the application of his theory to cold chain logistics is rare.

Optimisation is an important issue in supply chain and logistics operations, especially for supply chain design and logistics activity configurations. Design and configuration is actually a continuous decision-making process of optimisation, wherein many problems can be described quantitatively; this makes possible the use of optimisation approaches that are mainly based on mathematical programming theory. However, few studies have been conducted on the optimisation of cold chain logistics operations.

Literature search in the Web of Science Core Collection by using the topic words ‘cold chain logistics AND value chain’ with the publication periods limited to 1985–

2021 retrieved 141 entries, which include only 14 that were published between 1985 and 2012. And literature search in the Web of Science Core Collection by using the topic words ‘cold chain logistics AND optimisation’ with the publication periods limited to 1985–2021 led to a retrieval of 146 entries, which include only 10 entries published during 1985–2012. The cumulative growth of the two categories of literature shows a significant increasing trend since 2012, especially in 2020–2021. The statistics are shown in Figure 1.

[Figure 1 near here]

From Fig. 1 we can see the value chain of cold chain logistics and the optimisation of cold chain logistics operations have recently attracted more attention and the number of literature reports is showing a significant increasing trend, especially the research on cold chain logistics optimisation. However, the research on these two aspects is still not much in general and the studies that cover the integration of both issues even fewer.

1.2 Literature Overview

(1) Value chain of cold chain logistics

The 141 articles retrieved with the topic words ‘cold chain logistics AND value chain’ can be roughly divided into three categories. Category 1 consists of 9 articles regarding value chains or value enhancement. For example, Singh et al. (2018) defined cold chain management as the management of the value chain for perishable foods and medicines and explored a method for the selection of third-party logistics in cold chain management in India. Carron et al. (2018) investigated a fast-evolving chicken meat system in Kenya and listed the risk factors that exist in each sector of the value chain. Yan (2018) investigated the synergistic creation and promotion of customer experience value in fruit cold chain logistics of third-party e-commerce platform. Singh et al. (2012) studied the global competitiveness improvement of Indian apples from the perspective of value chain. Mangla et al. (2019) addressed the logistics and distribution challenges in the synergistic and sustainable operations management of supply chain for Indian agrifoods and proposed improvements in the value chain of agricultural products. Peng et al. (2020) studied the influencing factors of the value co-creation of the platform ecological circle in the cold chain logistics enterprises and elaborates the internal relations between different influencing factors regarding the value cocreation and enterprises’ performance. Category 2 consists of

50 articles regarding pure technology research relevant to cold chains. The term 'value' in the articles often refers to technical measurement values, such as pH values, while having nothing to do with value chains. For example, Wei et al. (2018) investigated the use of electronic noise to provide non-destructive protection of perishable peach fruits in cold environments. Hao et al. (2019) studied the design of a real-time tracking system for ocean logistics based on the BeiDou satellite system. Bai et al. (2019) investigated the application of nano-sized storage materials to cold chain logistics of fresh agricultural products. Jarupan et al. (2021) studied the potential use of fiber from oil palm fronds for protective packaging under humid conditions. Category 3 consists of 82 articles, which are neither relevant to pure technology research nor relevant to value chain research but focus on managerial decision making related to cold chain logistics instead. For example, Ertan, Şenkayas, and Tuncay (2019) investigated the logistics performance management of Turkish figs in the late harvest period. Zhang, Cao, and Park (2019) conducted reliability analysis and optimisation of the cold chain distribution system for fresh agricultural products by establishing a Bayesian network-based evaluation model. Siddh et al. (2018) established a supply chain structure model of perishable foods to improve organisational performance. Turan and Ozturkoglu (2021) studied all potential factors affecting the cold chain performance in the food industry and to design a framework that includes these factors. This framework provided a roadmap for managers, food providers and logistics parties for sustainable cold chain management. The term 'value' in the articles of category 3 often refers to an economic value or the value (i.e., importance) of the articles, and has nothing to do with value chains.

As shown above, most of the 141 articles did not involve a substantial study on value chains, with the term 'value' often having other meanings, such as 'the value of this article' or a 'measured value'; thus, only a limited number of studies have been dedicated to cold chain logistics businesses, and an even smaller number covers value chain-based synergy of cold chain logistics businesses.

(2) Cold chain logistics optimisation

The 146 articles retrieved with the topic words 'cold chain logistics AND optimisation' can be roughly divided into two categories. Category 1 consists of 103 articles that involve mathematical programming models. These papers are mostly about models and algorithms for optimising the routing of cold chain logistics vehicles. For example, Li, Yang, and Qin (2019) built a routing optimisation model to minimise the total cost of cold chain logistics storage by considering both carbon footprint and carbon regulation and solved the optimisation problem using a genetic simulated annealing algorithm. Li, Lim, and Tseng (2019) established an optimisation model for green vehicle routing of cold chain logistics and solved the problem using an improved particle swarm and bee colony algorithms. Wei et al. (2019) assigned customer-dependent travel time limits to routes in a cold-chain inventory routing problem and obtained optimised solutions using a genetic algorithm (GA) in a model applied to case analysis in the Yangtze River Delta of China. Zhao et al. (2020) established a multi-objective optimisation model based on cost, carbon emissions and customer satisfaction to solve the problem of cold chain logistics vehicle path optimisation. And an improved ant colony algorithm was designed to solve the model. Category 2 consists of 43 articles without mathematical programming models, mostly focusing on qualitative optimisation of management systems related to cold chain logistics. For example, Wang (2019) conducted cost control analysis for cold chain transportation of tropical fruits and fresh products. Sun (2019) investigated the key issue in the storage management system of cold chain logistics for fruits and vegetables; Zhang et al. (2019) developed and evaluated an intelligent traceability system for waterless live fish transportation. Wang and Tao (2021) studied the reverse integration of agricultural products e-commerce omnichannel supply chain.

As shown above, some of the 146 articles did not establish mathematical programming models for quantitative optimisation, while few of the 103 articles with mathematical programming models in Category 1 investigated value chain-based synergistic optimisation of cold chain logistics. Moreover, the mathematical programming models in this category were only single-level programming models, where the term ‘single-level’ represents a simpler structure relative to the term ‘bilevel’ of bilevel programming. Single-level programming, the basic form of mathematical programming, is based on simple and welldeveloped models and methods, but it has a single agent which limits its ability to describe some practical problems. It is evident that the synergistic decision-making process of cold chain logistics operations usually involves multiple agents (Lailossa 2015).

(3) Bilevel programming

Bilevel programming (BLP) is a mathematical programming with sub-optimisation problems in model constraints, which was proposed in 1973 (Bracken and McGill 1973) and has quickly developed since then into an important branch of mathematical programming (Bard 1998), because of its abstraction of important practical backgrounds including the Stackelberg game problems, as well as its unique advantages in describing multiagent, leader-follower problems. However, due to the complexity of BLP (Dempe 2002), its research application has been rare. In fact, the upper level of a BLP model contains the optimal solution or optimal value function of the lower level, which makes the model a non-smooth optimisation problem in general and makes even a linear BLP model NP-hard (Jeroslow 1985). The solution of BLP can be divided into two categories. One is that the model is relatively simple and can be transformed into single-level mathematical programming. The other is that the model is complex and generally only approximate algorithms can be used (Du et al. 2019). Commonly used approximate algorithms are mainly based on genetic algorithm, particle swarm optimisation algorithm and ant colony algorithm (Kumar, Gupta, and Mehra 2018).

In addition, domain problem modelling in BLP also presents a challenge (Kalashnikov et al. 2015). Therefore, exploring application-oriented BLP models and methods has become an important field in BLP research (Kalashnikov et al. 2015). Recently, some studies have been conducted on the application of BLP. Du, Jiao, and Chen (2014) formulated a bilevel programming model for joint optimisation of product family configuration and scaling design; and Levandowski, Michaelis, and Johannesson (2014) cited this paper, and they believed that achieving a validated design space for the entire platform is conceivable and is subject to future work. Some subsequent articles, for example, Wang et al. (2016) established a BLP model for the joint optimisation of product family design and supply chain configuration. Miao et al. (2017) built a BLP model for the joint optimisation of product line planning and product platform. Tawfik and Limbourg (2019) made a recent contribution with a BLP model using utility and profit as the joint bilinear objectives for a transportation network design and pricing problem. Wu, Du, and Jiao (2020) established a BLP model for the joint optimisation of product design and postponement strategy. The BLP-solving methods based on a genetic algorithm of Xiong, Du, and Jiao (2018) and Wu, Du, and Jiao (2020) have achieved good results. However, there are few studies on the application of BLP to the synergistic operations of value activities in cold chain logistics.

