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UTILIZING ENERGY TRANSITION TO DRIVE SUSTAINABILITY IN COLD SUPPLY CHAINS: A CASE STUDY IN THE FROZEN FOOD INDUSTRY

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Abstract. In alignment with the ever-growing interest in adopting sustainable practices, this paper devises a cold supply chain (CSC) planning model that integrates the three pillars of sustainability into the decision-making process while accounting for the shift towards clean energy sources. Interrelated decisions pertaining to production-distribution strategy, backorder and inventory levels, choice of truck type, and selection of third-party logistics (3PLs) providers are jointly optimized. For global CSCs in specific, such decisions are particularly sensitive to the energy sources of the refrigerated facilities and the accompanying levels of CO_2 emissions generated. As such, a multi-objective mixed-integer non-linear programming (MINLP) model is developed and then solved *via* the weighted-sum method. In essence, the model seeks to operationalize sustainability goals by considering the rapidly evolving transition in energy sources across different regions when deciding on which 3PLs to engage in a contractual agreement with while adjusting the production and distribution strategy accordingly. The practical relevance of the model is illustrated using a case study drawn from the North American frozen food industry. The conducted trade-off analysis indicates the possibility of obtaining a drastic improvement of 86% in jobs' stability levels (social measure) with a maximum cost increase of around 9% as compared to the economic measure. Furthermore, the analysis reveals that it is possible to reduce 71% of CO_2 emissions while attaining 63% reduction in worker variations at the expense of only 4.47% cost increase once compared to solely optimizing the economic objective.

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1. Introduction

1.1. Background

Sustainable supply chain management has steadily become a growing concern for numerous industries and companies of all sizes [19]. The notion of sustainability calls for the adoption of an integrated (system) approach and close collaboration between supply chain partners to address the challenges related to its three pillars (economic, environmental, and social), which directly impact supply chain operations [1, 22]. For the food industry in particular, the operationalization of sustainability targets as an integral part of an organization's

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strategy and the reduction of environmental and social problems are still far from reality [36, 45, 66]. This is partly attributed to the fact that this sector is highly energy-intensive and is held accountable for excessive greenhouse gas emissions (GHGs). Indeed, a wide spectrum of food products needs to be retained at controllable temperatures to prevent product deterioration and prolong shelf life. The Food and Agriculture Organization (FAO) reported that energy consumption in the food sector, in general, accounts for 30% of total world energy consumption [33]. Moreover, it shall be noted that 15% of the world's energy generated from fossil fuels is used in food transport refrigeration where vehicles used for food transport also account for 40% of the global greenhouse effect [3]. James and James [32] pointed out that cold chain logistics, in specific, is responsible for almost 1% of the world's GHG emissions. Moreover, the United Nations' FAO estimated that food waste-related carbon emissions amount to 3.3 gigatons of carbon dioxide, representing approximately 7% of the global emissions.

For a wide range of temperature-sensitive (cold) products, such as fruits, vegetables, frozen food, dairy products and ice cream, the demand profile exhibits a highly seasonal pattern, which renders the production and distribution planning of such products a daunting task. Zhang *et al.* [65] noted that one of the main reasons behind the shortage of 3PL warehousing for cold chains is the low utilization rate per year due to such products' seasonality. From a social perspective, some companies match their production throughput with variation in the demand *via* hiring and firing workers (*e.g.*, see [55] for the case of a Brazilian ice cream manufacturer). However, upon following this plan, the company offers to hire temporary workers without any job stability guarantee. Flexibility in employment contracts typically leaves workers with little hope for job security since workers dealing with the risk of job loss are in a more vulnerable position, especially in countries with lessened social security benefits. Bardasi and Fansesconi [13] reported low job satisfaction and ill mental health among seasonal/temporary workers. Zeytinoglu *et al.* [64] also indicated that job insecurity contributes significantly to stress, high turnover, and workplace conflicts. This social aspect, coupled with the elevated levels of energy consumption and CO_2 emissions, exemplifies the cold chain's significance and the tremendous socio-economic and environmental benefits that exist upon optimizing the logistical operations governing the movement and storage of such products along every step across supply chain.

The fast-paced transition towards clean energy sources taking place in many countries to align with the Paris Agreement's goals emphasizes the importance of "*coordinated effort between policy, technology development, and behavior from all society sections to drive change*" [62]. Indeed, energy transition represents every policy's main objective aimed at decarbonization and can be achieved by deploying clean energy technologies [41]. Therefore, adopting proper strategies that enable food companies to satisfy customers' demand while adhering to sustainability measures and accounting for such shift in the energy generation paradigm has become an inevitable necessity. Furthermore, diverse operational and technological constraints along with different conflicting objectives render this problem more challenging and bring out the need for a more sophisticated decision-making approach that better captures the reality of food production and distribution planning.

1.2. Research gaps

Given its paramount importance, several research works have incorporated sustainability aspects into strategic supply chain planning. As can be seen in Tables 1 and 2, most of the papers integrating sustainability considerations into food supply chains (FSCs) in specific emphasize the strategic issues of network design and facility location, with some also tackling the material flow and lot sizing strategy (*e.g.*, [30, 46, 59]). Yet, there is still a lack of understanding as to how sustainable supply chain decisions must be set at the tactical and operational phases. For instance, the outsourcing of transportation activities through selected 3PL service providers as well as the determination of the workforce size to retain per period, and accordingly the production throughput, are two tactical decisions that influence the sustainable performance of supply chains (see [48] for the former). From the social standpoint, most of the previous works addressing multi-stage sustainable supply chains have either overlooked the social aspect (*e.g.*, [47]) or utilized social attributes (performance indicators) related to strategic decision-making. As such, they are not necessarily relevant for the tactical and operational planning of sustainable FSC.

Another issue that further complicates the problem is the globalization of supply chains. Different environmental regulations are implemented in many countries, accelerating the global energy transition, which might significantly impact supply chain operations. Indeed, in many real-life situations, facilities are located in different and possibly distant areas where various energy sources are used. As such, supply chain managers must explicitly consider such diversity in energy sources, especially for energy-intensive facilities characterizing CSCs. From a carbon emissions perspective, the vast majority of the existing research addressing sustainable supply chain planning assumes carbon emission factors are constant parameters across different regions, which is not necessarily the case in global supply chains. It is important to point out that data aggregation related to environmental (greenhouse gases) and social supply chain network activities in the model development phase are essential in generating the final decisions. Different studies assume that the GHG emissions factor might depend on the facility, the technology, and the product managed in this facility (*e.g.*, [42,44,45]). Nevertheless, in practice, the GHG factors depend highly on the type of energies constituting each location's mix of energy sources, which shall be explicitly accounted for when managing global CSCs logistical operations.

