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Developing a multi-product three-level cold supply chain considering quality evaluation function and pricing mechanism

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Cold supply chain;
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Multi-product;
Multi-period.

Abstract. Paying attention to cold supply chains is critical in light of rising global warming and public awareness of the issue. In addition, a lack of appropriate quality control in supply chains has resulted in significant waste in the industry. This research sought to create a three-level cold supply chain (firm, distribution center, and retailer) with a quality evaluation function. The chain has been modelled for a multiplicity of products and time periods. The parameters in this model are analyzed in three separate scenarios to reflect uncertainty. The model also includes direct delivery from the firm to the store. Various factors can affect the quality evaluation variables, which in this model are assigned to two main parameters: Temperature and humidity. The quality of the products in this model is used to estimate their selling price. Due to the nonlinearity of the model, the Baron approach is applied in this work.

1. Introduction

Over the past few years, global warming has become a vital issue especially since scientists have provided persuasive reasons for its existence and detrimental effects on the environment [1]. Nowadays, experts believe that radiation that leads to GreenHouse Gas (GHG) emissions is the main cause of global warming, therefore many efforts have been made around the world by governments, organizations and factories to reduce GHG emissions [2].

In many industries, supply chain operations are the main sources of GHG emissions. It is estimated that more than three-quarters of GHG emissions in many industries are caused by supply chain activities [3]. Companies have been focusing heavily on reducing the environmental impact of their supply chains in order to meet their sustainability commitments, reduce the risk of brand value of the company, and keep customers with environmental concerns satisfied [4]. Today, several major companies such as IBM, Johnson and Johnson and Pepsi, require their suppliers to monitor and report on their GHG emissions. In 2015, Wal-Mart announced a significant reduction of GHG emissions from their supply chain by 18 million tons [5].

Environmental aspects in supply chain manage-

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ment have become more frequent as public awareness of sustainability has grown. As a result, traditional methods that are primarily concerned with cost cannot be used to address complex environmental issues. The Kyoto Protocol obligates countries to commit to reducing a certain percentage of the six different types of GHG (including CO_2). Fossil fuel emissions, such as CO_2, are the largest contributor to global warming. The rest of the gases play an important role in global warming and may become a determining factor in the near future. Between 1998 and 2005 concentrations of many GHGs including fluorine, such as HFCs, PFCs and SF6, increased by factors of 1.3 to 4.3 and their radiation increased approximately 10% annually. The heating effect of a GHG is usually determined by two factors, it's density in the atmosphere and the ratio of GWP (Global Warming Potential: The ratio of its radiation from the emission of one kilogram of that specified gas to the emission of one kilogram of CO_2). Despite the fact that the density of these gases in the atmosphere is lower than CO_2, most of these gases have a high GWP. For example, the GWP for HFC-134A, commonly used in home refrigerators and car air conditioners, is 3830 in 20 years. Although the density of HFC-134A in 2005 was only 7–10 times the CO_2, it increased by 349% between 1998 and 2005. This percentage is very weighty compared to the 13% increase in CO_2 over the same period. It is estimated that if the CO_2 reduction targets are met but nothing is done for HFCs, these gases will be responsible for emissions between 28 and 45% of carbon emissions by 2050. If no action is taken for reducing CO_2, HFCs will be responsible for emissions ranging from 10 to 20% of carbon emissions by 2050 [6].

These days, the greenhouse effect and climate change are getting a lot of press. Cold supply networks are one example of where this focus is highlighted. GHG emissions are a serious concern since the temperature of the vehicles and storage places in these chains must be kept within a certain range. Since CO_2 accounts for 65% of GHGs, different carbon emission policies are used in literature to model cold supply chains. Policies can be price-based (based on tax) or value-based (using the exchange and capacity system). With carbon tax policies, the organization pays a fixed tax rate for every ton of carbon released. Such policies have been shown to reduce energy consumption and encourage companies to invest in cleaner technologies. Organizations are subject to tax for emissions exceeding the permissible limit based on carbon capacity policies. The exchange and capacity system operate similar to the carbon capacity and allow the organization to exchange its non-consumed carbons [7]. Litto states that the main elements of GHGs are carbon dioxide (64%), methane (19%) and nitrogen oxide (8%). Methane and nitrogen oxide emissions can also be considered in GHG emissions from vehicles [8].

Cold chains are highly appreciated in the food, pharmaceutical, and chemical sectors. To preserve product availability, quality, and health, all temperature-sensitive products require cold chains. In recent decades, cold supply chain research has gotten a lot of attention. Lately, more researches are being conducted to analyze the effects of sustainability decisions (especially carbon emissions) on cold chains performance [9].

Given the foregoing, the significance of the cold supply chain is obvious. There is a void in the literature on this subject in terms of a study that considers environmental issues and quality at the same time. A supply chain that precisely balances the costs of regulating environmental parameters like temperature and humidity against the price of doing so with energy. This strategy can be used by managers and decision-makers to balance quality and cost based on their needs. Another issue that receives less attention is determining quality based on the characteristics of cold commodities. Consumer surveys have been used to assess quality in some studies (such as Ref. [10]), and quality is not appraised according to environmental factors. Aside from these concerns, the relationship between quality and end product pricing has received less attention. Taking into account the model's environmental conditions, paying attention to environmental issues, formulating quality, and pricing based on quality are some of the most important issues addressed in this study.

1.1. The question of research

The major research questions in this study are:

- How much of each product should be produced in order to maximize income, despite the uncertainty of demand for multiple goods?
- Which routes and to what extent should goods reach the retailer, based on the availability of distribution centers, and is it more cost-effective to deliver directly from the manufacturer to the retailer or is it more acceptable to use distribution centers?
- Due to sensitivity of commodities to environmental conditions, what environmental conditions should be provided for goods transfer and storage so that they arrive in the best possible quality?
- What factors will be used to evaluate the quality of environmentally sensitive goods?
- What will be the mechanism for pricing cold goods?
- What impact do commodities that require more difficult storage have on overall revenue?

2. Literature review

Various researches have been done in the literature of the cold supply chain. In [5,9,11–42] each have dealt with the problem in their specific approach and from a different angle. The present study is unique in that it focuses on multiple features at the same time and it's vital to know whether these features have been covered in the literature and, if so, how they were handled. The following are some of the characteristics:

- Environmental considerations and energy usage in the context of cold commodities in certain environmental circumstances (reviewed in Subsection 2.1);
- How to deal with cold goods in different issues (reviewed in Subsection 2.2);
- Quality assessment of items and quality-based pricing (reviewed in Subsection 2.3).

2.1. Environmental impacts in cold chains

Environmental impacts in cold chains have gained impressive attentions in recently supply chain models which main concern of them is the environment and their objective is to reduce GHG emissions with different constraints and considerations. The world's expanding population has exacerbated community nutritional issues. As a result, previous food supply systems need be updated to meet today's expanding demand [43]. Besides the food supply system and the food sector are both affected by the COVID-19 pandemic, according to Rizou et al. more safety precautions are required when the food chain moves from farm to fork. More safeguards are required as we get to the final stages of the supply chain, since more individuals are involved in the process. In the delivery sector of supply chains, maintaining time and temperature restrictions is important [44]. The equilibrium between overall cost and environmental impacts is examined in an article by Wang et al. In this study, they have taken advantages of the normalized normal constraint method and has attempted to obtain a set of optimized Pareto solutions and has studied the sensitivity of the problem parameters [45]. The supply chain design framework is presented in the Chaabane et al. study. Their model is closed-loop form, with multiple aspects of previous references (including Life Cycle Assessment (LCA) and emission exchange). Their mixed integer programming model includes the environmental and economic costs of production, distribution, warehousing, and recovery activities [17]. The carbon emissions from transportation and cold storage activities in a multilevel supply chain, were addressed in Hariga's paper. In this study, a model is developed that minimizes operating costs, minimizes carbon footprint, and develops a hybrid environmental and economic model in which all elements are optimized for optimal storage and transport size. The results show that as the carbon tax rate increases, the amount of carbon released decreases [9]. Xu et al. have proposed various ways to reduce the carbon footprint of a food system's lifecycle in terms of environmental policies, consumer behaviors, and technical considerations [46]. In another study, Toptal et al. have analyzed retailers inventory decisions and investment policy decisions to reduce carbon emissions [47]. In a temperature-controlled supply chain, Stellingwerf et al. developed an IRP model to investigate the economic and environmental benefits of cooperation. The authors discovered that collaborating on Vendor Managed Inventory (VMI) can save money and reduce emissions [48].