1.3 Research Significance and Technical Challenges

The rapid development of Internet-based commerce and the continuous improvement in cold chain logistics technology provide a great opportunity for cold chain logistics businesses to satisfy the rapidly growing market demand, even with the challenge of high investment risks under increasingly competitive market conditions. For providing customer utility to the greatest extent with better cost performance, achieving a synergistic optimisation of the operations of value chain activities in cold chain logistics has become a practical issue that cold chain logistics businesses face. Meanwhile, literature review shows that the value chain of cold chain logistics enterprises is relatively less studied despite the maturing of the theory of value chains. How to achieve value chain-based synergistic operations and how to optimise the synergistic operations are among the topics worthy of exploration and investigation.

The abovementioned issue will be addressed in this study. The following are some of the technical challenges to be overcome.

(1) Value chain of cold chain logistics businesses

Porter’s value chain theory is mainly based on manufacturing businesses; however, logistics businesses are significantly different from them. For example, the marketing activities of manufacturing businesses are usually conducted after product manufacturing, while those of logistics businesses usually occur before it. In addition, cold chain logistics have some unique features that make them different from general logistics. Therefore, it is necessary to first analyse and identify the value chain structure of cold chain logistics businesses.

(2) Value chain-based synergy

Synergy theories, such as the synergy theory of Haken (1977) and the strategic synergy theory of Ansoff (1965), provide a general foundation for synergy research, but there are few literature reports on value chain-based synergistic operations of cold chain logistics businesses. Porter did not specifically address synergy when proposing the value chain theory (Porter 1985). Therefore, it is necessary to look into the concept and logic of value chain-based synergy to establish a framework for synergistic optimisation.

(3) Establishment of mathematical model for quantitative optimisation

After the synergistic optimisation framework is established, it is necessary to further establish a corresponding mathematical programming model. To this end, it is necessary to explore how to properly set decision variables, optimisation objectives, and model constraints, as well as construct relevant mathematical expressions, acquire data, and computationally solve the problem. However, the previous studies on mathematical programming model based on value chain synergy, especially the bilevel programming modelling research that may be involved are still few.

2. Value Chain of Cold Chain Logistics Enterprises

2.1 Value Chains

The value chain of an enterprise is a chain of all value activities in the business. Value activities can be divided into two categories: basic activities that create value directly and ancillary activities that create value indirectly (Porter 1985).

Cold chain logistics enterprises can be divided into different types according to service functions and service providers. This paper is mainly based on third-party cold chain logistics enterprises that can provide comprehensive cold chain services. The third-party cold chain logistics enterprises start with market investment, customer development, and related front-end services. After receiving orders, the goods are transported from the supplier to the cold chain logistics enterprise, stored in the cold storage and conducted warehouse management according to different low-temperature condition requirements of the customers. Subsequently, they are shipped from the storage facilities to the destination according to the order specifications. In the storage facilities, the goods may be processed to some extent, according to customer requests. Finally, after delivery sign-off, the cold chain logistics enterprises may still need to provide after-sales services. Meantime, the cold chain logistics enterprises have a series of managerial and ancillary activities to support the operations.

According to Porter's criteria for identification of value activities (Porter 1985), the basic value activities of cold chain logistics enterprises mainly include: market development and front-end services, transportation and loading/unloading, warehousing and storage, processing and shipment from warehouses, distribution and delivery sign-off, and back-end services. The ancillary activities mainly include basic enterprise management, procurement, human resource management, technology development, and information system management of cold chain. Put together, these activities constitute a general value chain for cold chain logistics enterprises (Fig. 2).

[Figure 2 near here]

Compared with the general value chain proposed by Porter (1985) for general businesses, the general value chain of a cold chain logistics enterprise established in this paper in Fig. 2 differs mainly in the placing of market development and front-end services at the front of the basic activities of value chain. In contrast, the general value chain of Porter starts with internal logistics because manufacturing businesses have to conduct manufacturing activities in advance even if there are no customer orders; cold chain logistics enterprises do not conduct warehousing and transportation activities in the absence of customer orders. Moreover, compared with general logistics businesses, the value activities of cold chain logistics enterprises also have significant differences and characteristics. For example, the procurement of cold chain storage and transportation equipment with heavy investment, the technology development and information system management of cold chain, and other auxiliary activities have a unique or more important position.

2.2 Synergy

Synergy refers to the process in which each subsystem in the system creates value in a ‘1 + 1 > 2’ manner through cooperation and resource sharing (Ansoff 1965). This definition provides the underlying logic of synergy. Although Porter did not specifically address synergy when proposing the value chain theory (Porter 1985), he mentioned a synergy-related concept called ‘connection’. Furthermore, he argued that companies should establish and focus on the relationships among the activities within the value chain and the relationships among the activities beyond the value chain or the companies, in which one of the most important external factors is the impact of buyers or customers.

Therefore, value chain-based synergistic operations of cold chain logistics enterprise can be achieved mainly through two pathways – the synergy between intra-enterprise value chain activities and the synergy of intra-enterprise value chain and extra-enterprise factors such as buyers, so as to achieve synergistic benefits. It can be considered as a synergistic framework: intra-enterprise synergy, and synergy of internal and external enterprise. The following synergistic optimisation modelling will be based on the above analysis and synergistic framework. A synergistic optimisation model of intra-enterprise value activities will be established first. Then a synergistic optimisation model between value activities of enterprise and demands of external buyers’ markets will be established.

3. Synergistic Optimisation of the Operations of Value Activities

A synergistic optimisation model of intra-enterprise value activities will be established in this section.

3.1 Problem Description

In the general value chain of a cold chain logistics enterprise (Fig. 2), warehousing and storage, processing and shipment from warehouses, and distribution and delivery sign-off are the three basic types of activity that are closely related to each other and most in need of synergy. These basic activities are conducted in accordance with the orders obtained through the market development activities at the front end.

Therefore, decision variables in the synergistic optimisation of cold chain logistics operations may be set mainly for the four basic activities – market development, warehousing and storage, processing and shipment from warehouses, and distribution and delivery sign-off. The orders obtained through market development activities are used as the source of synergy to support the subsequent three basic types of activity, while the synergy requirements of other activities may be used as constraints.

Accordingly, this study proposes a refined problem: the synergistic optimisation of warehousing, processing and distribution based on orders, that is, the synergistic planning problem of a batch of orders from warehousing to processing and to distribution. It is assumed in this study that the decisions for storage, processing, and distribution are the layout of cold storage locations, selection of processing methods, and selection of distribution routes, respectively. The optimisation objective is to maximise the enterprise benefits under a number of constraints, which include some additional requirements related to the orders, as well as the synergy requirements of some basic and ancillary activities in the enterprise.

3.2 Model Parameters

Given the above problem description and analysis, the following main parameters are chosen for inclusion in the mathematical programming model.

I: the total number of customer orders received for the next planning period, supposing that there is one type of goods per order;

J: the number of locations with different temperature in a cold storage facility;

K: the number of processing methods that the enterprise can provide;

L: the number of deferent distribution routes that the enterprise can choose;

C_{ij}^{1}: the unit storage cost at location *j* for order *i*;

C_{ik}^{2}: the unit processing cost for order *i* using processing method *k*;

C_{il}^{3}: the unit distribution cost for order *i* using route *l*;

t_i^{1}: the storage time of order *i*;

t_{ik}^{2}: the processing time of order *i* using processing method *k*;

t_{il}^{3}: the distribution time of order *i* using route *l*;

T_i: the total processing time to compete order *i*;

$T_{i\,\max}$: the maximum time allowed for order *i*;

q_i: the quantity of goods in order *i*; and

$r_{ii'}$: the consolidated delivery coefficient between orders *i* and *i*′, which is 0 when the two orders have the same destination or are delivered using the same route and 1 otherwise;

α_{ji}: the maximum storage capacity of location *j* for order *i*.

where *i*=1,…,*I*; *j*=1,…,*J*; *k*=1,…,*K*; *l*=1,…,*L*, the different distribution routes refer to different routes from the departure places to the distribution destinations. The distribution destinations of cold chain logistics enterprises such as large supermarkets are usually fixed and limited in number. In the optimisation model, the total number of distribution routes which can be selected is denoted as *L*.

3.3 Decision Variables

Warehouse layout selection variable:

$$x_{ij} = \begin{cases} 1 & \textit{Storage location j chosen for oder i} \\ 0 & \textit{Otherwise} \end{cases}$$

Processing method selection variable:

$$y_{ik} = \begin{cases} 1 & \textit{Processing method k chosen for order i} \\ 0 & \textit{Otherwise} \end{cases}$$

Distribution method selection variable:

$$z_{il} = \begin{cases} 1 & \textit{Distribution route l chosen for order i} \\ 0 & \textit{Otherwise} \end{cases}$$

Here, *i* = 1,…,*I*; *j* = 1,…,*J*; *k* = 1,…,*K*; *l* = 1,…,*L*. The corresponding matrices of x_{ij}, y_{ik}, z_{il} are denoted as $\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}$ respectively.