Besides considering a mix of energy sources across various geographic zones and associating carbon emissions for each source, the dynamic multi-period treatment of FSC planning adds another dimension of complexity and better resembles the reality of such an industry. This approach captures the time-varying profile of the demand and allows for periodic adjustments to the production levels by changing the workforce's size. Furthermore, it enables supply chain managers to continuously revise their distribution plans and decide on establishing contracts with 3PLs that are shifting towards greener energy sources. It shall be noted that there exist many recent research works that have accounted for both energy and carbon emissions considerations in the context of multi-echelon sustainable supply chains (*e.g.*, [37,51]). However, besides overlooking the possible shift in energy paradigm over time, these works address the case of a continuous and an infinite planning horizon, where the former assumes a constant demand while the latter assumes a demand that is a function of selling price and credit period.

1.3. Research questions

To address the aforementioned gaps, this research adopts the mathematical modeling approach to operationalize the role of sustainability in driving collaboration among global supply chain partners in the frozen food industry whilst accounting for the effect of the unprecedented transition toward clean energy across different regions. In particular, it tackles the global production-distribution-inventory planning problem for the frozen food industry. A real-life case study is also provided to illustrate the practical relevance of the problem. The selection of third-party logistic providers (3PLs) and the accompanying warehousing facilities to manage transportation and inventory operations is also optimized while considering the existence of varying energy sources with varying emissions factors across the different geographic zones. The aim is to achieve an economically viable solution that also strikes an acceptable balance between environmental and social dimensions. Formally stated, the main research questions tackled in this study are:

- How to address the planning of global CSCs at the tactical level while adjusting in a timely manner for the emerging shift toward clean energy sources across different regions?
- What are the implications of incorporating vital sustainability dimensions on CSC operations in the presence of a discrete time-varying demand profile of multiple products?
- What is the most effective strategy to produce, store and distribute frozen food items while addressing all sustainability pillars at once *vs.* considering one aspect at a time?
- What are the limitations of non-coordinated transboundary sustainability policies?

The remainder of the article is structured as follows. Section 2 reviews the state-of-the-art literature pertaining to food logistics and sustainable supply chains. Section 3 presents the problem description along with the assumptions and notations. Section 4 introduces the multi-objective optimization (MOO) model for sustainable FSC planning, whereas Section 5 details the industrial case example. Section 6 presents the experimentation and analysis of the results and a solution method for the MOO model. This is followed by a detailed discussion of managerial insights in Section 7. Concluding remarks and future research avenues are highlighted in Section 8.

2. Relevant literature

Based on timeframe and criticality, supply chain-related decisions can be categorized into strategic, tactical, and operational levels [5, 17]. The area of Sustainable FSC recently attracted the attention of many researchers. In reality, several criteria and metrics for performance evaluation shall be jointly considered, adding other dimensions of complexity from the modeling perspective and the solution approach [23, 35]. For interested readers, thorough reviews highlighting the most recent advances in the sustainable FSC literature are provided by Zhu *et al.* [66] and Kumar *et al.* [34]. This section focuses on the recent literature dealing with mathematical models for sustainable FSC while considering economic, environmental and/or social objectives. Table 1 provides a categorization of the relevant studies based on several dimensions, including the planning scope, the sustainability dimensions considered, the model type, and the solution approach adopted, among others. The application area is vast and ranges from perishable food in general to more specific products such as fruits and vegetables, dairy industry, frozen food, and vaccines. As seen in the table, while most papers only included economic and environmental aspects, very few papers integrated sustainability's social dimensions. Moreover, Table 2 provides a more elaborate classification highlighting the supply chain attributes considered, the major decisions involved, and the distinguishing model peculiarities for each work. The summary presented in Tables 1 and 2 better helps position the work at hand and highlight its novelty.

Table 1. A classification of model-oriented literature on sustainable food supply chain planning.

Publication	Planning scope			Sustainability dimension			Metrics for assessment of environmental impact		Model type	Solution approach	Application area
	S	T	O	Eco	Env	Soc	GHG	Energy use			
Akkerman *et al.* [6]		✓	✓	✓	✓		✓		MILP	Unspecified	Prepared meals
van der Vorst *et al.* [59]			✓	✓	✓		✓	✓	Simulation	ALADIN	Pineapple
Sutopo *et al.* [54]		✓		✓		✓			MILP	CPLEX	Vegetables
Validi *et al.* [57]	✓			✓	✓		✓	✓	TOPSIS	MOGA	Milk
Costa *et al.* [25]		✓		✓	✓				LP	Column generation	Perishable items
Govindan *et al.* [30]	✓	✓		✓	✓		✓		MILP	MOPSO + AMOVNS	Perishable foods
Validi *et al.* [58]		✓		✓	✓		✓		AHP + MIP	MOGA-II + DoE	Dairy Industry
Chaabane and Geramianfar [21]		✓		✓	✓		✓		MILP	ϵ-Constraint	Frozen food
Azadnia *et al.* [9]	✓	✓		✓	✓	✓	✓		AHP- MILP	ϵ-Constraint-weighted sum	Packaging films
Soysal *et al.* [52]			✓	✓	✓		✓	✓	MILP	CPLEX	Tomatoes
Bortolini *et al.* [15]		✓		✓	✓		✓		MILP	Multi-objective optimization	Perishable food
Daghigh *et al.* [26]		✓	✓	✓	✓	✓	✓		MILP	Augmented ϵ-Constraint	Perishable items
Saif and Elhedhli [46]	✓	✓		✓	✓		✓	✓	MILP-Simulation	Lagrangian decomposition	Perishables items
Bozorgi [16]		✓	✓	✓	✓		✓	✓	MILP	Heuristic	Cold items
Colicchia *et al.* [24]	✓	✓		✓	✓		✓		LP	Weighted sum method	Chocolate
Accorsi *et al.* [2]	✓			✓	✓		✓	✓	LP	Gurobi	Potatoes
Varsei and Polyakovskiy [60]	✓	✓		✓	✓	✓	✓		MILP	Augmented ϵ-Constraint	Wine industry
Banasik *et al.* [11]			✓	✓	✓		✓	✓	MILP	ϵ-Constraint	Bread
Banasik *et al.* [12]	✓	✓		✓	✓		✓		MILP	ϵ-Constraint	Mushrooms
Gallo *et al.* [28]		✓	✓	✓	✓		✓	✓	MILP	AMPL, Gurobi	Perishable food
Hariga *et al.* [31]		✓	✓	✓	✓		✓		Mathematical model	Search procedure algorithm	Perishable items
Musavi and Bozorgi-Amiri [40]		✓	✓	✓	✓		✓		MILP	Genetic algorithms	Perishable food
Mogale *et al.* [39]		✓	✓	✓	✓		✓		MILP	Multi-objective algorithms	Food grains
Babagolzadeh *et al.* [10]		✓	✓	✓	✓		✓	✓	Stochastic model	Iterative local search algorithm	Perishable items
Yadav *et al.* [63]	✓			✓	✓	✓			MILP	ϵ-Constraint	Tomato
Current study		✓		✓	✓	✓	✓	✓	Multi-objective MINLP	Weighted Sum Method	Frozen food