Since the lack of energy and its expensive financial and environmental costs, improving energy efficiency becomes so crucial in businesses. It reflects strategic advantages and therefore requires greater coordination among companies. Planning and controlling production to avoid peak demand (for example by balancing orders), optimal use of technical building equipment and service structures are among the parameters that can be evaluated in designing and controlling production equipment. Among these indicators, it has been proven that energy efficient production planning can create low cost opportunities compared to large investments for launching new technologies. Hence the issue of energy efficiency in supply chain management and lot sizing has attracted the attention of researchers [49]. Zanoni et al. have developed an energy consumption model in a two-stage production system with controllable production rate and studied the impact of production speed on energy consumption at each stage [27]. Bazan et al. have introduced a closed-loop supply chain model that considers gas emissions and investigated different synchronization decisions for the consumption of energy [50].

2.2. Cold supply chain challenges

There are several challenges in the field of cold supply chain modeling. The lot sizing problems are those that have always been addressed in the supply chain and how to deal with these issues is very important. The literature on cold supply chains also deals with the lot sizing problems and the economic ordering quantity models or briefly EOQ [21–25,29,51]. Another challenge in the cold supply chain is routing problems. Routing problems typically are dealing with finding reasonable routs for transportation of goods considering wide range of different concerns such as costs of transportation and trying to deal with these concerns in cold chains means considering issues like temperature-sensitive products transportation, GHG emissions and energy consumption in objective function which has been addressed in the literature [32,33,52–56]. Designing a good supply network is always effective in using current resources, minimizing weaknesses, and lowering transportation costs. Most cold supply chain network design models were created to reduce transportation, maintenance, and inventory expenses at cold temperatures. Carbon emissions expenses and temperature settings are also considered as constraints in many cases. The model that Diabat and Simchi-Levi have developed is a supply chain model in which carbon consumption is low. Production is intended and storage capacity is available in this model, but the issue of carbon exchange has not been addressed [12]. A detailed sophisticated multi-objective model has been developed by Bojarski et al., in which LCA is integrated with supply chain design concepts. Model decisions include facility locating, choosing processing technology and planning of production and distribution [15]. Hsiao et al. have used mathematical optimization techniques for temperature adjustments in a transportation where different products require different temperatures for storage. His ultimate objective was to minimize costs [18]. Catalá et al. have formulated a supply chain planning problem in its various phases (production, processing, distribution, and inventory decisions) with the aim of reducing costs as well as shortage. All this modeling has been done with respect to temperature changes during processing and transportation [19]. Chen and Hsu have worked on a model that estimates GHG emissions from multi-vehicle and multi-temperature distribution systems. For time-dependent demands of multi-temperature foods they have considered a send schedule [57]. Hammami et al. have also developed a deterministic model that includes carbon emissions in a multi-level production and inventory model with time constraints [28]. The balance between inventory, transportation and distribution costs is analyzed in the Hoen et al. model. He has developed a mathematical formulation for the problem of selecting the mode of transport and various regulatory policies are examined [58]. Jaber et al. have investigated carbon emissions at two levels (seller and buyer) in the supply chain under different emission trading schemes (including scheme combinations). His goal was to minimize associated inventory costs and carbon emissions costs under the penalties for excess carbon emissions [59]. In 2014, Bozorgi et al. attempted to find the optimal order quantity using exact solution algorithms to minimize overall costs. His proposed inventory model includes shipping and maintenance costs for cold goods. This model has been developed for an environment where temperature-controlled items must be kept at a specified temperature without change, using modular temperature control units [30]. In addition, he further developed an inventory model with emission considerations that can be applied to groups of cold products looking for an inventory level where overall costs would be minimized. The capacity and storage of transport units are also included in the model [60]. In the context of carbon price regulation and under uncertain demand, Babagolzadeha's paper studies the impact of carbon emissions resulting from storage and transit in the cold supply chain. To minimize both operational and emissions costs, a two-stage stochastic programming model is created to establish optimal replenishment policies and transportation schedules. To address the problem in practical sizes, a Matheuristic algorithm based on the Iterated Local Search (ILS) algorithm is proposed [61]. The rising demand for food will result in increased energy usage in supply chains. From a different perspective, Yakavenka et al. recognize the importance of transport system time in the transportation of perishable goods, and they propose an SSCND model with multiple objectives for all three aspects of sustainability. They gave an instance of fresh fruit in order to investigate product perishability. They also took into account product delivery via chilled containers and provided a model with deterministic parameters. Total CO_2 emissions and total transportation time are used to illustrate the environmental and social implications in their study [62].

2.3. Quality evaluation approach

Quality deterioration owing to a lack of effective quality control is a contentious issue in managing perishable food and temperature-sensitive goods supply chains. Advances in food tracking techniques and technology along the supply chain have opened up a lot of possibilities for increasing the efficiency of operations. Food quality evaluation studies have been conducted in the field of food science, and supply chain models have also been included in these researches. Researchers have taken a variety of approaches to this problem. Wang et al. specifically focused on the damage to goods caused by opening truck's door and consideration of the effects of this issue on the freshness of goods [63]. In Wang and Li's research, they have used product pricing methods and set different pricing policies according to product quality [64]. Behzadi et al. have developed a stochastic two-tier supply chain model for profit optimization that includes an exponential decay function that reduces the risks of disconnection [20]. Hoang et al. have analyzed the cold chain distribution process using available data from databases and formulated the evolution of temperature and microbial growth in food using deterministic and stochastic approaches [37]. One of the most important dilemmas to be careful about is what features the developed quality evaluation function should include. Predicting quality in food products is complicated due to the wide range of quality characteristics, dynamics of product specifications and storage conditions. For perishable foods, freshness as a product life expectancy is usually considered to be the most important quality feature. Some studies have suggested that freshness is a quality feature that is remarkable for consumers of perishable products [65,66]. Among the features used in quality evaluation functions, temperature has been used in many cases. One approach for predicting the product lifecycle is the kinetic model. In this model the product life span is usually estimated by measuring one or more quality characteristics. In order to monitor changes in quality parameters, the quality equation can be written as an exponential function in which quality is a function of quality key parameters (such as temperature), the constant rate of feedback and the rate of chemical feedback (power of constant rate) [67–69]. The quality level of a product at a given location in the food supply chain can be based on an initial ideal quality and expressed in consecutive intervals of time and temperature. If temperature values are available over time, the quality level can be calculated numerically. Since temperature fluctuations are usually random, it is problematic to estimate the exact quality level. Recently, developments in monitoring technologies such as RFID and TTI have the potential to provide real-time product quality recognition for a high volume of complex supply chain products and processes. It can be said that the quality of a food product can be accurately measured and recorded at all times throughout the supply chain. In the work of Wang and Li it is proposed to use temperature-dependent quality degradation rate [64]. Lytou et al. have developed prediction models for livestock meat products under constant temperature and fluctuating temperature conditions [70]. Gwanpua et al. have introduced a tool that simulates food quality changes in cold chains using a food freshness model and considering heat exchange in refrigerators. This tool (called FRISBEE) evaluates the energy consumption and global warming effects of the cold supply chain based on user inputs of cold chain parameters such as performance index, type and structure of refrigerant systems [36]. Currently temperatures inside the vehicle, product packages, inventory and showcases are measured and these temperatures are assumed to be food temperatures. If outside temperature varies significantly or the heat capacity of the food is high, there is a gap between the temperature of the food and its environment, which makes it impossible to accurately monitor the quality. To this end, it is necessary to use technology to predict food temperature from the monitored ambient temperature [71]. Raab et al. collect the temperature history of foods in large packaging units using constant temperature sensors [72]. The rate of food temperature change can be calculated using the rate of exchange of food temperature and its ambient [73]. Hoang's work has also used temperature as a key quality attribute [37]. Exponential functions are the best expressions for quality. Since the quality decline does not occur linearly and is exponential, the best way to express this is to use exponential functions. This issue makes the objective function of the model nonlinear, and thus to solve it requires methods to solve nonlinear functions, exact methods such as Epsilon cutting techniques, Lagrangian relaxation or Banders decomposition, or stochastic methods such as search algorithms and heuristic methods. For smart food logistics systems, Chan et al. utilized multi-objective mixed-integer linear programming for maximizing the average food quality [74]. In their closed-loop supply chain model, Giri and Masanta used quality as a decision variable that ranged from 0 to 1. The rate of demand is determined by the retail price as well as the quality of the product. This model assumes a random return of used goods and a stochastic lead time at the retailer. Aside from that, they considered the production process is subject to learning. It has been discovered that learning in the manufacturing process has a considerable positive impact on the closed-loop supply chain's best decisions [75]. Supplier and customer quality integration are two important techniques for structuring inter-organizational strategies, practices, and procedures into collaborative and synchronized quality-related activities in order to meet the quality criteria of its customers [76]. Yu et al. investigate the links between Supply Chain Quality Integration (SCQI), Green Supply Chain Management (GSCM), and environmental performance by developing a model. Supplier and customer quality integration, as well as environmental performance, were measured using a survey instrument. For all constructs, a multiple-item, seven-point Likert-type scale was used [10].