3.4 Objective Function

Enterprise benefits manifest as profits in the value chain. Considering price changes and other uncertain factors, the cost can be used as a representative indicator of enterprise benefits, and the optimisation objective is to minimise the total cost C of the three types of value-creating activity. Cost can be divided into fixed cost and variable cost. Given that the optimisation model in this study is mainly intended to provide support for short-term decision making, fixed cost can be omitted while considering only the variable cost. Accordingly, the cost is related to the order quantity, that is, the unit cost is a function of the quantity q_i of goods in the order. The objective function can be expressed as follows:

$$\min C = \sum_{i=1}^{I} q_i [\sum_{j=1}^{J} C_{ij}^{1} t_i^{1} x_{ij} + \sum_{k=1}^{K} C_{ik}^{2} t_{ik}^{2} y_{ik} + \sum_{l=1}^{L} C_{il}^{3} t_{il}^{3} z_{il}] + C_S(x, y, z)$$

where $C_S(x, y, z)$ is a real-valued function of x, y, z, which is the synergistic cost consisting of the shared inputs, for example, the cost of joint advertising will be lower than that of separate advertising. Similar costs may also include sales expenses, marketing expenses, sales channel construction expenses, development expenses of cold chain information system, etc.

3.5 Constraints

(1) Storage constraints

$$\sum_{j=1}^{J} x_{ij} = 1, \quad i = 1, \dots, I$$

$$\sum_{j=1}^{J} \left| x_{ij} - x_{i'j} \right| > 0, \quad i, i' = 1, \dots, I, i \neq i'$$

$$\sum_{i=1}^{I} x_{ij} \cdot q_i \leq \sum_{i=1}^{I} x_{ij} \cdot \alpha_{ji}, \; j = 1, \dots, J$$

The first constraint above is that the goods of the same order are assigned one storage location; the second constraint is that goods of different orders are assigned different storage locations; the third constraint presents the limitation of capacity of the assigned storage location.

In addition, there may be a few more constraints used in practice to narrow the selection of storage locations. For example, fruits and vegetables only need to be stored at locations in the refrigerated zone, while frozen foods need only to be stored in the low temperature frozen zone.

(2) Processing constraints

$$\sum_{k=1}^{K} y_{ik} = 1, \quad i = 1,\dots,I$$

This constraint means that goods from the same order must be processed using the same method, while goods from different orders can be processed using the same method. In addition, there may be a few selective constraints in practice to narrow the selection of processing methods. For example, although splitting, coding, and packing are the most common processing methods, some goods do not need to be split but should be packaged, while some others, depending on customers' requests, do not need any processing at all.

(3) Distribution constraints

$$\sum_{l=1}^{L} z_{il} = 1, \quad i = 1,\dots,I$$

$$\left| z_{il} - z_{i'l} \right| = r_{ii'}(z_{il} + z_{i'l}), \ i, i' = 1,\dots,I, i \neq i', \quad l = 1,\dots,L$$

The first constraint above is that goods of the same order must be distributed by the same route. The second constraint above is intended to meet the requirements of consolidated delivery, that is, when the goods of two orders i and i' have the same destination, they should be shipped through the same route l; otherwise, they may be shipped via different routes. In addition, there may be more selective constraints in practice to narrow the selection of distribution routes for some decision variables. In addition, transport vehicles may also be subject to capacity constraints. For orders whose total goods volume is not an integral multiple of the capacity of a single vehicle, the goods of one order may need to be merged with goods of other orders and delivered using a coordinated distribution route.

(4) Synergistic constraints

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} = \sum_{i=1}^{I}\sum_{k=1}^{K} y_{ik} = \sum_{i=1}^{I}\sum_{l=1}^{L} z_{il} = I$$

$$\sum_{j=1}^{J} t_i^1 x_{ij} + \sum_{k=1}^{K} t_{ik}^2 y_{ik} + \sum_{l=1}^{L} t_{il}^3 z_{il} = T_i \leq T_{i\max}$$

The first constraint above is an order quantity constraint, which indicates that the total number of common orders throughout the three activities remains unchanged. The second constraint is an order completion time constraint, that is, the total time taken by the three types of activity to complete an order should be equal to the time available to fulfill the order. Meanwhile, other synergistic constraints may include the needs to have consistent control of temperature zones and consistent fulfillment of special operational requirements throughout the three types of activity.

3.6 Synergistic Optimisation Model of the Operations of Value Activities

The whole model is expressed by Eq. (3-1) as follows.

$$\min C=\sum_{i=1}^{I} q_i[\sum_{j=1}^{J} C_{ij}^1 t_i^1 x_{ij}+\sum_{k=1}^{K} C_{ik}^2 t_{ik}^2 y_{ik}+\sum_{l=1}^{L} C_{il}^3 t_{il}^3 z_{il}]+C_S(x,y,z) \qquad (3\text{-}1)$$

$$s.t.\quad \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij}=\sum_{i=1}^{I}\sum_{k=1}^{K} y_{ik}=\sum_{i=1}^{I}\sum_{l=1}^{L} z_{il}=I$$

$$\sum_{j=1}^{J} t_i^1 x_{ij}+\sum_{k=1}^{K} t_{ik}^2 y_{ik}+\sum_{l=1}^{L} t_{il}^3 z_{il}=T_i\le T_{i\max}$$

$$\sum_{j=1}^{J} x_{ij}=1,\ i=1,\dots,I$$

$$\sum_{j=1}^{J}\left|x_{ij}-x_{i'j}\right|>0,\ i,i'=1,\dots,I,i\ne i'$$

$$\sum_{i=1}^{I} x_{ij}\cdot q_i\le\sum_{i=1}^{I} x_{ij}\cdot\alpha_{ji},\ j=1,\dots,J$$

$$\sum_{k=1}^{K} y_{ik}=1,\ i=1,\dots,I$$

$$\sum_{l=1}^{L} z_{il}=1,\ i=1,\dots,I$$

$$\left|z_{il}-z_{i'l}\right|=r_{ii'}(z_{il}+z_{i'l}),\ i,i'=1,\dots,I,i\ne i',\ l=1,\dots,L$$

where x_{ij} , y_{ik} , and z_{il} are 0-1variables.

Model (3-1) has made reasonable abstraction and simplification of real situations. In practical applications, it may be necessary to impose additional selective constraints, capacity constraints, cargo merging constraints, and synergistic requirements of other value activities in the model. A highlight of this model is that it reflects the relatively independent yet intercorrelation between the three types of value activities, so the model has a block-diagonal form of constraints. The block-diagonal form not only makes the constraint structure clear, but also facilitates the use of a decomposition method to computationally solve the problem.

3.7 Model Solving

The synergistic optimisation model (3-1) for the basic value activities of cold chain logistics enterprises is a nonlinear, 0-1 integer programming problem. GAs with the population-based generation and evolution mechanism are suitable for this kind of problem (Jiao, Zhang, and Wang 2007). MATLAB provides such GAs that makes it possible to adopt or design problem-solving methods to resolve the model. Because the model has a 'block diagonal' constraint structure, when the scale of the actual problem is large and the model can be simplified to a linear programming problem, their corresponding models can be decomposed and dimensionally reduced using decomposition algorithms (Dantzig and Wolfe 1960) of large-scale linear programming. The model solution is an optimised scheme for the synergistic operations of value-creating activities of the enterprise.

4. Synergistic Optimisation of the Configurations and Operations of Value Activities

A synergistic optimisation model of intra-enterprise value activities and external buyer market demands will be established in this section.

4.1 Problem description

Model (3-1) is intended to optimise the basic value activities inside an enterprise. The premise is that the value activity configuration, i.e. the service business structure and production capacity that the enterprise can provide, has been determined. In this model, the different types of customers that the orders come from are not distinguished. The model is suitable for the simple case of intra-enterprise operations plan when the market is stable. However, the market demand is generally variable. In order to make a synergistic optimisation with the external market demand, this section further studies the situation that the value activity configuration has not been determined and hence needs to be optimised and adjusted according to the market demand and subdivides the corresponding different types of customers.

When customers decide whether to choose an enterprise as a cold chain logistics service provider, they generally choose based on customer utility (Kaul and Rao 1995). The customer utility of a product reflects the purchase intention of customers in a competitive market. In this model, customer utility is regarded as customer preference and purchase surplus. Surplus is the difference between the price customers are willing to pay and the actual price of the product. If no product creates a positive surplus, they cannot buy any products, but also buy competitors' products.