Notes. S: Strategic; T: Tactical; O: Operational; Eco: Economic; Env: Environmental; Soc: Social; MOPSO: Multi-objective particle swarm optimization; AMOVNS: Adapted multi-objective variable neighborhood search; MOGA: Multi-objective genetic algorithm; ALADIN: Agro-Logistic Analysis and Design Instrument; TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution.

TABLE 2. Summary of food supply chain planning models' attributes and peculiarities.

Publication	Supply chain attributes				Decisions scope (FSC processes)							Model peculiarities
	No. of echelons	Multi-product	Multi-period	Heterogeneous transport system	Demand	Sourcing	Production	Distribution	Transport	Inventory	Backorder	
Akkerman *et al.* [6]	2		✓		D		✓	✓	✓			Packaging type, delivery structure
van der Vorst *et al.* [59]	4		✓	✓	D	✓	✓	✓	✓	✓		Product quality
Sutopo *et al.* [54]	2	✓	✓		D	✓	✓					Training skills; product quality
Validi *et al.* [57]	2	✓		✓	D	✓	✓	✓	✓			Sustainable transportation routes
Costa *et al.* [25]	1	✓	✓		S	✓				✓	✓	Crop rotation schedule (ecological based-production constraint)
Govindan *et al.* [30]	2		✓	✓	D		✓	✓	✓	✓		Technology investment
Validi *et al.* [58]	2			✓	D		✓	✓	✓			Distribution routes selection
Chaabane and Geramianfar [21]	2	✓	✓	✓	D		✓	✓	✓	✓	✓	Service level consideration
Azadnia *et al.* [9]	1	✓	✓		D	✓			✓	✓		Supplier selection; lot sizing
Soysal *et al.* [52]	1		✓	✓	S			✓	✓			Limited product shelf life (perishables); fuel consumption
Bortolini *et al.* [15]	3	✓	✓	✓	D		✓	✓	✓	✓		Delivery time; perishable products
Daghigh *et al.* [26]	3	✓	✓	✓	S		✓	✓	✓	✓	✓	Cross dock selection
Saif and Elhedhli [46]	2	✓		✓	S		✓	✓	✓	✓	✓	Shipping lot sizes; effect of refrigerant gas leakage
Bozorgi [16]	2	✓			D		✓	✓	✓	✓		Compatibility of products for storage/transportation
Colicchia *et al.* [24]	2			✓	D			✓	✓	✓		Network design for transportation/warehouses
Accorsi *et al.* [2]	2				D	✓	✓	✓				Land-use allocation
Varsei and Polyakovskiy [60]	4	✓		✓	D	✓	✓	✓	✓	✓		Social impact for selecting a supply chain member
Banasik *et al.* [11]	2	✓	✓		D	✓	✓		✓	✓		Production planning
Banasik *et al.* [12]	2	✓	✓		D	✓	✓		✓	✓		Waste processing; recycling
Gallo *et al.* [28]	3	✓	✓	✓	D	✓	✓	✓	✓			Product quality level; packaging; waste
Hariga *et al.* [31]	2				D			✓	✓	✓		Lot sizing; number of trucks; number of freezers
Musavi and Bozorgi-Amiri [40]	1				D			✓	✓			Vehicles sequence for goods distribution; product quality
Mogale *et al.* [39]	2			✓	D	✓		✓	✓	✓		Network of procurement centers, warehouses, shops; product flows
Babagolzadeh *et al.* [10]	1		✓	✓	S			✓	✓	✓		Replenishment policy; transportation schedules
Yadav *et al.* [63]	2			✓	D		✓	✓	✓	✓		Multi-channel distribution, customer preference, farming laws
Current study	2	✓	✓	✓	D		✓	✓	✓	✓	✓	Number of workers; production rate; energy mix

Notes. Deterministic (D); Stochastic (S).

Few authors integrated lot-sizing and replenishment policies with product distribution planning. Akkerman *et al.* [6] developed a mixed-integer linear programming (MILP) formulation to support production and distribution planning for prepared meals. Their formulation allows evaluating the supply chain performance and the trade-off between economic and environmental objectives. Chaabane and Geramianfar [21] formulated a multi-objective MILP model to evaluate sustainability aspects based on cost, GHG emissions, and service level.

Hariga *et al.* [31] developed an integrated economic and environmental inventory model for a multi-stage CSC. They determined optimal lot-sizing and shipping quantities along with the optimal number of trucks and freezers. Recently, Babagolzadeh *et al.* [10] extended the work of Hariga *et al.* [31] to assess the impact of storage and transportation carbon emissions for CSCs in the presence of a heterogeneous fleet of trucks. They developed a sustainable two-stage stochastic model to generate replenishment policies and transportation schedules. Most of these studies concluded that when sustainability objectives are considered, it is possible to make minor adjustments to the operational policy so that a substantial reduction in the generated carbon footprint is attained at the expense of a slight increase in the total cost.