2.4. Literature summary

The traces of current research topics in the literature were expressed in the previous part. This review focuses on two main issues of cold supply chain and quality evaluation. Table 1 summarizes the works done in these areas. At the bottom of this table, the characteristics of the present study are outlined. According to the literature study, there is a research gap in the design of cold supply chain models that take uncertainty and the quality evaluation function into account. The model will be explained and numerical results will be examined in the next section. This study is unique in that it considers the role of quality evaluation in the design of the cold supply chain distribution network and the pricing of items based on their quality. It's also worth noting that the model was created at three tiers during multiple periods. The model that has been constructed is nonlinear. The most significant aspect of this research is that quality is expressed mathematically and quantified in terms of temperature and humidity. Unlike Yu et al., who employed a survey, the method used in this study

Table 1. Literature summary.

	Reference	Year	Number of levels		Solution method			Problem space		Considerations		Other features				
			More than two levels	Two-level	Simulation based	Heuristic	Exact	Certain	Uncertain	Quality	Cold	Multi period	Multi product	Multi objective	Mixed integer	Nonlinear
1	Fibich [80]	2003	–	*	–	–	*	*	–	*	–	–	–	–	–	*
2	Jiang and Yang [39]	2003	*	–	–	*	–	*	–	–	*	–	–	–	–	–
3	Wang Hai-li and Wang Yong [40]	2008	*	–	–	*	–	*	–	–	*	–	–	–	–	–
4	Raab [72]	2008	*	–	–	–	*	*	–	*	–	–	*	–	–	*
5	Diabat and Simchi-levi [12]	2009	–	*	–	–	*	*	–	–	*	–	*	–	*	–
6	Harris et al. [13]	2009	–	*	–	*	–	*	–	–	*	–	–	*	*	–
7	Bin & Jun [14]	2009	*	–	–	–	*	*	–	–	*	–	*	–	*	*
8	Bojarski et al. [15]	2009	*	–	–	–	*	*	–	–	*	*	*	*	*	–
9	Ramudhin et al. [11]	2010	*	–	–	–	*	*	–	–	*	–	*	–	*	–
10	Wang and Zhao [41]	2010	*	–	–	*	–	*	–	*	*	–	–	*	–	–
11	Miao [32]	2011	–	*	–	*	–	*	–	–	*	–	–	–	–	–
12	Rong et al. [81]	2011	–	*	–	–	*	*	–	*	–	*	–	–	*	–
13	Yang et al. [42]	2011	–	*	–	–	*	*	–	–	*	–	–	*	–	–
14	Wang [16]	2011	*	–	–	*	–	*	–	–	*	–	*	*	*	–
15	Chaabane [17]	2012	*	–	–	–	*	*	–	–	*	–	*	*	*	–
16	Hua [21]	2012	*	–	–	–	*	*	–	–	*	–	–	–	–	*
17	Bouchery [22]	2012	–	*	–	*	–	*	–	–	*	–	–	*	–	–
18	Hoang et al. [37]	2012	*	–	*	–	–	–	*	*	*	–	–	–	–	*
19	Benjaafar [23]	2013	–	*	–	–	*	*	–	–	*	–	–	–	–	–
20	Chen et al. [24]	2013	*	–	–	–	*	*	–	–	*	–	–	–	–	*
21	Absi [25]	2013	*	–	–	–	*	*	–	–	*	*	–	–	*	–
22	Jaber [26]	2013	–	*	–	–	*	*	–	–	*	–	–	*	*	*
23	Zanoni [27]	2014	–	*	–	–	*	*	–	–	*	–	–	–	–	*
24	Konur and Schaefer [29]	2014	–	*	–	–	*	*	–	–	*	–	–	–	*	*
25	Bozorgi [30]	2014	–	*	–	–	*	*	–	–	*	–	–	–	–	*
26	Hammami [28]	2015	*	–	–	–	*	*	–	–	*	*	*	–	*	–
27	Gwanpua et al. [36]	2015	*	–	*	*	–	*	–	*	*	–	–	*	–	–
28	Catalá [19]	2016	*	–	–	–	*	*	–	–	*	*	–	*	*	–
29	Bozorgi [31]	2016	–	*	–	–	–	–	–	–	–	–	–	–	–	–
30	Li et al. [33]	2016	–	*	–	*	–	*	–	–	*	–	–	–	*	–
31	Lytou [70]	2016	–	*	–	–	*	*	–	*	–	–	–	–	–	*
32	Saif [5]	2016	*	–	*	–	–	*	–	–	*	–	–	*	*	–
33	Hsiao [18]	2017	*	–	–	*	–	*	–	*	*	–	*	–	*	–
34	Hariga [9]	2017	*	–	–	*	–	*	–	–	*	–	–	*	–	–
35	Behzadi [20]	2017	–	*	–	–	*	–	*	–	*	–	*	–	*	*
36	Li et al. [52]	2019	–	*	–	*	–	*	–	*	–	–	–	*	–	–
37	Gonela [38]	2019	–	*	–	–	*	–	*	–	*	*	–	–	*	–
38	Yu et al. [10]	2019	–	*	–	–	*	*	–	*	*	–	*	–	–	–
39	Zhang et al. [76]	2019	–	*	–	–	*	*	–	*	–	–	–	–	–	–
40	Leng et al. [56]	2020	*	–	–	*	–	*	–	–	*	–	–	*	–	–
41	Chan et al. [74]	2020	–	*	–	*	–	*	–	*	*	*	–	*	*	–
42	Babagolzadeh et al. [61]	2020	–	*	–	*	–	–	*	–	–	*	–	–	*	*
43	Giri and Masanta [75]	2020	–	*	–	–	*	–	–	*	–	–	–	–	*	–
44	Yakavenka et al. [62]	2020	*	–	–	*	–	–	–	–	*	–	–	*	*	–
45	**This study**	–	*	–	–	*	*	–	*	*	*	*	*	*	*	*

focuses on environmental elements rather than human perceptions of quality [10]. Quality is used as an indicator in the work of Giri and Masanta, but the method of calculating quality is unclear, and it is only a number between 0 and 1, which is determined as a decision variable on the manufacturer's side, and in the process of distributing this number varies, whereas quality is a function of several factors in the current study [75]. The exponential function, which was utilized in this study, is a typical way for calculating quality. This method has been utilized, for example, in Behzadi et al. (and other works), with the difference that Behzadi has defined a quality limit and assesses quality with a rate of perishability, which is related to the type of product and the amount of time the product is in various phase [20]. Such methods are incompatible with our approach since they do not account for environmental influences. The current study takes a similar strategy to studies like Wang and Li [64]. He's also used quality to model pricing, and he considers quality to be an exponential function. The current study differs from wang's work in that wang evaluates quality as a function of time and deterioration rate. In Wang's work, the deterioration rate is a parameter that is fed into the model, however in this study, quality is a function of temperature and humidity, and these two variables are used as decision variables. This difference allows the model to replicate a wider range of environmental situations. Wang assumes that the customer is aware of quality and that quality degradation reduces the price by a predefined factor when it comes to pricing. Since customer perception of quality is not measurable and varies from person to person, the pricing in our study is only related to the quality of the product and Wang's assumption in the present study is not true. In this study, humidity is taken into account in addition to temperature, which has received less attention in the Literature. The effect of temperature on products is addressed in depth in the article of Hoang et al. [37]. The effect of temperature on product temperature at several phases of distribution (display cabinet, shopping basket, and domestic refrigerator) is explored in his research, and the temporal evolution of product temperature is determined. The microbial growth of products along the supply chain is also explored in relation to this evolution. Such studies consider the different temperatures of the environments in which the product is present as a parameter and their purpose is to predict the condition of the product at the end point. In order to help decision makers to regulate the temperature of fleets and distribution centers, in the present study, temperature is a decision variable, and one of the research questions is how appropriate is the temperature regulation of fleets and distribution centers? In Li et al. research, he used an exponential function to correlate his quality and temperature [52]. For this purpose, a parameter called sensitivity factor of cold chain products has been used. They have not proposed a method for calculating this parameter, and this makes it impossible to use this method for goods with unknown sensitivity factor. One of the goals of Hsiao et al was to find the optimal temperature settings and, like the present study, considered these temperature settings as decision variables [18]. The difference between our research and him is in the formulation of temperature-related costs. Hsiao et al. have used a linear relationship for these costs, assuming only two levels of quality. The total temperature setting cost is calculated by multiplying the sum of the basic and temperature variable costs of one unit of food by the total units of carried foods when refrigerated vehicles transport foods at a certain temperature. While the exponential function has been used for the present study.