Therefore, when making a decision, a business should consider both its profits and customer benefits so as to maximise their common benefits. Enterprise profits may be represented by minimal costs with maximal number of profitable customer orders, while customer benefits can be represented by customer utility. Customer preferences utility values can be obtained through market research-based utility analysis, conjoint analysis, and numerical simulation (Kaul and Rao 1995).

Considering that the problem involves the benefits of two different decision-making agents of the enterprise and customers who possess different decision variables and constraints. And the enterprise must be dominated by the market and customers, that is, the two decision-making units stand at different decision levels, which have a leader-follower coordinated structure. Therefore, it is necessary to establish a BLP model in this section.

The modelling idea is to consider customer utility and enterprise cost optimisation as the upper-level model to determine the service business structure and enterprise capability, and take the corresponding synergistic optimisation of enterprise operations as the lower level of the model to determine the corresponding operations plan. For each decision made at the upper level, there exists a corresponding optimised scheme at the lower level with the optimised cost fed back to the upper level.

4.2 Model Parameters

The main parameters of the proposed BLP model are listed as follows.

$\boldsymbol{V}$ is the number of customers.

$\boldsymbol{I}_v$ is the number of orders from customer *v*, supposing that there is one type of goods per order.

$\boldsymbol{A}_J$, $\boldsymbol{A}_K$, $\boldsymbol{A}_L$ are the total number of available storage locations, processing methods, and distribution routes in the enterprise respectively.

$\boldsymbol{B}_{JU}$, $\boldsymbol{B}_{KU}$, $\boldsymbol{B}_{LU}$ are the maximum number of storage locations, processing methods, and distribution routes of the enterprise respectively.

$\boldsymbol{B}_{JL}$, $\boldsymbol{B}_{KL}$, $\boldsymbol{B}_{LL}$ are the minimal number of storage locations, processing methods, and distribution routes of the enterprise respectively.

$\boldsymbol{u}_{vij}$, $\boldsymbol{u}_{vik}$, $\boldsymbol{u}_{vil}$ are the utility of order *i* of customer *v* for storage location *j*, processing method *k*, and distribution route *l*, respectively.

Q_{vi} is the demand quantity of cold chain services for order *i* of customer *v*.

p_{vi} is the estimated probability that the order *i* of customer *v* chooses the enterprise as a service provider.

C_{vij}^{1}, C_{vik}^{2}, C_{vil}^{3} are the unit cost of order *i* of customer *v* for storage location *j*, processing method *k*, and distribution route *l*, respectively.

t_{vi}^{1}, t_{vik}^{2}, t_{vil}^{3} are the time of order *i* of customer *v* for storage, processing method *k* and distribution route *l*, respectively.

T_{vi} is the completion time for order *i* of customer *v*.

$T_{vi\max}$ is the maximum time allowed for order *i* of customer *v*.

α_{ji} is the maximum storage capacity of location *j* for order *i*.

Where $v = 1,\ldots,V, i = 1,\ldots, I_v, k = 1,\ldots, A_K, l = 1,\ldots, A_L, j = 1,\ldots, A_J$, *V* can be used as the number of investigated customers when calculating the utility. The customers considered should reflect the customers in the main market segments of the enterprise, and the type and quantity of goods ordered by customers can be estimated.

4.3 Decision Variables

(1) Upper-level Decision Variables

Storage location selection variable:

$$x_j = \begin{cases} 1 & \textit{Storage location j chosen by the enterprise} \\ 0 & \textit{Otherwise} \end{cases}$$

Processing method selection variable:

$$y_k = \begin{cases} 1 & \textit{Processing method k chosen by the enterprise} \\ 0 & \textit{Otherwise} \end{cases}$$

Distribution route selection variable:

$$z_l = \begin{cases} 1 & \textit{Distribution route l chosen by the enterprise} \\ 0 & \textit{Otherwise} \end{cases}$$

Here, $j = 1,\ldots, A_J$; $k = 1,\ldots, A_K$; $l = 1,\ldots, A_L$. The corresponding vectors of x_j, y_k, z_l are denoted as $\overline{x}, \overline{y}, \overline{z}$ respectively.

(2) Lower-level Decision Variables

Warehouse layout selection variable:

$$x_{vij} = \begin{cases} 1 & \textit{Storage location j chosen for oder i of customer v} \\ 0 & \textit{Otherwise} \end{cases}$$

Processing method selection variable:

$$y_{vik} = \begin{cases} 1 & \textit{Processing method k chosen for order i of customer v} \\ 0 & \textit{Otherwise} \end{cases}$$

Distribution method selection variable:

$$z_{il} = \begin{cases} 1 & \textit{Distribution route l chosen for order i of customer v} \\ 0 & \textit{Otherwise} \end{cases}$$

Here, v=1,…,V; i=1,…, $\boldsymbol{I}_v$; j=1,…, $\boldsymbol{A}_J$; k=1,…, $\boldsymbol{A}_K$; l=1,…, $\boldsymbol{A}_L$. The corresponding matrices of $\boldsymbol{x}_{vij}, \boldsymbol{y}_{vik}, \boldsymbol{z}_{vil}$ are denoted as $\boldsymbol{x}_v, \boldsymbol{y}_v, \boldsymbol{z}_v$ respectively.

4.4 Objective Function

The upper-level objective function presents a comprehensive consideration of the benefits of customers and the enterprise; it is aimed at fulfilling the goal of maximising customer utility, as well as the goal of minimising enterprise cost, and the two goals can be integrated into a single goal, which is to maximise the ratio of customer utility to enterprise cost in this study (Du, Jiao, and Chen 2014). In other words, the goal is to maximise the utility per cost as follows:

$$\max \boldsymbol{F} = \sum_{v=1}^{V} \sum_{i=1}^{I_v} \frac{\boldsymbol{U}_{vi}}{\boldsymbol{C}} \boldsymbol{p}_{vi} \boldsymbol{Q}_{vi}$$

The utility is estimated as follows:

$$\boldsymbol{U}_{vi} = \sum_{j=1}^{A_J} \boldsymbol{u}_{vij} \boldsymbol{x}_j + \sum_{k=1}^{A_K} \boldsymbol{u}_{vik} \boldsymbol{y}_k + \sum_{l=1}^{A_L} \boldsymbol{u}_{vil} \boldsymbol{z}_l + \boldsymbol{U}_{Sv}(\overline{\boldsymbol{x}}, \overline{\boldsymbol{y}}, \overline{\boldsymbol{z}})$$

where $\boldsymbol{U}_{Sv}(\overline{\boldsymbol{x}}, \overline{\boldsymbol{y}}, \overline{\boldsymbol{z}})$ is a real-valued function of $\overline{\boldsymbol{x}}, \overline{\boldsymbol{y}}, \overline{\boldsymbol{z}}$, which denotes the function of synergistic utility considered by the v-th customer, that is, the overall utility for the three types of activity (storage, processing and shipment) synergised together. The utility can be estimated through conjoint analysis based on statistics. The probability p_{vi} is the probability of selecting an enterprise for the i-th order of the v-th customer, which can be calculated by following the probability selection rules (Jiao and Zhang 2005), such as the customer utility-based multinomial logit (MNL) method (Ben-Akiva, Lerman, and Lerman 1985).

The lower-level objective function is basically the same as that of the model (3-1), except the dimensions of decision variables and shared costs, and the choice probability of customer orders.

4.5 Constraints

(1) Upper-level Constraints

Constraints on the upper level of the model are mainly the lower and upper limits of the number of options for each type of service provided by the enterprise.

$$B_{JL} \le \sum_{j=1}^{A_J} x_j \le B_{JU}$$

$$B_{KL} \le \sum_{k=1}^{A_K} y_k \le B_{KU}$$

$$B_{LL} \le \sum_{l=1}^{A_L} z_l \le B_{LU}$$

(2) Lower-level Constraints

The lower-level constraints are basically the same as those of the model (3-1), except the dimension of decision variables and the choice probability of customer orders. In addition, the synergistic constraints between the upper and lower level are added.

$$\left(1 - x_j\right) x_{vij} = 0, v = 1, ..., V; i = 1, ..., I_v; j = 1, ..., A_J$$

$$\left(1 - y_k\right) y_{vik} = 0, v = 1, ..., V; i = 1, ..., I_v; k = 1, ..., A_K$$

$$\left(1 - z_l\right) z_{vil} = 0, v = 1, ..., V; i = 1, ..., I_v; l = 1, ..., A_L$$

where the first constraint indicates that when the j-th storage location is allocated to the order i of customer v it cannot be assigned to any other order or customer. The second and third constraints are similar to the first constraint.