Other works focused on the configuration of food distribution networks while incorporating only the environmental aspect alongside the economic criterion. For instance, van der Vorst *et al.* [59] used discrete event simulation to redesign a pineapple distribution network. The amount of energy consumption for transportation and inventory-related activities is considered to measure environmental impacts in their work. For the case of perishable food distribution, a multi-objective MILP model was developed by Govindan *et al.* [30]. The study considers environmental impacts related to opening facilities, transportation, and operational activities, including the most damaging GHG emissions (CO_2, CFC, and NOx). In addition to multi-objective mathematical optimization, Validi *et al.* [58] presented a model based on the Analytic Hierarchy Process (AHP) to support decision-making in the dairy industry's distribution system. Bortolini *et al.* [15] developed a tactical planning model for multi-modal fresh food distribution networks. The proposed model reduced the carbon footprint by 9.6% with only a 2.7% cost increase. In another study, Saif and Elhedhli [46] adopted a simulation-optimization-based approach for CSC design with cost (capacity, transportation, and inventory costs) and sustainable objectives. Through two real case studies, the authors showed that it is possible to significantly reduce GHG emissions upon changing the operational policy at the expense of a small increase in the operational cost. Gallo *et al.* [28] put forward a MILP model to optimize cold chains' design and identify optimal routes considering shelf life and conservation temperature. Musavi and Bozorgi-Amiri [40] developed a multi-objective location-vehicle scheduling model for perishable products. The model jointly optimizes transportation cost, the freshness of delivered products, and carbon emissions. Recently, Mogale *et al.* [39] developed a bi-objective model that seeks to minimize cost and carbon emissions. They considered transportation, sourcing, and distribution over various procurement centers, warehouses, and retailers while using heterogeneous capacitated vehicles.

Since social responsibility is fast becoming an emerging concern for food companies, social aspects have recently attracted researchers' attention. However, due to social issues' complex nature, measuring and assessing social impacts is a daunting task [43]. To achieve corporate social sustainability in the supply chain, the International Standard Organization (ISO) developed a standard called the "International Guidance Standard on Social Responsibility-ISO 26000" [20]. The Food and Agriculture Organization of the United Nations (FAO) also provided a comprehensive framework known as SAFA (Sustainability Assessment of Food and Agriculture systems) for assessing sustainability performance that is tailored for agriculture and food systems [14]. Moreover, researchers have introduced various guidelines and methodologies to assess social impacts in the supply chain. Sureau *et al.* [53] presented a review of criteria and indicators proposed to assess social and socio-economic impacts.

Despite its emerging importance, it is worth noting that very few authors included social concerns alongside both economic and environmental criteria. For instance, Sutopo *et al.* [54] proposed a multi-objective optimization model to improve the quality of vegetable distribution networks and social aspects. Azadnia *et al.* [9] developed an integrated model for supplier selection and order lot-sizing that minimizes total cost along with environmental and social scores. The social score considers the health and safety management system, the worker safety and labor health, training education, and community development. Daghigh *et al.* [26] designed a 3PL network for perishable product distribution *via* a multi-objective model that seeks to minimize cost and GHG emissions and maximize social responsibility by allowing fair access to products. They also noted that transshipment among inventory facilities could improve sustainability criteria. Finally, Varsei and Polyakovskiy [60] proposed a sustainable wine supply chain design model where unemployment rates and regional gross domestic product are used as indicators to assess social impacts.

At this juncture, we formally state the contributions that this paper brings to the existing literature:

(1) An integrated supply chain planning model that supports tactical decision-making while incorporating the three sustainability dimensions (total cost, GHG emissions, and social responsibilities) is devised. The selection of 3PLs is carried out based on the type of energy source used in their facilities and the location. For a better resemblance to reality, the GHG emissions at the respective facilities are determined based on the energy source mix used in each country or region, allowing for a more accurate estimation of the supply chain's environmental performance.
(2) A multi-objective mathematical formulation and a solution approach that seeks to analyze the trade-offs involved in global frozen food supply chain operations and identify the best sustainable supply chain practices are proposed. In particular, besides selection of 3PLs and their facilities, interrelated decisions pertaining to selection of truck type from a fleet of heterogeneous trucks, inventory and backorder levels, hiring and firing of workers, production level, and shipping lot sizes are jointly optimized on a periodic basis assuming a time-varying demand profile for all products involved.
(3) We introduce a new indicator related to job stability at manufacturing sites, as denoted by the workforce level variation throughout the planning horizon. To the authors' best knowledge, none of the existing research works have included social measures related to job stability at the manufacturing sites, alongside economic and environmental aspects.
(4) The proposed model's applicability to real-life settings is exemplified *via* an industrial case study drawn from the North American frozen food industry. To provide managerial insights, the multi-faceted treatment of the problem is compared to its single objective counterpart, and the differences in the chain-wide performance are highlighted.

3. Problem definition and notations

3.1. Problem description

Amid the substantial amount of GHG emissions generated by the frozen food industry, companies are particularly keen on quantifying the negative environmental impact while exploring the most effective potential strategies to reduce such impact. One of the main environmental challenges facing such companies is to reduce the excessive amount of energy consumption due primarily to temperature-controlled storage facilities at the DCs and retailers. To that end, it is essential to point out that DCs in various regions make use of different energy sources, or a mix of them, with each source producing different amounts of GHG emissions. An energy mix refers to the spectrum of energy sources adopted in a particular region. For instance, in Ontario's province of Canada, electricity generation occurs from a combination of energy sources, such as nuclear, hydro, gas, coal, wind, and others. As such, to calculate the environmental impacts associated with cold-storage facilities, the per-unit energy requirement at various locations are multiplied by the GHG emission generated from the corresponding energy sources.

From a products' distribution perspective, it is obvious that the choice of the transportation fleet encompasses a trade-off between transportation and inventory-related costs. Furthermore, the transportation of frozen food products using freight trucks requires energy-intensive refrigeration systems with naturally higher energy consumption and more severe environmental impacts than their non-refrigerated counterparts. This study uses the distance-based method to calculate GHG emissions due to transportation activities. Given that the products are assumed to have the same characteristics in terms of weight, emission factors are independent of the products. Thus, the distance estimate can be converted to GHG emission by multiplying the distance traveled by a distance-based emission factor.

The focus of the problem at hand is largely on planning production, distribution, and inventory control activities of cold products, and accordingly the proposed model supports decision making at the tactical planning level. Depending on customer location and demand, the products are manufactured in several plants and delivered to customer sites directly or through DCs (see Fig. 1). There are potential 3PL companies, and a

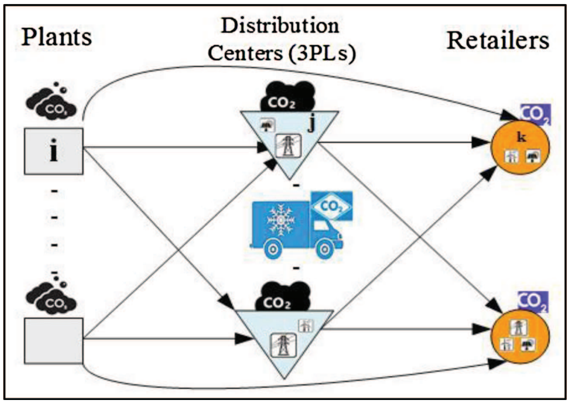


Figure 1. Configuration of the supply chain system under consideration.

contractual agreement is to be signed with selected 3PLs (each with its own DCs) throughout the planning horizon to better resemble many existing cold chains. The primary mission of 3PL companies is to cater to the needs of the frozen food industry through managing transportation and storage activities while providing the technology needed to retain the quality of the products at a minimal cost. In particular, such 3PL companies offer a fleet of refrigerated trucks with different load capacities, commonly referred to as reefers [49], and temperature-monitored warehouses/DCs.