3. Problem definition

In this section the developed model will be expressed. Our model is a three-level model that includes the manufacturer, the distribution center and the retailer. This model's major purpose is to optimise the profit from transporting goods from manufacturer to retailer. The amount of product to be carried from which manufacturer to which distribution centre is determined at each step. The temperature and humidity of the carrier vehicle will be maintained to some level, which will be costly. The higher the cost, the closer this temperature is to the ideal product temperature. Our overall costs includes production, transportation and maintenance costs, costs of preservation goods at specified temperatures and humidities (in the vehicle as well as distribution centers), quality degradation costs, shortage costs, costs of cooling equipment, costs of electricity consumed for cooling, and carbon tax. Since the supply chain studied is for cold goods, the goods are in the temperature range of -9 to $+2$ degrees Celsius [77]. In order to maintain temperature throughout the supply chain refrigerators are used in transport fleets and storage centers to maintain a constant temperature using a thermostat. According to Stlingraf et al. the amount of energy used in this process is proportional to the temperature difference between the inside and outside of the equipment [48]. This case is taken into account in the developed model where the ambient temperature parameter is considered.

A price estimation function is used to compute the income. This function shows how much the price of a commodity fluctuates depending on its quality. In the estimation function, the lower the price, the poorer the quality of the goods. Only the effect of quality on price was investigated in this study. Other factors, such as demand or purchasers' perceptions of product quality, undoubtedly influence product pricing, but they were not included in this study. The profit maximisation function is the model's primary goal. This benefit is derived from the income cost differential. This model is applicable for commodities such as carcass meat (+1 to +3 degrees Celsius), steak, chopsticks, stewed meat (+2 to +4 degrees Celsius), fresh seafood (−1 to +2 degrees Celsius), dairy products (+2 to +4 degrees Celsius) [78]. Apart from foodstuff, which will be examined in this research's case study, the issues of the pharmaceutical and vaccine supply chain are another key application of supply chains that consider environmental factors. Given that some medications and vaccines must be stored at low temperatures, models like the one produced in this work can be used to investigate this issue. With the onset of COVID-19 in 2020, this application has become more significant, and Rizou et al. have looked into some of the supply chain difficulties during the pandemic [44].

The problem is planned in several planning periods and for several products. Demand is also considered uncertain in different scenarios. Figure 1 illustrates the overall scheme of the supply chain.

3.1. Assumptions

The following assumptions are included in the model:

- The model has been developed in several planning periods;
- All shortages become lost sales;
- Demand in this model is considered uncertain and subject to different scenarios;
- The quality of each product is assumed to be an exponential function of the temperature deviation and its humidity from the ideal temperature and humidity;
- For each commodity, an ideal price is assumed to be the highest price. Each commodity's price is determined by its quality. The ideal price parameter of the commodity (which is considered as input) incorporates the effect of other price-influencing elements, and such factors are not discussed;
- Sale of all merchandises delivered to the retailer is guaranteed;
- Distribution center capacity is limited and constant.

3.2. Indexes

i	Factories index (production site) $(i = 1, 2, 3, \cdots, I)$
j	Distribution Centers Index $(j = 1, 2, 3, \cdots, J)$
k	Retailers index $(k = 1, 2, 3, \cdots, K)$
p	Products Index $(p = 1, 2, 3, \cdots, P)$
t	Time periods index $(t = 1, 2, 3, \cdots, T)$

3.3. Decision variables

$x_{i,j,p,t}$	The quantity of produced product p sent from factory i to distribution center j at period t
$y_{j,k,p,t}$	The quantity of produced product p sent from distribution center j to retailer k at period t
$z_{i,k,p,t}$	The quantity of produced product p sent from factory i to retailer k at period t
$i_{k,p,t}$	The inventory quantity of retailer k from product p at period t

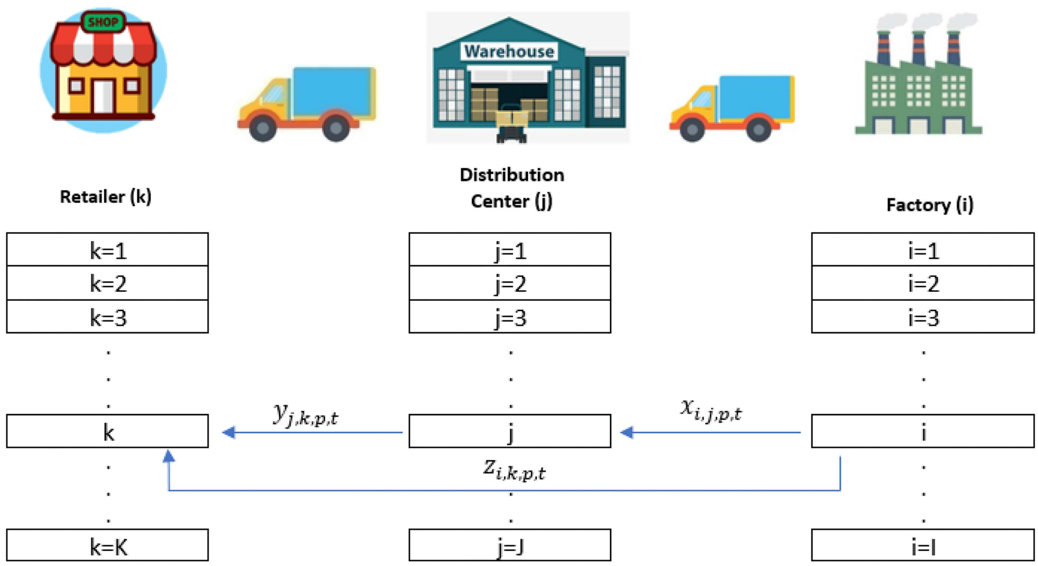

Figure 1. The supply chain of the problem along with the important decision variables.

$l_{k,p,t}$ The shortage quantity of retailer k of product p at period t

$T_{i,j,p,t}$ Temperature of product p sent from factory i to distribution center j in vehicle at period t

$\dot{T}_{j,k,p,t}$ Temperature of product p sent from distribution center j to retailer k in vehicle at period t

$\ddot{T}_{i,k,p,t}$ Temperature of product p sent from factory i to retailer k in vehicle at period t

$M_{i,j,p,t}$ Moisture of product p sent from factory i to distribution center j in vehicle at period t

$\dot{M}_{j,k,p,t}$ Moisture of product p sent from distribution center j to retailer k in vehicle at period t

$\ddot{M}_{i,k,p,t}$ Moisture of product p sent from factory i to retailer k in vehicle at period t

3.4. Parameters

$d_{k,p,t}$ Demand of retailer k for product p at period t

$c_{i,p,t}$ The capacity of the factory i for product p at period t

$c_{B_{k,p,t}}$ The cost of lost sale of each unit of product p of retailer k at period t

$h_{k,p,t}$ The cost of maintaining each unit of product p of retailer k at period t

$v_{j,p,t}$ The capacity of distribution center j for product p at period t

$C_{i,j,p,t}$ The cost of producing and sending each unit of product p from factory i to distribution center j at period t

$\dot{C}_{j,k,p,t}$ The cost of sending each unit of product p from distribution center j to retailer k at period t

$\ddot{C}_{i,k,p,t}$ The cost of producing and sending each unit of product p from factory i to retailer k at period t

$CE_{i,j,p,t}$ The cost of cooling equipment for sending each unit of product p from factory i to distribution center j at period t