4.6 Synergistic Optimisation Model of the Configuration and Operations of Value Activities

$$\max F = \sum_{v=1}^{V} \sum_{i=1}^{I_v} \frac{U_{vi}}{C} p_{vi} Q_{vi} \qquad (4\text{-}1)$$

$$\text{s.t. } U_{vi} = \sum_{j=1}^{A_J} u_{vij} x_j + \sum_{k=1}^{A_K} u_{vik} y_k + \sum_{l=1}^{A_L} u_{vil} z_l + U_{Sv}(\bar{x}, \bar{y}, \bar{z})$$

$$B_{JL} \le \sum_{j=1}^{A_J} x_j \le B_{JU}$$

$$B_{KL} \le \sum_{k=1}^{A_K} y_k \le B_{KU}$$

$$B_{LL} \le \sum_{l=1}^{A_L} z_l \le B_{LU}$$

$$\min C = \sum_{v=1}^{V}[\sum_{i=1}^{I_v} p_{vi}Q_{vi}(\sum_{j=1}^{A_J} C_{vij}^1 t_{vi}^1 x_{vij} + \sum_{k=1}^{A_K} C_{vik}^2 t_{vik}^2 y_{vik} + \sum_{l=1}^{A_L} C_{vil}^3 t_{vil}^3 z_{vil}) + C_{Sv}\left(x_v, y_v, z_v\right)]$$

$$s.t.\ \sum_{i=1}^{I_v}\sum_{j=1}^{A_J} x_{vij} = \sum_{i=1}^{I_v}\sum_{k=1}^{A_K} y_{vik} = \sum_{i=1}^{I_v}\sum_{l=1}^{A_L} z_{vil} = I_v, v = 1,\dots,V; i = 1,\dots,I_v$$

$$\sum_{j=1}^{A_J} t_{vi}^1 x_{vij} + \sum_{k=1}^{A_K} t_{vik}^2 y_{vik} + \sum_{l=1}^{A_L} t_{vil}^3 z_{vil} = T_{vi} \le T_{vi\max}, v = 1,\dots,V; i = 1,\dots,I_v$$

$$\sum_{j=1}^{A_J} x_{vij} = 1,\ v = 1,\dots,V; i = 1,\dots,I_v$$

$$\sum_{j=1}^{A_J} \left| x_{vij} - x_{vi'j} \right| > 0,\ v = 1,\dots,V; i, i' = 1,\dots,I_v; i \ne i'$$

$$\sum_{v=1}^{V} x_{vij} \cdot p_{vi}Q_{vi} \le \sum_{v=1}^{V} x_{vij} \cdot \alpha_{ji}, i = 1,\dots,I_v; j = 1,\dots,A_J$$

$$\sum_{k=1}^{A_K} y_{vik} = 1,\ v = 1,\dots,V; i = 1,\dots,I_v$$

$$\sum_{l=1}^{A_L} z_{vil} = 1,\ v = 1,\dots,V; i = 1,\dots,I_v$$

$$\left| z_{vil} - z_{vi'l} \right| = r_{ii'}(z_{vil} + z_{vi'l}),\ v = 1,\dots,V; i, i' = 1,\dots,I, i \ne i'; l = 1,\dots,A_L$$

$$\left(1 - x_j\right) x_{vij} = 0, v = 1,\dots,V; i = 1,\dots,I_v; j = 1,\dots,A_J$$

$$\left(1 - y_k\right) y_{vik} = 0, v = 1,\dots,V; i = 1,\dots,I_v; k = 1,\dots,A_K$$

$$\left(1 - z_l\right) z_{vil} = 0, v = 1,\dots,V; i = 1,\dots,I_v; l = 1,\dots,A_L$$

where x_j, y_k, z_l, x_{vij}, y_{vik} and z_{vil} are 0-1variables.

This model assumes that the order completion time is fixed. For the situation that the order completion time may not be fixed in practice, such as the completion time is required to be as short as possible, it can be adjusted and solved appropriately based on this model. At this time, the order completion time T_{vi} is a decision variable. In order to minimise it, a completion speed coefficient θ_{vi} can be added on the upper-level objective function,

$$\theta_{vi} = \frac{T_{vi\max} - T_{vi}}{T_{vi\max}}, \ v = 1, \ldots, V; i = 1, \ldots, I_v$$

At the same time, increase the constraint of the lower bound of T_{vi} and adjust the data such as cost and utility that increase with the decrease of T_{vi}.

4.7 Model Solving

The optimal solutions of a BLP model (Bard 1998). should fulfill three requirements: (1) first, they should satisfy all lower-level and upper-level constraints, i.e., they should be solutions in the constraint space; (2) second, the lower-level solution should be optimal with respect to the upper-level solution, that is, all the lower-level solutions form a rational response set; and (3) last, the upper-level objective function should be optimised. We can see that the most basic requirement is that the solutions should be in the constraint space. For complex BLP problems, the approximate solutions should at least satisfy the requirement to be in the constraint space.

Model (4-1) is a nonlinear, 0-1 integer BLP model. It belongs to the complex BLP model, which cannot be transformed into single-level programming generally. Therefore, this study developed a bilevel nested genetic algorithm (BNGA). The GA function in the MATLAB toolbox can be used in BNGA programming and implementation. The algorithm flow is shown in Fig. 3.

[Figure 3 near here]

In Fig. 3, the initial population of solutions is required to satisfy all constraints to ensure that the final solutions are at least in the constraint space of the BLP problem. Some lower-level decision variables are subject to upper-level decision variables, and, thus, the total number of lower-level decision variables is not fixed; this issue can be resolved using a method (Wang et al. 2016) based on the consideration of specific circumstances. Moreover, there may be some specific requirements to meet when coding. For example, due to the requirement of modular packaging, some variables cannot be separated from others and instead should be properly dealt with in the crossover or mutation operations of the GA. The model solution is a rational optimisation scheme that synergises the configuration and operations of the enterprise's value activities that are oriented to market demands.

5 Case Analysis

5.1 Background

The case study company L Cold Chain Logistics Ltd. is a wholly owned subsidiary of L Food Group Corporation established in 2010. Both are located in the Hainan province of China. L Cold Chain Logistics Ltd is a third-party cold chain logistics provider. Since L Food Group Corporation expanded cold chain logistics business recently, the Corporation needs to achieve synergy and optimisation of its operations.

From a survey at the company, a simplified problem is extracted. A company needs operational configuration of the storage, processing, and distribution of goods. There are six types of goods which are mainly fruits, milk, pork, poultry, aquatic products, and other types of frozen food, and each type of goods can correspond to one customer. Based on the information provided by the marketing and front-end service departments, the estimated quantity of each type of goods and the cost breakdowns in each optional business mode are provided in Table 1. The completion time per unit of goods in each business activity and the estimated total completion time per unit of goods over all business activities are shown in Table 2.

[Table 1 near here]

In addition, the following three requirements have to be met: (1) fruits and milk goods can only be placed in refrigerated locations; (2) pork, poultry meat, aquatic products, and frozen food can only be placed in frozen locations; and (3) pork and frozen food have the same destination of delivery.

[Table 2 near here]

In Table 2, the time of distribution routes includes the time of loading, transportation, and unloading.

5.2 Model Construction and Solving

Model (4-1) is applied to the problem described above. And constraints are imposed according to the problem requirements which are shown below,

$$\sum_{j=1}^{j=3} x_{vij} x_j = 1, v = 1, 2; I_v = 1$$

$$\sum_{j=4}^{j=8} x_{vij} x_j = 1, \ \ v = 3, ..., 6; I_v = 1$$

$$z_{31l} - z_{61l} = 0, l = 1, ..., 6$$

$$z_{11l} - z_{41l} = 0, l = 1, ..., 6$$

Next, a conjoint analysis was carried out. For each market, a questionnaire survey was conducted with 50 of its customers to investigate individual customer preferences for the storage, processing, and distribution sectors separately, as well as for the three sectors combined. SPSS software was employed to calculate customer utility for storage locations, processing methods, and distribution routes separately (Table 3).

[Table 3 near here]

The probability that a customer selects the enterprise was estimated using the MNL method (Ben-Akiva, Lerman, and Lerman 1985) expressed as follows:

$$p_{vi} = \frac{e^{\mu U_{vi}}}{\sum_{v=1}^{V} \sum_{i=1}^{I_v} e^{\mu U_{vi}}}$$

The model was solved using the nested GA proposed in this study. The upper-level and lower-level decision variables were considered to form an upper-level chromosome and lower-level chromosomes, respectively. The upper-level chromosome was coded by 0/1. The upper-level decision variable x_j, for example, has chromosome length of A_J, in which the value of each gene indicates whether the company chooses storage location *j* or not. To reduce the population size, the lower-level chromosome is coded by integers. The lower-level decision variable x_{vij}, for example, has shorter chromosome length of V, in which the value of each gene stands for a specific storage location *j* assigned to customer *v*. The lower-level coding is illustrated in Fig. 4.