The manufacturing plants comprise a fixed number of workers, where the production capacity at a particular plant can be altered *via* hiring and laying-off workers at any period of the planning horizon. We assume that inventory at the DCs is not allowed at the end of the planning horizon. Inventory capacities are also imposed on each product at the plants, DCs, and retailers' premises during each period. Moreover, since products' durability does not apply to the frozen food sector at the tactical level of planning, products may be stored for the whole planning horizon without impacting their quality. A restriction on the maximum surplus and backorder is imposed to ensure supply chain agility.

In this study, the economic performance indicator is quantified by the production, transportation, inventory, and backorder costs. The cost of hiring and laying-off as well as workers' wages are assumed to be both plant and time-dependent. Furthermore, since production-related costs also include raw materials costs, which might change over time, the generalized case of a time-varying production cost is considered herein. Transportation costs are incurred due to outbound shipments from plants to DCs or retailers and DCs to retailers. To be aligned with standard 3PL fulfillment pricing models, the adopted transportation cost structure assumes a fixed component associated with using a specific truck size and a variable part charged on a per-unit shipped basis. Inventory holding costs are associated with the inventory held at plants, DCs, and retailers' premises.

The tactical decisions addressed herein can directly or indirectly influence the social impacts in the supply chain. In this study, production quantity at the various production sites – which is set as a decision variable – is related to the social aspect in the sense that the production throughput is determined by hiring and laying-off workers. Although many companies capitalize on the flexibility provided by having seasonal workers, this strategy has adverse social effects. An organization shall deploy active workforce planning to avoid relying on the work performed on a temporary or casual basis, and recognize the significance of secure employment to both the society and the individual workers. Also, companies must provide conditions for stable employment to be sustainable [66]. To the best of the authors' knowledge, there have been no attempts to mitigate job insecurity impacts while simultaneously accounting for the environmental and economic aspects at the tactical level. In particular, we seek in this work to minimize the number of workers hired or laid-off throughout the planning horizon. To that end, we propose minimizing the deviation from the average number of workers at manufacturing sites, which can be defined as a company's set target. The concept of the average number of workers in each period helps build stable production rates while ensuring demand satisfaction is attained.

3.2. Notations

The following notations are adopted in the development of the mathematical model.

– Sets and indices:

p	Set of products, $p \in \{1, 2, \ldots, P\}$
i	Set of plants, $i \in \{1, 2, \ldots, I\}$
j	Set of distribution centers, $j \in \{1, 2, \ldots, J\}$
k	Set of retailers, $k \in \{1, 2, \ldots, K\}$
t	Set of time-periods, $t \in \{1, 2, \ldots, T\}$
m	Set of truck types, $m \in \{1, 2, \ldots, M\}$
n, n'	Set of all nodes: $n, n' \in \{i, j, k\}$
e_j	Set of energy sources mix at DC j: $e_j \in \{1, 2, \ldots, E_j\}$
e_k	Set of energy sources mix at retailer k: $e_k \in \{1, 2, \ldots, E_k\}$

– Input parameters:

Sw_{it}	Number of working hours per worker at plant i during time period t
Wr_{it}	The hourly wage rate of each worker at plant i during time period t[$/hour]
Hc_{it}	Cost of hiring a worker at plant i during time period t
Fc_{it}	Cost of laying off a worker at plant i during time period t
Ldc_j	Fixed cost of establishing contracts with DC j
d_{pkt}	Demand of product p form retailer k during period t
Pc_{pit}	Per unit production cost of product p at plant i during period t
$TFc_{nn'mt}$	Fixed cost of using truck type m between nodes n and n' during period t
$Tc_{nn'mt}$	Per unit transportation cost of truck type m from node n to node n' during period t
$Cap_{nn'mt}$	Transportation capacity using truck type m between nodes n and n' during period t
Bc_{pkt}	Per unit backorder cost of product p at retailer k during period t
U_{pit}	Per unit holding cost of product p at plant i from period t to period $t+1$
V_{pjt}	Per unit holding cost of product p at DC j from period t to period $t+1$
W_{pkt}	Per unit holding cost of product p at retailer k from period t to period $t+1$
FW_{it}	Minimum number of workers at plant i during period t
K_{it}	Number of products that each worker can produce at plant i during period t
KK_{pit}	Inventory capacity for product p at plant i during period t
WW_{pkt}	Inventory capacity for product p at retailer k during period t
VV_{pjt}	Inventory capacity for product p at DC j during period t
LC_{jt}	Global reception capacity for DC j during period t
LD_{kt}	Global reception capacity for retailer k during period t
$F_{nn'}$	Distance between nodes n and n' [km]
M_{kpt}	Maximum amount of permitted backorders of product p at retailer k during period t
EF_{pi}	GHG (CO_2) emission factor due to the production of one unit of product p in plant i [kg]
$\mathrm{EF}_{pnn'm}$	(CO_2) emission factor due to the transportation of one unit of product p using truck type m between nodes n and n' [kg/km]
EM_{ej}	The percentage share of energy source e in the energy mix of the region where DC j is located $\left(\sum_{e_j=1}^{E_j} \mathrm{EM}_{e_j} = 1\ \forall j\right)$
ER_{jp}	Energy requirement for storing one unit of product p at DC j [kWh/period]
EF_{ej}	CO_2 emission factor for energy source e_j [kg/kWh]

EM_{ek} The percentage share of energy source e in the energy mix of the region where retailer k is located $\left(\sum_{e_{k=1}}^{E_k} \mathrm{EM}_{e_k} = 1 \ \forall k\right)$

ER_{kp} Energy requirement for storing one unit of product p at retailer k [kWh/period]

EF_{ek} CO_2 emission factor for energy source e_k [kg/kWh]