$\ddot{C}E_{j,k,p,t}$ The cost of cooling equipment for sending each unit of product p from distribution center j to retailer k at period t

$\ddot{C}E_{i,k,p,t}$ The cost of cooling equipment for sending each unit of product p from factory i to retailer k at period t

$hE_{k,p,t}$ The cost of cooling equipment for maintenance of each unit of product p at retailer k at period t

$CC_{i,j,p,t}$ Carbon tax cost for each unit of product p sent from factory i to distribution center j at period t

$\dot{C}C_{j,k,p,t}$ Carbon tax cost for each unit product p sent from distribution center j to retailer k at period t

$\ddot{C}C_{i,k,p,t}$ Carbon tax cost for each unit product p sent from plant i to retailer k at period t

T_p^* Desired temperature of product p

M_p^* Desired moisture of product p

P_p^* Ideal price of each unit of product p at the best quality

$T_p^{\max}$ Maximum temperature of product p

$T_p^{\min}$ Minimum temperature of product p

$M_p^{\max}$ Maximum moisture of product p

$M_p^{\min}$ Minimum moisture of product p

c_q Penalty cost for the violation of any unit of quality from factory to distribution center

$\dot{c}_q$ Penalty cost for the violation of any unit of quality from distribution center to retailer

$\ddot{c}_q$ Penalty cost for the violation of any unit of quality from factory to retailer

c_t The electricity cost for maintaining each unit of vehicle's temperature from factory to distribution center

$\dot{c}_t$ The electricity cost for maintaining each unit of vehicle's temperature from distribution center to retailer

$\ddot{c}_t$ The electricity cost for maintaining each unit of vehicle's temperature from factory to retailer

c_m The electricity cost for maintaining each unit of vehicle's moisture from factory to distribution center

$\dot{c}_m$ The electricity cost for maintaining each unit of vehicle's moisture from distribution center to retailer

$\ddot{c}_m$ The electricity cost for maintaining each unit of vehicle's moisture from factory to retailer

$T_{ambient}$ Ambient temperature

$M_{ambient}$ Ambient moisture

3.5. Model

The purpose of this model is to maximize the final profit that results from the difference of costs and income. The following sections describe the cost and income components. Profit follows the following equation:

$$\begin{aligned} Profit = & Income - Cost_{total} \\ = & Income - (Cost_{send} + Cost_{backorder} \\ & + Cost_{Equipment} + Cost_{carbontax} \\ & + Cost_{quality} + Cost_{temp} + Cost_{moisure}). \end{aligned} \quad (1)$$

3.6. Transportation and maintenance costs

Production and transportation cost from manufacturer to distribution center ($C_{i,j,p,t}$), transportation cost from distribution center to retailer ($\dot{C}_{j,k,p,t}$) as well as production and direct transportation cost from factory to retailer ($\ddot{C}_{i,k,p,t}$) are considered in this section. Discharged goods at the distribution center are also subject to maintenance cost ($h_{k,p,t}$).

$$\begin{aligned} Cost_{send} = & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{i,j,p,t}.C_{i,j,p,t} \\ & + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} y_{j,k,p,t}.\dot{C}_{j,k,p,t} \\ & + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} z_{i,k,p,t}.\ddot{C}_{i,k,p,t} \\ & + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} i_{k,p,t}.h_{k,p,t}. \end{aligned} \quad (2)$$

3.7. Shortage costs

Unfulfilled requests will be penalized at any period with the cost parameter c_B.

$$Cost_{backorder} = \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} l_{k,p,t}.c_{B\,k,p,t}. \quad (3)$$

3.8. Cost of cooling equipment

The cost of cooling equipment for vehicles and distribution centers is considered. This cost is independent of the temperature and humidity of the products and is only related to the amount of products moved.

$$\begin{aligned} Cost_{Equipment} = & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{i,j,p,t}.CE_{i,j,p,t} \\ & + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} y_{j,k,p,t}.\dot{C}E_{j,k,p,t} \\ & + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} z_{i,k,p,t}.\ddot{C}E_{i,k,p,t} \\ & + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} i_{k,p,t}.hE_{k,p,t}. \end{aligned} \quad (4)$$

3.9. Cost of carbon tax

The cost of vehicle carbon tax is considered as a function of quantity of commodity in transit.

$$\begin{aligned} Cost_{carbontax} = & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{i,j,p,t}.CC_{i,j,p,t} \\ & + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} y_{j,k,p,t}.\dot{C}Cj,k,p,t \\ & + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} z_{i,k,p,t}.\underset{i,k,p,t}{\ddot{C}C}. \end{aligned} \quad (5)$$

3.10. Quality penalty function

In order to formulate quality penalty, in the work of Wang and Li [64] proposed that the temperature dependent quality degradation function be expressed as follows:

$$q(t) = q_0 e^{-\sum_{i=1}^{m} \lambda_i t_i}, \quad (6)$$

where λ is the degradation rate of quality, q_0 is the best quality, and q(t) is the ultimate quality. In Wang's research, the degradation rate of λ is calculated with available data from the reservoir temperature and time and kinetic parameter. Since in our study temperature and humidity are essential properties and must be taken into account, by partial correction to the parameter λ of the Wang formula, the quality penalty function is considered as follows:

$$\lambda = |(T_{i,j,p,t} - T_p^*).(M_{i,j,p,t} - M_p^*)|. \quad (7)$$

As a result, quality will become a function of temperature and humidity:

$$q(T, M) = q_0 e^{-|(T_{i,j,p,t} - T_p^*).(M_{i,j,p,t} - M_p^*)|}. \quad (8)$$

The worse the quality, the greater the differential between the product temperature and the desired temperature. The cost of quality penalty is used to persuade the objective function to lower the temperature difference from the desired temperature. Lower quality comes at a higher price in terms of quality penalties. The expense of maintaining temperature and humidity is at conflict with the cost of quality, and according to the policy, a balance must be achieved between the two. The result of this balance is temperature and humidity that must be established in the product vehicle.

It is suggested that the quality cost parameter (c_q) be estimated using the manufacturer's policies, taking into account customer desirability, referred products and corrupted products.

$$Cost_{quality} =$$

$$c_q \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{i,j,p,t}.e^{|(T_{i,j,p,t}-T_p^*).(M_{i,j,p,t}-M_p^*)|}$$

$$+ \dot{c}_q \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} y_{j,k,p,t}.e^{|(T_{j,k,p,t}-T_p^*).(M_{j,k,p,t}-M_p^*)|}$$

$$+\ddot{c}_q \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} z_{i,k,p,t}.e^{|(T_{i,k,p,t}-T_p^*).(M_{i,k,p,t}-M_p^*)|}. \quad (9)$$

3.11. Cost of electricity

Cost of electricity is divided into two parts. Cost of maintaining temperature at a specific temperature and cost of maintaining moisture at a specific moisture. The cost of electricity is considered a function of temperature and moisture of products.

$$Cost_{temp} = c_t \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{|T_{ambient} - T_{i,j,p,t}|}{T_{ambient}}$$

$$+ \dot{c}_t \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{|T_{ambient} - T_{j,k,p,t}|}{T_{ambient}}$$

$$+ \ddot{c}_t \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{|T_{ambient} - T_{i,k,p,t}|}{T_{ambient}}, \quad (10)$$

$$Cost_{moisure} = c_m \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{|M_{ambient} - M_{i,j,p,t}|}{M_{ambient}}$$

$$+ \dot{c}_m \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{|M_{ambient} - M_{j,k,p,t}|}{M_{ambient}}$$

$$+ \ddot{c}_m \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{|M_{ambient} - M_{i,k,p,t}|}{M_{ambient}}. \quad (11)$$

3.12. Income

It is assumed that all goods would be sold in retailers. Since the ideal price will be in the ideal quality, adjusted price is the price that is actually set for products. This price is equal to the maximum price in a perfect circumstance. The β coefficient is used to adjust the ideal price. β is a factor that has the following characteristics:

1. Must be between zero and one. (If quality is ideal its 1 and otherwise its less than 1;)
2. It should approach one with increasing quality and approach zero with decreasing quality.

The adjusted price is as follows:

$$P_p^c = \beta_p.P_p^*, \quad (12)$$

where P_p^c is the actual price of each unit of product p, P_p^* is the ideal price of each unit of product p, and β_p is price moderating factor.