[Figure 4 near here]

The calculation parameters were set as follows (Miao et al. 2017; Liu, Du and Jiao 2017 and Miao et al. 2016): both of the population sizes of the upper-level and lower-level GAs were 100; the maximum number of iterations was 120; the accuracy of the binary coding was 0.001; the crossover probability was 0.80; and the mutation probability was 0.01. Considering the characteristics of the company, the choice probability parameter μ was set to 0.5. The stable near optimal results (best found) were obtained through repeated running. The computational solving process is shown in Fig. 5.

[Figure 5 near here]

Table 4 presents the approximate optimal solutions and objective values of the BLP model. The corresponding optimal configuration of storage locations, processing methods and distribution routes, and the corresponding optimal configuration of the services among different orders in Table 5.

[Table 4 near here]

[Table 5 near here]

5.3 Model Validity and Comparison

To test the validity of the BLP model, the model is compared with the traditional single-level two-stage programming model (Miao et al. 2017) by using the case data. The traditional model was solved using a two-stage method (TSM) as follows. In stage 1, optimal solutions for the configuration problems of storage locations, processing methods, and distribution routes were obtained and the maximal utility per cost was 0.0138. In stage 2, the optimal solutions and optimal objective value regarding the configuration of business activities in stage 1 were adopted to solve the problem of selecting value-creating activity options for different orders so as to obtain the optimal storage locations, processing methods, and distribution routes and the minimal cost (i.e., 1.5987×10^3) was obtained. In contrast, the BLP model leads to the maximal utility per cost of 0.0962 and the minimal cost of 1.0447×10^3, respectively. The comparison between the two modes is shown in.

The utility per cost achieved by the BLP method is 597% higher than that by the TSM and the cost made by BLP is 34.7% lower. The results indicate that the BLP is obviously superior to the TSM in solving this type of leader-follower optimisation problems.

Because the TSM is actually two single-level optimisation problems, although it is related, it does not reflect the closer relation between ‘leader-follower’ and ‘overall synergy’, which is just reflected by the dynamic interactive solution mechanism of BLP.

5.4 Sensitivity Analysis

(1) Impact of choice probability parameter μ

When using an MNL model to estimate the choice probability, μ, is a scalable parameter greater than zero. If μ is large enough, the MNL model tends to be a deterministic choice model; if μ is small or equals 0, the MNL model tends to be a uniform distribution model (Kaul and Rao 1995). Since changes in the value of μ can cause changes in the choice probability and, in turn, affect the optimal solutions and optimal objective value of the model, it is necessary to perform a sensitivity analysis of parameter μ.

In the model calculation, μ was set to 0.5. To analyse the impact of μ’s variation, it was arranged to vary from 0-10 with an increment of 0.25 when μ varied from 0 to 1 and with an increment of 0.5 when it varied from 1 to 10. The effects of μ on the objective values are shown in Fig. 6.

[Figure 6 near here]

Fig. 6 shows that when μ was set between 0 and 1, the upper-level objective of the model, i.e., the utility per cost, shows an increasing trend, while the lower-level objective of the model, i.e., the cost, decreased first and then increases; the minimal value appeared at μ = 0.5. When μ was set between 1 and 7.5, the objective value of the upper level was unstable and fluctuated as μ increased; in the lower level, the objective value shows an increase and then a decrease until μ = 2; the objective increased again to the maximum at μ = 5, where a large fluctuation occurred. When $\mu \geq 8$, the objective values of both upper and lower levels tended to be stable. Since the variation of μ has a significant impact on customer utility and enterprise cost, it is necessary to investigate further the estimation of μ.

(2) Effects of the maximum number $\boldsymbol{B_{JU}}$ of storage locations

The maximum number $\boldsymbol{B_{JU}}$ of storage locations affects the range of the model constraint space and, in turn, the solutions and objective values of the model; thus, it is necessary to perform a sensitivity analysis of $\boldsymbol{B_{JU}}$.

In the model calculation, B_{JU} was set to 8. To evaluate the impact of B_{JU} variation, it is allowed to vary from 6 to 23 in increments of 1; the effects of B_{JU}'s variation on the objective values are shown in Fig. 7.

[Figure 7 near here]

Fig. 7 shows that the variation of B_{JU} has a significant impact on the objective values, especially when B_{JU} varies between 6 and 17 there are large fluctuations in the objective values. When $B_{JU} > 17$, the objective values tend to be stable. When $B_{JU} = 7$, both objective values of the upper and lower levels are at low level, while when B_{JU} is at 13 or 16, both objective values reach relatively ideal levels, i.e., high utility per cost and low total cost. This result can provide support for the company to determine the allocation level of storage capacity. Similarly, sensitivity analysis can be conducted on other parameters, such as the upper and lower allocation limits of processing and distribution capacities.

6. Concluding Remarks

The synergistic framework of cold-chain logistics operations is studied based on the Porter's value chain theory. The corresponding mathematical models and algorithms of synergistic optimisation are established in this study.

The following theoretical contributions of this study are made: (1) a universal value chain for cold chain logistics businesses has been established based on the analysis of the differences of general logistics enterprises from the value chains of manufacturing industry. Based on this, a synergistic framework is proposed: intra-enterprise synergy, and synergy of internal and external enterprise. (2) Based on the synergistic framework, a single-level programing model has been built first to minimise the operational cost through synergy within the value chain activities, which quantitatively characterise the block diagonal structure of intra-enterprise synergy. (3) Then, a BLP model of cost utility rates and business operations has been established, which quantitatively characterise the leader-follower relationship between synergy of internal and external enterprise. and (4) a BNGA has been developed to solve the synergistic optimisation model and a computational test has been conducted to demonstrate the validity of the model by the data from a case study of a real cold chain logistics company.

The case analysis has the following application value and management implications: (1) quantitative optimisation models can provide a decision-making support for cold chain logistics enterprises to synergise operational schemes and achieve joint optimisation of configurations and operations; (2) sensitivity analysis shows that some parameters in operations may affect the operational costs and the customer utilities, which should be considered in the decision-making.

Envision the design in the new era, the intersection of value chain and supply chain disciplines is an important domain for the new design field (Jiao et al. 2022). This paper can further study: (1) make the model general so as to adapt variable order completion times and multiple types of goods per order; (2) service quality can be included in the customer utility value calculation as it affects the supply chain configurations; and (3) study further the sensitivity of parameters for more robust solutions.

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Table 1. Cost for each alternative method of storage, processing, and distribution (Chinese RMB / ton * hour)

Activity and method / Unit cost / Estimated order quantity		1.Fruit	2.Milk	3.Pork	4.Poultry meat	5.Aquatic product	6.Other frozen food
		3.00	3.00	6.00	9.00	9.00	3.00
Storage location	1.Refrigerated location1	0.30	0.25	—	—	—	—
	2.Refrigerated location2	0.25	0.25	—	—	—	—
	3.Refrigerated location3	0.23	0.26	—	—	—	—
	4.Frozen location1	—	—	0.25	0.29	0.25	0.20
	5.Frozen location2	—	—	0.27	0.27	0.24	0.23
	6.Frozen location3	—	—	0.25	0.28	0.27	0.25
	7.Frozen location4	—	—	0.25	0.25	0.20	0.20
	8.Frozen location5	—	—	0.27	0.27	0.20	0.23
Processing method	1.Splitting (small size to large size)	125.00	122.50	275.00	183.33	132.50	100.00
	2.Splitting (large size to small size)	71.43	112.50	95.00	82.86	90.00	75.00
	3.Splitting, coding and labeling	50.00	38.80	66.67	66.67	58.82	58.82
	4.Pakcing 1	12.12	—	—	—	—	15.15
	5.Pakcing 2	10.40	—	—	—	—	17.59
Distribution route	1.Route 1	66.67	83.33	55.00	73.33	70.00	57.14
	2.Route 2-1	33.33	40.00	32.73	37.78	36.00	95.00
	3.Route 2-2	40.00	61.67	27.86	40.00	44.44	57.14
	4.Route 3	36.00	170.00	25.00	28.57	33.33	36.36
	5.Route 4-1	25.00	75.00	34.00	28.33	25.00	38.00
	6.Route 4-2	17.50	35.56	25.71	19.00	25.71	24.29

Table 2. Total time taken to complete orders and time taken by each method (hours/ton)