– Decisions variables

Different decision variables are simultaneously optimized hereafter, which directly influence the supply chain performance:

- Continuous variables

Q_{pit} Quantity of product p manufactured at plant i during period t

$X_{pnn'mt}$ Quantity of product p shipped from node n to node n' using truck type m during period t

IP_{pit} Inventory level of product p at plant i at the end of period t

ID_{pjt} Inventory level of product p at DC j at the end of period t

R_{pkt} Quantity of product p backordered at retailer k during period t

S_{pkt} Quantity of surplus of product p delivered to retailer k during period t

- Integer variables

NW_{it} Number of workers at plant i during time period t

NH_{it} Number of workers hired at plant i during time period t

NL_{it} Number of workers laid off at plant i during time period t

$Z_{nn'mt}$ Number of trucks of type m between nodes n and n' during period t

- Binary variables

$$L_j \quad \begin{Bmatrix} 1; & \text{if distribution center } j \text{ is selected} \\ 0; & \text{otherwise} \end{Bmatrix}$$

4. Model formulation

The main objective of the model developed herein is to optimize production and logistics activities of multiple cold products towards the attainment of sustainable supply chain performance. To that end, we devise a mixed-integer non-linear programming (MINLP) optimization model for the problem at hand. To concurrently cater to the three pillars of sustainability, a multi-objective optimization model is developed. The first objective minimizes the total logistics-related costs, the second objective considers the GHG emissions generated by production and distribution activities, while the third objective seeks to minimize job instability at the various manufacturing sites.

4.1. Objective functions

Using the previously defined notations, the logistics costs related to objective function (Z_1) is given in equation (4.1). It comprises production costs, inventory holding costs at manufacturing plants, DCs and retailers' locations, transportation costs, penalty/shortage costs of backordered demand, and labor costs throughout the planning horizon.

$$\text{Minimize } Z_1 = Z_a + Z_b + Z_c + Z_d + Z_e + Z_f + Z_g + Z_h + Z_i + Z_j + Z_k \tag{4.1}$$

where

$$Z_a = \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T} Pc_{pit}Q_{pit} \tag{4.2}$$

is the production cost at all plants.

$$Z_b = \sum_{n}\sum_{n'}\sum_{m=1}^{M}\sum_{t=1}^{T} TFc_{nn'mt}Z_{nn'mt} \tag{4.3}$$

is the fixed transportation cost for the heterogeneous fleet of trucks.

$$Z_c = \sum_{n} \sum_{n'} \sum_{m=1}^{M} \sum_{t=1}^{T} \sum_{p=1}^{P} Tc_{nn'mt} X_{pnn'mt} \tag{4.4}$$

is the variable transportation cost component.

$$Z_d = \sum_{p=1}^{P} \sum_{i=1}^{I} \sum_{t=1}^{T} U_{pit} \mathrm{IP}_{pit} \tag{4.5}$$

is the inventory holding cost across all plants.

$$Z_e = \sum_{p=1}^{P} \sum_{j=1}^{I} \sum_{t=1}^{T} V_{pjt} \mathrm{ID}_{pjt} \tag{4.6}$$

is the inventory holding costs at the DCs.

$$Z_f = \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{t=1}^{T} W_{pkt} S_{pkt} \tag{4.7}$$

is the inventory holding cost at the retailers premises.

$$Z_g = \sum_{j=1}^{J} Ldc_j L_j \tag{4.8}$$

is the fixed costs associated with establishing contracts with the DCs.

$$Z_h = \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{t=1}^{T} Bc_{pkt} R_{pkt} \tag{4.9}$$

is the backordering cost for all retailers.

$$Z_i = \sum_{i=1}^{I} \sum_{t=1}^{T} Sw_{it} Wr_{it} \mathrm{NW}_{it} \tag{4.10}$$

is the labor cost across all plants.

$$Z_j = \sum_{i=1}^{I} \sum_{t=1}^{T} Hc_{it} \mathrm{NH}_{it} \tag{4.11}$$

is the hiring cost across all plants.

$$Z_k = \sum_{i=1}^{I} \sum_{t=1}^{T} Fc_{it} \mathrm{NL}_{it} \tag{4.12}$$

is the layoff cost across all plants.

The environmental performance of the supply chain is measured by the total CO_2 emissions generated (Z_2). These emissions are caused by production activities at each plant, energy consumption at DCs and retailers' premises, and transportation activities between the different supply chain members.

$$\text{Minimize } Z_2 = Z_l + Z_m + Z_n + Z_o \tag{4.13}$$

where

$$Z_l = \sum_{p=1}^{P} \sum_{i=1}^{I} \sum_{t=1}^{T} \mathrm{EF}_{pi} Q_{pit} \tag{4.14}$$

is the emissions due to production.

$$Z_m = \sum_{n} \sum_{n'} \sum_{m=1}^{M} \sum_{p=1}^{P} \sum_{t=1}^{T} \mathrm{EF}_{pnn'm} F_{nn'} X_{pnn'mt} \tag{4.15}$$

is the transportation-related emissions.

$$Z_n = \sum_{p=1}^{P} \sum_{j=1}^{J} \sum_{t=1}^{T} \left[\sum_{e_j}^{E_j} \mathrm{EM}_{e_j} \mathrm{EF}_{e_j} \right] \mathrm{ER}_{jp} \mathrm{ID}_{pjt} \tag{4.16}$$

is the emissions generated at the DCs.

$$Z_o = \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{t=1}^{T} \left[\sum_{e_k}^{E_k} \mathrm{EM}_{e_k} \mathrm{EF}_{e_k} \right] \mathrm{ER}_{kp} S_{pkt} \tag{4.17}$$

is the emissions generated at the retailers facilities.

In the third objective (Z_3), we aim to promote the supply chain's social responsibility by minimizing the deviations from the average number of workers, leading to increased job stability at the manufacturing sites. Let μ_i denote the average number of workers at plant i.

$$\text{Minimize } Z_3 = Z_p \tag{4.18}$$

where

$$Z_p = \sum_{i=1}^{I} \sum_{t=1}^{T} |\mathrm{NW}_{it} - \mu_i| \tag{4.19}$$

is the total deviations from the mean value across all plants.