In our model, inverse of quality penalty function is used as a factor β_p. This function has both of the explained characteristics:

Proof of the first β_p characteristics:

$$0 < \left| \frac{(T_p^* - T_{i,j,p,t})}{T_p^*} . \frac{(M_p^* - M_{i,j,p,t})}{M_p^*} \right|$$

$$\rightarrow e^0 < e^{\left| \frac{(T_p^* - T_{i,j,p,t})}{T_p^*} . \frac{(M_p^* - M_{i,j,p,t})}{M_p^*} \right|}$$

$$\rightarrow 1 < e^{\left| \frac{(T_p^* - T_{i,j,p,t})}{T_p^*} . \frac{(M_p^* - M_{i,j,p,t})}{M_p^*} \right|}$$

$$\rightarrow 0 < \frac{1}{e^{\left| \frac{(T_p^* - T_{i,j,p,t})}{T_p^*} . \frac{(M_p^* - M_{i,j,p,t})}{M_p^*} \right|}} < 1. \quad (13)$$

The quality penalty function also decreases with increasing quality. As a result, with increasing quality the inverse of the quality penalty function approaches 1 (second characteristic of β_p).

In our model goods come in two ways to retailers that the quality of each way can be different. The first route is the route that runs through distribution center and the second route is the one directly from factory. β_p can be different for these two classes. A weighted average is used for β_p to reach a common price for both categories. The final price formula will look like Eq. (14) and (15) are shown in Box I.

3.13. Constraints

1. Inventory balance in successive periods:

$$\sum_{j=1}^{J} y_{j,k,p,t} + \sum_{i=1}^{I} z_{i,k,p,t} + l_{k,p,t}$$

$$= d_{k,p,t} + i_{k,p,t} - i_{k,p,t-1} + l_{k,p,t-1}$$

$$\forall (k,p,t). \quad (16)$$

2. Production capacity:

$$\sum_{j=1}^{J} x_{i,j,p,t} + \sum_{k=1}^{K} z_{i,k,p,t} \leq c_{i,p,t} \qquad \forall (i,p,t). \quad (17)$$

3. Distribution center inventory balance:

$$P_p^c = \left(\frac{y_{j,k,p,t}}{d_{k,p,t}}.\beta_y + \frac{z_{i,k,p,t}}{d_{k,p,t}}.\beta_z\right).P_p^*$$

$$= \left(\frac{\frac{y_{j,k,p,t}}{e^{|(T_p^*-T_{i,j,p,t})/T_p^*.(M_p^*-M_{i,j,p,t})/M_p^*|}} + \frac{z_{i,k,p,t}}{e^{|(T_p^*-T_{i,k,p,t})/T_p^*.(M_{p-}^* M_{i,k,p,t})/M_p^*|}}}{d_{k,p,t}}\right).P_p^*, \tag{14}$$

consequently, the income formula is as follows:

$$\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(\frac{\left(\frac{y_{j,k,p,t}}{e^{|(T_p^*-T_{i,j,p,t})/T_p^*.(M_p^*-M_{i,j,p,t})/M_p^*|}} + \frac{z_{i,k,p,t}}{e^{|(T_p^*-T_{i,k,p,t})/T_p^*.(M_{p-}^* M_{i,k,p,t})/M_p^*|}}\right)}{d_{k,p,t}}.P_p^*.d_{k,p,t}\right). \tag{15}$$

Box I

$$\sum_{i=1}^{I} x_{i,j,p,t} \geq \sum_{k=1}^{K} y_{i,k,p,t} \qquad \forall\,(j,p,t)\,. \tag{18}$$

4. Demand satisfaction:

$$\sum_{j=1}^{J} y_{j,k,p,t} + \sum_{i=1}^{I} z_{i,k,p,t} \geq d_{k,p,t} \qquad \forall(k,p,t)\,. \tag{19}$$

5. Distribution center capacity:

$$\sum_{i=1}^{I} x_{i,j,p,t} \leq v_{j,p,t} \qquad \forall\,(j,p,t)\,. \tag{20}$$

6. Temperature and humidity range:

$$T_p^{\min} \leq T_{i,j,p,t} \leq T_p^{\max}$$

$$T_p^{\min} \leq \dot{T}_{j,k,p,t} \leq T_p^{\max}$$

$$T_p^{\min} \leq \ddot{T}_{i,k,p,t} \leq T_p^{\max}$$

$$M_p^{\min} \leq M_{i,j,p,t} \leq M_p^{\max}$$

$$M_p^{\min} \leq \dot{M}_{j,k,p,t} \leq M_p^{\max}$$

$$M_p^{\min} \leq \ddot{M}_{i,k,p,t} \leq M_p^{\max} \qquad \forall\,(i,j,k,p,t)\,. \tag{21}$$

7. Positive integer decision variables:

$$x_{i,j,p,t} \geq 0, int$$

$$y_{j,k,p,t} \geq 0, int$$

$$z_{i,k,p,t} \geq 0, int$$

$$i_{k,p,t} \geq 0, int$$

$$l_{k,p,t} \geq 0, int \qquad \forall\,(i,j,k,p,t)\,. \tag{22}$$

4. Method of solving and numerical tests

In this section, the results of a numerical example are presented and solved using GAMS software and BARON solver. Baron is a branch-bound method. The Baron's global optimization approach combines traditional branch-and-bound with a number of range reduction tests. To limit the search space and reduce the relaxation gap, these tests are applied to each subproblem of the search tree in pre- and post-processing steps [79]. The temperature and humidity of the transported goods (shown in Table 2) are extracted from cargo handbook [78] and prices are also obtained from walmart. The sample consists of two factories, two distribution centers and three retailers (Indexes are shown in Table 3). Three products have been considered and there are four periods planned and there are also three scenarios for demand (shown in Table 4). The computational platform is a desktop computer that runs on Windows 10 with an Intel Core i5-4200

Table 2. The temperature and humidity of products.

Cargo handbook name	Walmart name	Temperature (F)	Humidity (%)	Price ($/oz)
Well vacuumed chilled beef	Beef chuck roast	30.2	80	0.28
Mushrooms	Fresh white mushrooms	32	95	0.23
Butter	Great value sweet cream salted butter sticks	33.8	75	0.19

Table 3. The dimensions of the numerical example.

Indexes	Factory index (i)	Distribution center index (j)	Retailers index (k)	Product index (p)	Time horizon index (t)
Value	{1, 2}	{1, 2}	{1, 2, 3}	{1, 2, 3}	{1, 2, 3, 4}

Table 4. Data for three scenarios for the demand.

Scenario 1	Scenario 2	Scenario 3
d (1,1,1)=35	d (1,1,1)=55	d (1,1,1)=76
d (1,1,2)=37	d (1,1,2)=60	d (1,1,2)=74
d (1,1,3)=37	d (1,1,3)=52	d (1,1,3)=71
d (1,1,4)=33	d (1,1,4)=54	d (1,1,4)=75
d (1,2,1)=36	d (1,2,1)=50	d (1,2,1)=76
d (1,2,2)=38	d (1,2,2)=52	d (1,2,2)=75
d (1,2,3)=37	d (1,2,3)=55	d (1,2,3)=73
d (1,2,4)=38	d (1,2,4)=58	d (1,2,4)=70
d (1,3,1)=35	d (1,3,1)=58	d (1,3,1)=76
d (1,3,2)=34	d (1,3,2)=59	d (1,3,2)=78
d (1,3,3)=32	d (1,3,3)=51	d (1,3,3)=70
d (1,3,4)=33	d (1,3,4)=55	d (1,3,4)=71
d (2,1,1)=32	d (2,1,1)=58	d (2,1,1)=78
d (2,1,2)=32	d (2,1,2)=55	d (2,1,2)=77
d (2,1,3)=36	d (2,1,3)=52	d (2,1,3)=79
d (2,1,4)=33	d (2,1,4)=56	d (2,1,4)=80
d (2,2,1)=30	d (2,2,1)=60	d (2,2,1)=70
d (2,2,2)=35	d (2,2,2)=50	d (2,2,2)=70
d (2,2,3)=31	d (2,2,3)=51	d (2,2,3)=80
d (2,2,4)=40	d (2,2,4)=55	d (2,2,4)=75
d (2,3,1)=36	d (2,3,1)=53	d (2,3,1)=71
d (2,3,2)=35	d (2,3,2)=59	d (2,3,2)=73
d (2,3,3)=30	d (2,3,3)=53	d (2,3,3)=74
d (2,3,4)=31	d (2,3,4)=56	d (2,3,4)=74
d (3,1,1)=37	d (3,1,1)=51	d (3,1,1)=77
d (3,1,2)=30	d (3,1,2)=50	d (3,1,2)=70
d (3,1,3)=40	d (3,1,3)=60	d (3,1,3)=75
d (3,1,4)=37	d (3,1,4)=56	d (3,1,4)=77
d (3,2,1)=30	d (3,2,1)=53	d (3,2,1)=71
d (3,2,2)=30	d (3,2,2)=59	d (3,2,2)=72
d (3,2,3)=32	d (3,2,3)=59	d (3,2,3)=80
d (3,2,4)=39	d (3,2,4)=51	d (3,2,4)=74
d (3,3,1)=35	d (3,3,1)=51	d (3,3,1)=76
d (3,3,2)=37	d (3,3,2)=59	d (3,3,2)=70
d (3,3,3)=36	d (3,3,3)=53	d (3,3,3)=76
d (3,3,4)=30	d (3,3,4)=60	d (3,3,4)=70

Table 5. The values for parameters of the numerical example.