Method / Time		1.Fruit	2.Milk	3.Pork	4.Poultry meat	5.Squatic product	6.Other frozen food
Processing method	1.Splitting (small size to large size)	0.4	0.4	0.2	0.3	0.4	0.5
	2.Splitting (large size to small size)	0.7	0.4	0.6	0.7	0.6	0.8
	3.Splitting, coding and labeling	2.0	2.5	1.5	1.5	1.7	1.7
	4.Packing 1	6.6	—	—	—	—	6.6
	5.Packing 2	7.5	—	—	—	—	5.8
Distribution route	1.Route 1	3.0	3.0	4.0	3.0	3.0	3.5
	2.Route 2-1	4.5	4.0	5.5	4.5	5.0	2.0
	3.Route 2-2	5.0	3.0	7.0	5.0	4.5	3.5
	4.Route 3	5.0	1.0	8.0	7.0	6.0	5.5
	5.Route 4-1	6.0	2.0	5.0	6.0	8.0	5.0
	6.Route 4-2	10.0	4.5	7.0	10.0	7.0	7.0
	Total time	48.0	18.0	120.0	240.0	120.0	72.0

Table 3. Utility of storage, processing, and distribution

		1.Fruits	2.Milk	3.Pork	4.Poultry meat	5.Aquatic product	6.Other frozen food
Storage location	Refrigerated location1	3.837	4.437	-3.275	-3.345	-3.275	-3.475
	Refrigerated location2	4.237	2.737	-3.275	-3.345	-3.275	-3.475
	…	…	…	…	…	…	…
	Frozen location5	-2.262	-2.162	2.325	2.675	3.525	1.525
Processing method	Splitting (small size to large size)	0.264	0.800	1.800	1.800	1.800	0.300
	Splitting (large size to small size)	-0.056	1.800	0.800	0.800	0.800	-0.500
	…	…	…	…	…	…	…
	Packing 2	0.076	-2.200	-2.200	-2.200	-2.200	-0.500
Distribution route	Route1	-1.800	-1.433	-2.067	-1.883	-1.133	-0.723
	Route2-1	-1.720	0.567	0.533	1.317	1.667	0.997
	…	…	…	…	…	…	…
	Route4-2	0.460	0.767	0.933	-0.183	0.467	1.997

Table 4 Optimal solutions and objective values of the BLP model

Upper-level optimal configuration decisions	
Optimal objective value	Chromosome
$F = 0.0962$	$[x_j]$ = [1 1 0 0 1 1 1 1] $[y_k]$ = [1 1 1 0 1 1] $[z_l]$ = [1 1 0 0 1 0]
Lower-level optimal configuration decisions	
Optimal objective value	Chromosome
$f = 1.0447 \times 10^3$	$[x_{vij}]$ = [1 2 8 5 7 6] $[y_{vik}]$ = [1 1 1, 1 1 1, 2 1 1, 2 1 1, 2 1 1, 2 1 2] $[z_{vil}]$ = [2 5 2 2 2 5]

Table 5 Optimal configuration and operations plan of storage locations, processing methods and distribution routes

Upper-level configuration

Storage location	Refrigerated location 1	Refrigerated location 2	Refrigerated location 3	Frozen location 1	Frozen location 2	Frozen location 3	Frozen location 4	Frozen location 5
	√	√			√	√	√	√

Processing method	Splitting (small size to large size)	Splitting (small size to large size)	Unpacking, coding and labeling	Packing 1	Packing 2
	√	√	√	√	√

Distribution route	Route 1	Route 2-1	Route 2-2	Route 3	Route 4-1	Route 4-2
	√	√			√	

Lower-level selection		1.Fruits	2.Milk	3.Pork	4.Poultry meat	5.Aquatic products	6. Other frozen food
Storage location	1.Refrigerated location 1	√					
	2.Refrigerated location 2		√				
	5.Frozen location 2				√		
	6.Frozen location 3						√
	7.Frozen location 4					√	
	8.Frozen location 5			√			
Processing method	1.Split (small size to large size)	√	√				
	2.Split (large size to small size)			√	√	√	√
	3.Spliting, coding and labeling	√	√	√	√	√	√
	4.Packing 1	√					
	5.Packing 2						√
Distribution route	1.Route1						
	2.Route 2-1	√		√	√	√	
	5.Route 4-1		√				√