4.2. Constraints

The aforementioned three objective functions are to be jointly optimized subject to the following sets of constraints:

The workforce balance constraints at each plant:

$$\mathrm{NW}_{it} = \mathrm{NW}_{i,t-1} + \mathrm{NH}_{it} - \mathrm{NL}_{it} \quad \forall i, t. \tag{4.20}$$

The number of workers at each plant cannot be less than the minimum needed capacity at that plant:

$$\mathrm{NW}_{it} \geq \mathrm{FW}_{it} \quad \forall i, t. \tag{4.21}$$

The total demand for each product shall be satisfied throughout the planning horizon:

$$\sum_{i=1}^{I} \sum_{t=1}^{T} Q_{pit} = \sum_{k=1}^{K} \sum_{t=1}^{T} d_{pkt} \quad \forall p. \tag{4.22}$$

The production capacity at each plant in each period cannot be exceeded:

$$\sum_{p=1}^{P} Q_{pit} \leq K_{it} \mathrm{NW}_{it} \quad \forall i, t. \tag{4.23}$$

The demand for each product at each retailer throughout the planning horizon is to be satisfied:

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{t=1}^{T} X_{pikmt} + \sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{t=1}^{T} X_{pjkmt} = \sum_{t=1}^{T} d_{pkt} \quad \forall p, k. \tag{4.24}$$

Inventory balance constraints at each plant and for each product:

$$\mathrm{IP}_{pit} = \sum_{\tau=1}^{t} Q_{pi\tau} - \sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{\tau=1}^{t} X_{pijm\tau} - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{\tau=1}^{t} X_{pikm\tau} \quad \forall i, p, t. \tag{4.25}$$

Inventory capacity for each product at each plant shall not be exceeded:

$$\mathrm{IP}_{pit} \leq \mathrm{KK}_{pit} \quad \forall i, p, t. \tag{4.26}$$

Conservation of flow at manufacturing plants:

$$\sum_{j=1}^{J}\sum_{m=1}^{M} X_{pijmt} + \sum_{k=1}^{K}\sum_{m=1}^{M} X_{pikmt} \leq Q_{pit} + \mathrm{IP}_{pi,t-1} \quad \forall i, p, t. \tag{4.27}$$

Inventory calculations at the DCs:

$$\mathrm{ID}_{pjt} = \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{\tau=1}^{t} X_{pijm\tau} - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{\tau=1}^{t} X_{pjkm\tau} \quad \forall j, p, t. \tag{4.28}$$

Inventory capacity at DCs in not to be exceeded:

$$\mathrm{ID}_{pjt} \leq \mathrm{VV}_{pjt} L_j \quad \forall j, p, t. \tag{4.29}$$

No inventory is maintained at the DCs at the end of the planning horizon:

$$\mathrm{ID}_{pjT} = 0 \quad \forall j, p. \tag{4.30}$$

Amount of each product delivered in advance or backordered for each retailer:

$$\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{\tau=1}^{t} X_{pjkm\tau} + \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{\tau=1}^{t} X_{pikm\tau} - \sum_{\tau=1}^{t} d_{pk\tau} = S_{pkt} - R_{pkt} \quad \forall k, p, t. \tag{4.31}$$

Global reception capacity at DCs shall not be exceeded:

$$\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{m=1}^{M} X_{pijmt} \leq \mathrm{LC}_{jt} L_j \quad \forall j, t. \tag{4.32}$$

Global reception capacity at the retailers shall not be exceeded:

$$\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{m=1}^{M} X_{pjkmt} + \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{m=1}^{M} X_{pikmt} \leq \mathrm{LD}_{kt} \quad \forall k, t. \tag{4.33}$$

Transportation capacity constraints:

$$\sum_{p=1}^{P} X_{pnn'mt} \leq Cap_{nn'mt} Z_{nn'mt} \quad \forall n \in i, j;\ \forall n' \in j, k;\ \forall m, t. \tag{4.34}$$

Maximum amount of each product delivered to each retailer in advance shall not be exceeded:

$$S_{pkt} \leq \mathrm{WW}_{pkt} \quad \forall k, p, t. \tag{4.35}$$

Maximum amount of permitted backordered products:

$$R_{pkt} \leq M_{pkt} \quad \forall k, p, t. \tag{4.36}$$

Non-negativity, integrality and binary restrictions:

$$Q_{pit}, X_{pnn'mt}, R_{pkt}, S_{pkt}, \mathrm{IP}_{pit}, \mathrm{ID}_{pjt} \geq 0 \tag{4.37}$$

$$\mathrm{NW}_{it}, \mathrm{NH}_{it}, \mathrm{NL}_{it}, Z_{nn'mt} \text{ are integers} \tag{4.38}$$

$$L_j \in \{0, 1\}. \tag{4.39}$$

Given that the third objective function, Z_3, comprises an absolute value, this induces non-linearity in the developed model. In order to linearize this objective function, a new set of auxiliary variables (JID_{it}) is added, where

$$\mathrm{JID}_{it} = |\mathrm{NW}_{it} - \mu_i| \quad \forall i, t.$$

Therefore

$$\mathrm{JID}_{it} = \max\{\mathrm{NW}_{it} - \mu_i, \mu_i - \mathrm{NW}_{it}\} \quad \forall i, t.$$

Thus, the objective function (Z_3) can be linearized by introducing two sets of auxiliary constraints into the model, as follows:

$$\text{Minimize } Z_3 = \sum_{i=1}^{I} \sum_{t=1}^{T} \mathrm{JID}_{it} \tag{4.40}$$

where

$$\mathrm{JID}_{it} \geq \mathrm{NW}_{it} - \mu_i \qquad \forall i, t \tag{4.41}$$

$$\mathrm{JID}_{it} \geq \mu_i - \mathrm{NW}_{it} \qquad \forall i, t. \tag{4.42}$$

5. An industrial case example

The upward desire for affordable, well-preserved, nutritious, and convenient food products has brought an enormous opportunity for the frozen product's market from a financial perspective. According to Grand View Research (2020), the global frozen food revenue was valued at \$291.3 billion in 2019, and it is expected to grow further into the future. A recent market research reported that the frozen food market is estimated to account for about \$244.3 billion in 2020 and is anticipated to reach a value of approximately \$312.3 billion by 2025[1]. From a social standpoint, the frozen food industry's total employment contribution to the U.S. economy amounted to 670 000 jobs in 2012 (AFFI 2015). To illustrate the practical relevance of the proposed approach, the model has been validated and applied to a real-life supply chain planning problem in the context of the frozen food industry. In what follows, we illustrate the production and distribution situation characterizing the case example to the best extent possible. However, due to the massive amount of data and confidentiality concerns, the authors are unable to provide the full details of the relevant input data needed for experimentation purposes.