Parameters		Value
$c_{i,p,t}$		300
$c_{B_{k,p,t}}$		14
$h_{k,p,t}$		2
$v_{j,p,t}$		250
$C_{i,j,p,t}$		5
$\dot{C}_{j,k,p,t}$		5
$\ddot{C}_{i,k,p,t}$		13
$CE_{i,j,p,t}$		5
$\dot{C}E_{j,k,p,t}$		5
$\ddot{C}E_{i,k,p,t}$		13
$hE_{k,p,t}$		2
$CC_{i,j,p,t}$		5
$\dot{C}C_{j,k,p,t}$		5
$\ddot{C}C_{i,k,p,t}$		13
T_p^*	T_1^*	30.2
	T_2^*	32
	T_3^*	33.8
M_p^*	M_1^*	0.8
	M_2^*	0.95
	M_3^*	0.75
c_q		2
$\dot{c}_q$		2
$\ddot{c}_q$		2
c_t		2
$\dot{c}_t$		2
$\ddot{c}_t$		2
c_m		2
$\dot{c}_m$		2
$\ddot{c}_m$		2
P_p^*	P_1^*	0.28
	P_2^*	0.23
	P_3^*	0.19

CPU running at 2.5 GHz and 8 GB of RAM. The values of parameters are shown in Table 5.

GAMS software and BARON solver have been used to solve this model. For three scenarios, the optimal response was not achieved and good solutions are reported. The results of each of these three scenarios are shown in Table 6.

4.1. Sensitivity analysis of temperature parameter

Due to the importance of temperature in the cold supply chain model, in this section, in order to analyze the sensitivity of the problem and the reaction of the model to the desired temperature parameter (T_p^*), the effect of this parameter on the objective function is investigated

Table 6. The value of profit in terms of each scenario.

	Profit	Probability
Scenario 1	239962.08	%30
Scenario 2	328584.32	%40
Scenario 3	414054.44	%30
Total	327638.69	–

at five points (shown in Table 7). The changes are reported based on the third point (midpoint). Detailed results of sensitivity analysis are shown in Table 8 and Figure 2 shows the results of sensitivity analysis of temperature parameter in each scenario. the trend of profit change is shown in Figure 3 (percentage of profit change) and Figure 4 (value of profit change).

Based on numerical experiments, it can be inferred that increasing the desired temperature reduces the overall profit in this case study. To further understand the situation, it may be said that if this setup is utilized to transport commodities that are warmer in temperature, the organization will lose profit. At first glance, this conclusion may appear to be incorrect. Because moving and maintaining

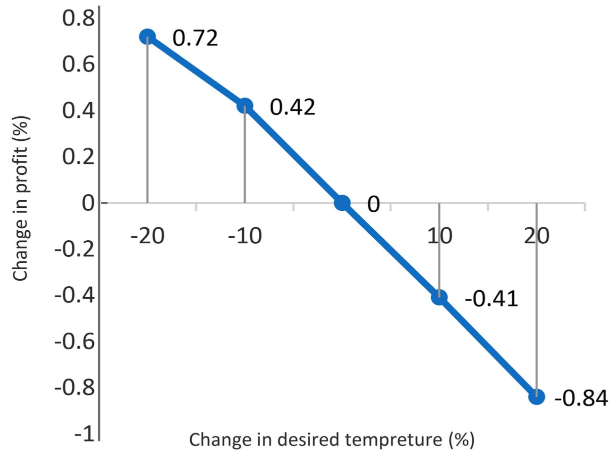

Figure 3. Percentage of profit change.

Table 7. Sensitivity analysis of temperature parameter.

	1	2	3	4	5
T_1^* (F)	30.2	27.18	24.16	21.14	18.12
T_2^* (F)	32	28.8	25.6	22.4	19.2
T_3^* (F)	33.8	30.42	27.04	23.66	20.28
Temperature change (F)	+6.04	+3.02	0	–3.02	–6.04
Temperature change (%)	+20	+10	0	–10	–20
Profit ($)	327638.69	326647.80	325284.70	323926.05	322541.60
Profit change ($)	–2743.10	–1358.65	0	1363.10	2353.99
Profit change (%)	–0.84	–0.41	0	0.42	0.72

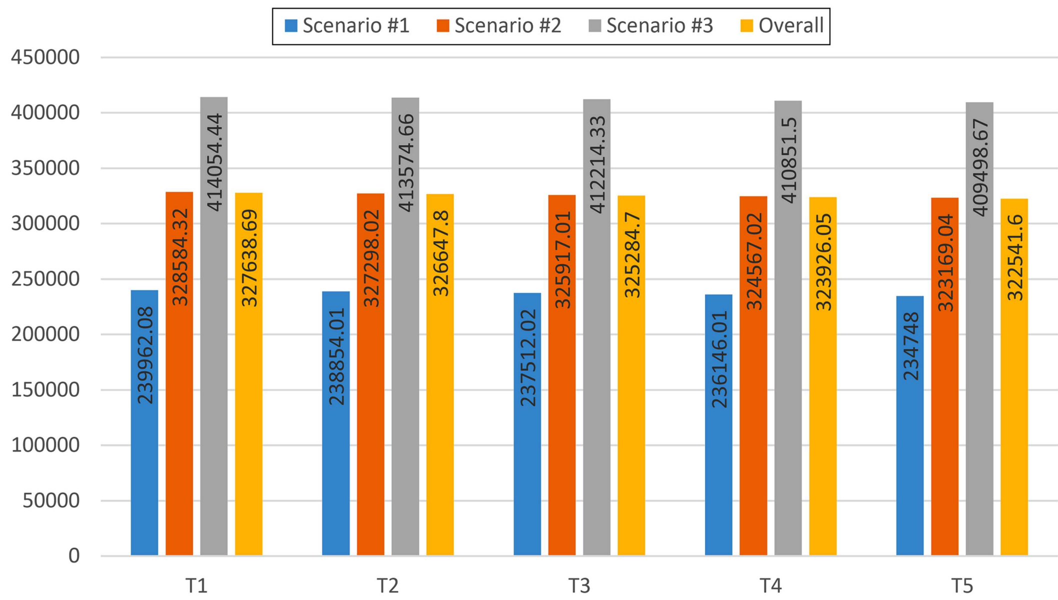

Figure 2. Results of sensitivity analysis of temperature parameter.

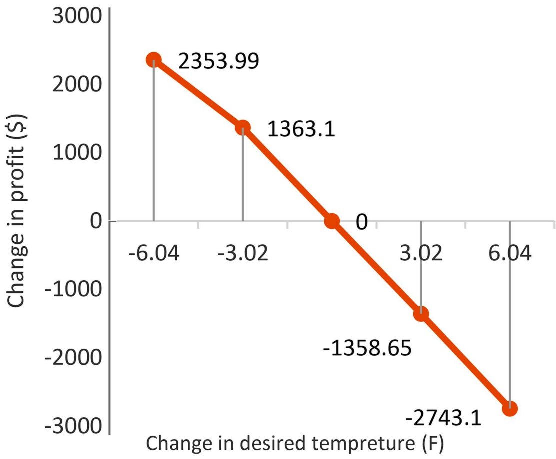

Figure 4. Value of profit change.

cooler items is more expensive, this increased cost should result in lower profitability. A more thorough investigation reveals two factors that make this system more profitable for supplying colder items. To begin with, income is influenced by environmental factors in addition to expenditures. In fact, it is the difference between the temperature during transit and storage with the desired temperature and the ambient temperature that alters costs and revenues, not the high or low temperature. The cost of cooling equipment (Subsection 3.8), which affects expenses and profits, is the next item to consider. It seems reasonable that using cooling equipment to offer warmer items is ineffective, and this has resulted in lower revenues in this approach. It may also be concluded from the numerical data that, in this scenario, increasing demand increases profitability. This finding is based on a comparison of many circumstances (Figure 2). The average demand in the first scenario is lower than the second, and the second scenario is lower than the third, and the quantity of demand in these three situations is generally increasing. Given the assumption that all goods that reach retailers are sold, this makes reasonable (Subsection 3.1 discusses this assumption).