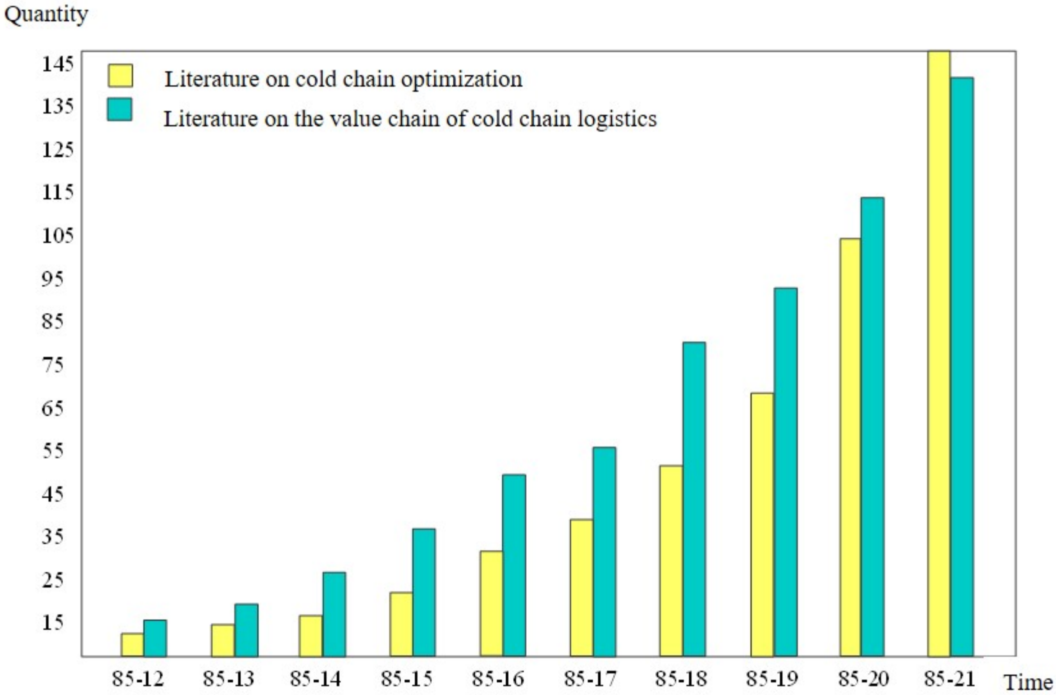

Figure 1. Increasing trends of the cumulative number of literature reports

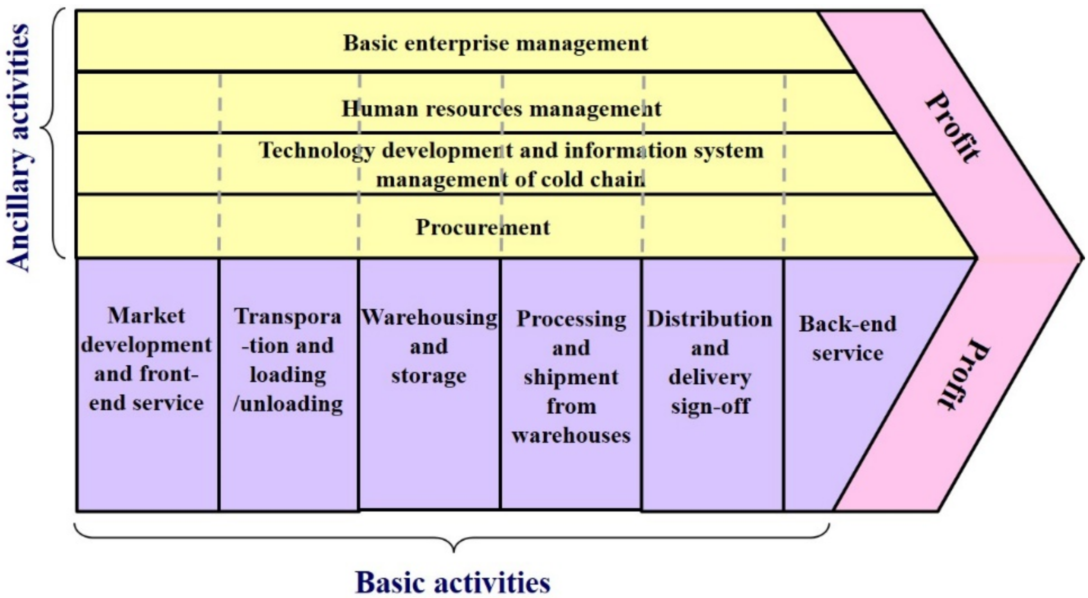

Figure 2. General value chain of cold chain logistics enterprises

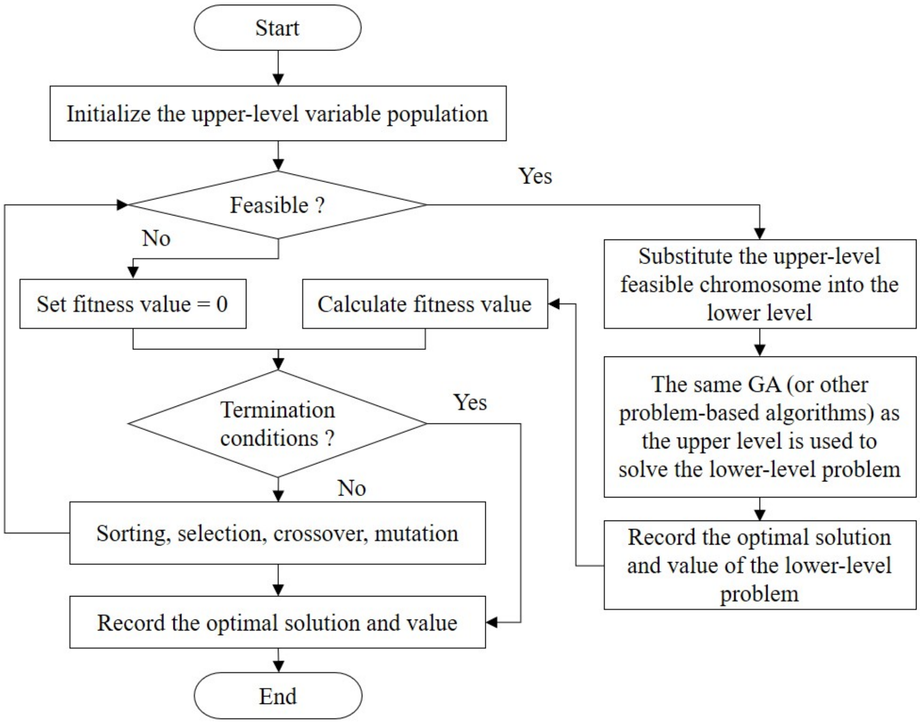

Figure 3. Flow chart of solving the BLP problem based on a nested GA

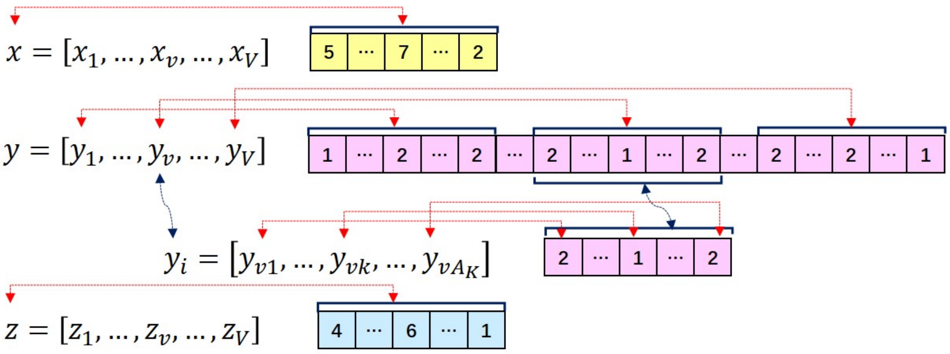

Figure 4. Schematic diagram of the coding of lower-level chromosome

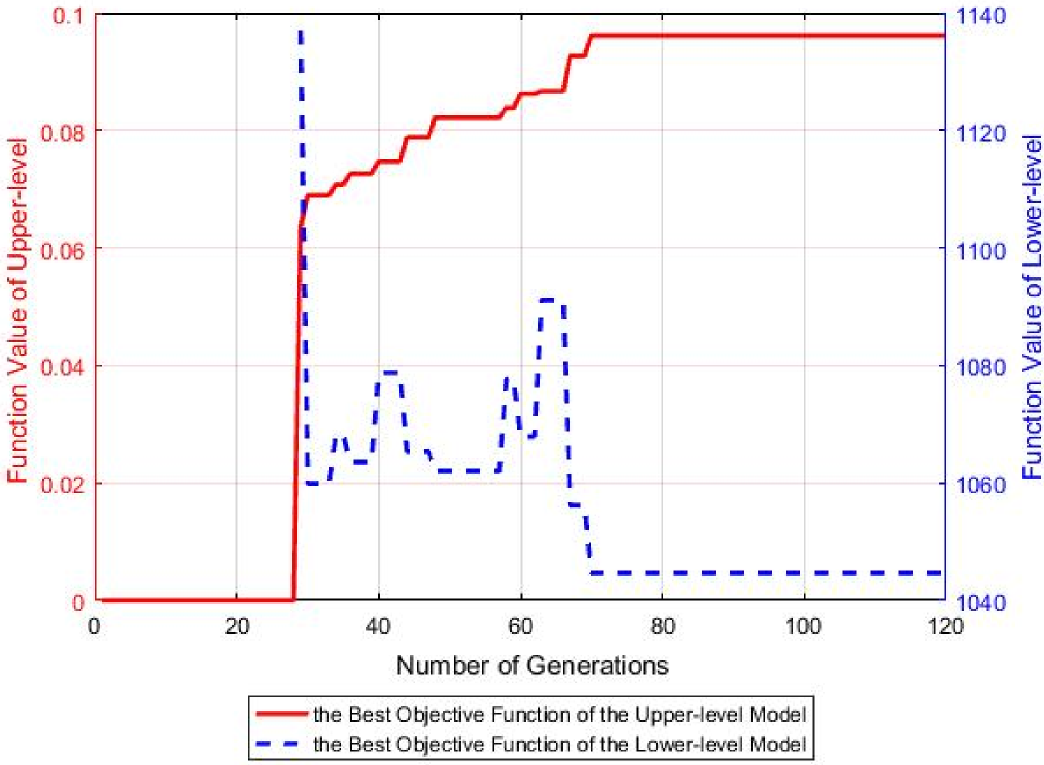

Figure 5. Iterative calculation process

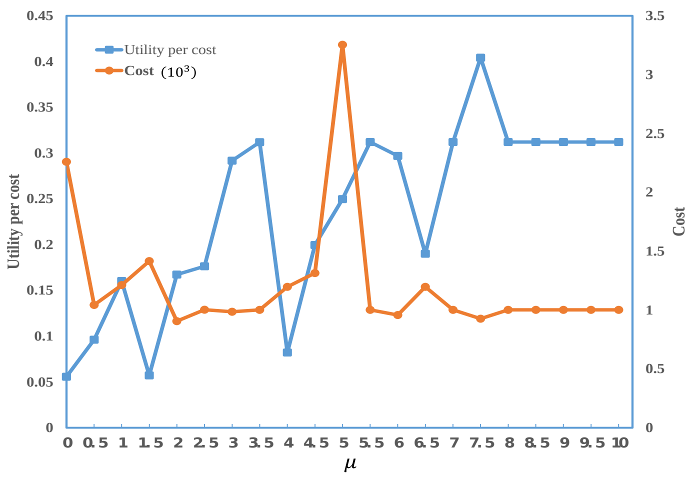

Figure 6. Effects of μ's variation on the objective values

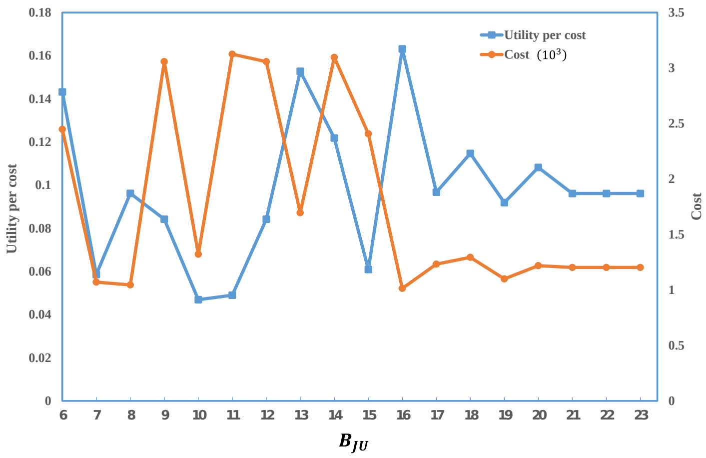

Figure 7. Effects of B_{JU}'s variation on the objective values