Regarding the range of changes in temperature and humidity variables, it should be noted that the maximum and minimum temperature and humidity parameters are introduced in Subsection 3.3, and the parameter's constraints are specified in Subsection 3.13 and Eq. (21). In addition, the temperature range for cold commodities is indicated in Section 3. Maximum and minimum numbers mean that decision makers do not allow goods above and below these limits. In other words, the product is only acceptable in this range of environmental conditions (in different quality ranges). Because the experimental conditions are dominant in numerical experiments, the goal is to give the variables as much range of variation as possible so that we can analyze how the model operates. In this situation environmental variables are attempting to get closer to the ambient parameter on the one hand (since it consumes less energy) and to the desired temperature and humidity on the other hand (because the quality is higher and as a consequence, revenue will rise, while quality penalties will fall). As a result, to attain the equilibrium point, the variables oscillate between the ambient parameter and the desired parameter. According to the formulas described in Subsections 3.10–3.12 of the model, It is not possible to select environmental variables in the range beyond the range of the ambient parameter and the desired parameter as the answer.

4.2. Managerial insight

In cold supply chains, neglecting to evaluate the relationship between quality and cost might result in irreversible management decisions. The reason for this is that if only costs are included in the model and quality is not considered, the model will shift the variables as much as possible toward lower costs, and lower costs will invariably lead to lower quality. As described in earlier sections, lower quality has an impact on revenue, and as a result, the variables begin to move in an unfavorable direction. If quality is modelled without costs, on the other hand, the variables will tend to increase revenue regardless of costs, resulting in high costs and low profitability. In face of challenges such as product quality being very sensitive and variable, and environmental circumstances having a significant impact on costs and revenues, a model that incorporates this quality-cost balance should be designed in order to achieve the reliable results and as a consequence, decisions would not be based on invalid results.

According to the numerical results obtained from this particular case, it is clear that the profits of moving goods that require less temperature to move are less. This is also reasonable, as it is more costly to transport cold goods and require cooling equipment, more electricity, and more carbon tax. Given that the analysis shows that commodities have the same prices and that only the desired temperature has changed, it can be said that the income does not change much and as our costs increase, the resulting profit will be lower. This is well illustrated in Figures 3 and 4.

According to the proposed model, the following can be concentrated on to increase the profitability of cold goods transportation in conditions similar to this model:

- Reducing costs of cooling equipment with using high efficiency and low energy consumption equipment (Reduction of parameters $CE_{i,j,p,t}$);
- Reducing costs of consuming electricity by using higher efficiency equipment and consuming less en-

Table 8. Parameters.

Parameters		**Value**				
		T_1	T_2	T_3	T_4	T_5
$c_{i,p,t}$		300	300	300	300	300
$c_{B_{k,p,t}}$		14	14	14	14	14
$h_{k,p,t}$		2	2	2	2	2
$v_{j,p,t}$		250	250	250	250	250
$C_{i,j,p,t}$		5	5	5	5	5
$\dot{C}_{j,k,p,t}$		5	5	5	5	5
$\ddot{C}_{i,k,p,t}$		13	13	13	13	13
$CE_{i,j,p,t}$		5	5	5	5	5
$\dot{C}E_{j,k,p,t}$		5	5	5	5	5
$\ddot{C}E_{i,k,p,t}$		13	13	13	13	13
$hE_{k,p,t}$		2	2	2	2	2
$CC_{i,j,p,t}$		5	5	5	5	5
$\dot{C}C_{j,k,p,t}$		5	5	5	5	5
$\ddot{C}C_{i,k,p,t}$		13	13	13	13	13
T_p^*	T_1^*	20.28	23.66	27.04	30.42	33.8
	T_2^*	19.2	22.4	25.6	28.8	32
	T_3^*	18.12	21.14	24.16	27.18	30.2
M_p^*	M_1^*	0.8	0.8	0.8	0.8	0.8
	M_2^*	0.95	0.95	0.95	0.95	0.95
	M_3^*	0.75	0.75	0.75	0.75	0.75
c_q		2	2	2	2	2
$\dot{c}_q$		2	2	2	2	2
$\ddot{c}_q$		2	2	2	2	2
c_t		2	2	2	2	2
$\dot{c}_t$		2	2	2	2	2
$\ddot{c}_t$		2	2	2	2	2
c_m		2	2	2	2	2
$\dot{c}_m$		2	2	2	2	2
$\ddot{c}_m$		2	2	2	2	2
P_p^*	P_1^*	0.28	0.28	0.28	0.28	0.28
	P_2^*	0.23	0.23	0.23	0.23	0.23
	P_3^*	0.19	0.19	0.19	0.19	0.19
Profit (Scenario 1)		239962.08	238854.01	237512.02	236146.01	234748.00
Profit (Scenario 2)		328584.32	327298.02	325917.01	324567.02	323169.04
Profit (Scenario 3)		414054.44	413574.66	412214.33	410851.50	409498.67
Profit (Total)		**327638.69**	**326647.80**	**325284.70**	**323926.05**	**322541.60**

ergy and using new methods for lower energy cooling (Reduction of parameters c_t);

- Reducing quality penalties by reducing c_q by increasing customer satisfaction;
- Reducing carbon tax, which is legislative powers (Reduction of parameters $CC_{i,j,p,t}$).

5. Conclusion

A supply chain model for cold commodities is presented in this paper. This three-tier model, which includes manufacturer, distribution centre, and retailer, has been developed over periods of time and for a variety of products. The exponential function of quality assessment is used in this model. This function assesses the quality of products based on their temperature and humidity. The final price of a product is also determined by its quality assessment. This model takes into account product demand uncertainty. To this goal, demand is supposed to be separated into three possible scenarios, each with a variable chance of occurrence. The objective function of this model is to maximise the overall profit generated by the gap between cost and revenue. The overall cost of transportation, shortages, electricity usage, carbon tax, quality degradation, and cooling equipment are all discussed in this study. The price, which is a function of the product's quality, is used to compute income. The better the product's quality, the closer it comes to the maximum price.

The lack of substantial literature in the topic of quality formulation was one of the study's limitations. Another limitation of the study is that the modelling was limited to cold commodities, which has resulted in two issues. To begin with, the paradigm is unsuitable for use in the realm of ordinary products. Second, this is a general model that can be more detailed if we want to work on specific goods. For example, if we construct the model specifically for ice cream, it will be able to assess the intricacies of the ice cream supply chain. In this scenario, we're dealing with a variety of raw materials, including vanilla and milk powder, which don't require a specific storage temperature, and milk, which must be stored at a higher temperature than cream. In a specific ice cream model, all of these phases can be explored. Taking into account two environmental parameters has also limited the model to the effects of temperature and humidity, making it useful only to commodities that are susceptible to these conditions.

A simple numerical example of this nonlinear model was developed using GAMS software and solved using BARON solver and the solutions are discussed. Sensitivity analysis was carried out on desired temperature of each product. For this purpose, increasing and decreasing this parameter and its effect on the objective function are investigated.

Multi-objective modelling should be employed in future investigations, and this model should be supplemented with other uncertainty strategies such as the fuzzy approach. It's a good idea to try out a few different optimization strategies and compare them. Also, because there is a void in the literature on quality evaluation, it is advised that the factors impacting quality be investigated in diverse environmental circumstances and for commodities other than cold goods. Other topics that might be researched include the construction of a closed loop model that takes into account environmental conditions and quality, as well as the recycling of commodities and the expansion of the model based on sustainable development concepts. Only the uncertain demand parameters are examined in this study. It is suggested that other influential parameters in the model be considered uncertain. Given how important environmental circumstances are in the model, developing a model that can handle environmental conditions in different seasons and across different geographies has a lot of promise. Finally, investigating the influence of various emissions regulations on cold supply chain operational decisions could be a future research topic.

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