[1] https://www.marketsandmarkets.com/Market-Reports/global-frozen-and-convenience-food-market-advanced-technologies-and-global-market-130.html.

5.1. Background

The case company is involved with the production and distribution of frozen food products in North America (Canada and the United States). It offers more than four hundred products grouped into four families: Breakfasts, Meals, Snacks, and Raw Doughs. The various products undergo several machining/processing stages during the manufacturing process at one of the two production plants located in Quebec and Ontario. Breakfast and Meals are produced in Ontario, while Snacks and Raw doughs are produced in Quebec. More carbon emissions are generated in Quebec's plant due to less efficient machinery, but production costs are considerably lower. The plant in Ontario is the greenest, which is attributed to the recent investment in new high-tech machines. The company currently employs 148 workers in Ontario's plant and 143 in Quebec. The potential third-party logistics (3PLs) providers offer storage space with limited capacities. Manufacturing plants supply six retail areas that are spread over various geographic regions, in East, Central, and West Canada, as well as East, Central, and West parts of the United States. The distribution from manufacturing plants to retailers can be carried out either directly or indirectly through thirty existing distribution centers. These distribution centers are owned and managed by 3PL service providers, where in this study, the potential 3PL companies are selected from those with a previously established business contract.

Two types of trucks are available: "Big trucks" and "Small trucks". The quantity of products shipped between some nodes may not be big enough to be carried out through big trucks. Also, there might be some restrictions concerning big trucks traveling to residential areas. The 3PL companies offer storage and transportation services at different rates for each direction and transportation mode. The planning horizon considered is one year long, and it is broken down into twelve periods (months). A pallet is defined as the product unit in production, transportation, and storage. The company is currently facing stringent environmental regulations that have been put in place by the legislative authorities in Quebec and Ontario. Moreover, the temperature-monitored storage facilities at the DCs and retailers consume a substantial amount of energy. Due to the fierce competition in this sector, the company ought to minimize production and distribution (inventory and transportation) costs across the supply chain while offering a good service level (no backorders) and guaranteeing the timely delivery of fresh products to end-customers.

5.2. Data collection

In this section, we first present the collected data pertinent to the study at hand. Only samples of selected input parameters are reported in Tables 3–6 due to confidentiality reasons. Note that the parameters associated with emission factors are estimated based on the information obtained from the relevant literature and/or concerned agencies' databases. Table 3 depicts the forecasts of aggregated retailers' demand for all product families throughout the planning horizon. There seems to be higher seasonality in several product families, such as breakfast, meals, and raw doughs. The noticed trend is that consumers prefer to buy these products when the weather is cold, as less demand is seen from April to August. All product families' consumption pattern somehow follows a similar trend, with varying degrees of seasonality. It is worth pointing out that there is high demand for the four product families in December, yet fewer working hours are available due to the Christmas holiday.

The monthly inventory holding costs per pallet for all the products at the different distribution centers are reported in the appendix. The 3PL companies under consideration offer two types of refrigerated trucks with average full truckloads of 16 tons and 40 tons. The transportation-related GHG emission factors are reported in Table 4. These emission factors for refrigerated trucks are estimated from the data provided by Global Food Cold Chain Council (GFCCC, 2015). To maintain the freshness level of the frozen items and prevent their quality degradation, the storage space (at the DCs and the retailers' locations) is equipped with refrigerated storage compartments, which are highly energy-intensive. In this work, we adopt the data provided by Adekomaya *et al.* [3] in measuring the energy requirements at these storage facilities.

Table 5 presents the per pallet energy consumption for the cooled storages in each period. Since the DCs and retailers are scattered over distantly located geographic zones across the United States and Canada, energy is

Table 3. Aggregate monthly demand by product family (in pallets).

Product family	Month												Total demand
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Breakfasts	281	366	242	208	491	793	1202	1792	971	1698	1565	1567	11 177
Meals	515	430	463	398	388	638	955	878	1251	1840	2325	1669	11 750
Snacks	82	118	110	88	85	98	90	147	111	161	162	249	1500
Raw doughs	734	529	540	496	679	1278	1423	3159	2819	3414	3171	3461	21 702

Table 4. Emission factors of refrigerated trucks (GFCCC, 2015).

Truck type	Emission factor (tons of CO_2 per pallet km)
16 Tons	0.0604
40 Tons	0.024

Table 5. Energy consumption by cooled storage [3].

Storage size	Monthly energy requirement (kWh/pallet)
Distribution centers (10 000 m^3)	25
Retailers (1000 m^3)	50

generated from different sources such as coal and natural gas with varying GHG emissions levels. About half of the products are sold in the US, where the US grid mix is mainly dependent on fossil fuels' combustion. The other half of the products are being sold using the Canadian grid mix, which utilizes cleaner energy sources such as hydroelectric.

6. Results and analysis

The model is implemented in General Algebraic Modeling System (GAMS) and solved using off-the-shelf IBM Ilog CPLEX solver version 12.6.1. With four product families ($P = 4$), two manufacturing plants ($I = 2$), thirty distribution centers ($J = 30$), five hundred and ninety-four retailers ($K = 594$), and twelve-time periods ($T = 12$), the proposed MILP (linearized MINLP) model has approximately 1 348 473 variables and 580 447 constraints. The model was solved for different scenarios, and the max solution time observed across all the scenarios was around 6000 s (∼1.6 h). In what follows, the model is first optimized with one objective to obtain the best economic, environmental, and social solutions one at a time, and allow for analyzing the differences compared to the obtained compromised solutions considering all three objectives at once.

6.1. Economic objective optimization

The developed model has been first solved from an economic perspective to obtain the supply chain settings that minimize the total production and distribution costs. This scenario, which seeks to optimize the economic objective only, is hereafter referred to as "Eco-optimal". In order to absorb the demand variations and retain lower inventories, the company hires temporary workers in periods exhibiting high demand. After solving the optimization model, the cost-minimizing optimal solution calls for utilizing 22 DCs, with the number of DCs

Table 6. Number of DCs in the "Eco-optimal" scenario.

Country	State/Province	Number of DCs	
		Potential	Selected
Canada	Quebec	6	6
	Ontario	7	5
	British Columbia	2	1
	Alberta	1	1
United States	California	2	1
	Washington	1	1
	Georgia	1	–
	Massachusetts	1	1
	Illinois	2	–
	Texas	1	1
	Florida	1	1
	Maryland	1	1
	Pennsylvania	1	1
	Missouri	1	1
	Connecticut	1	1
	Indiana	1	–
	Total number of DCs	30	22

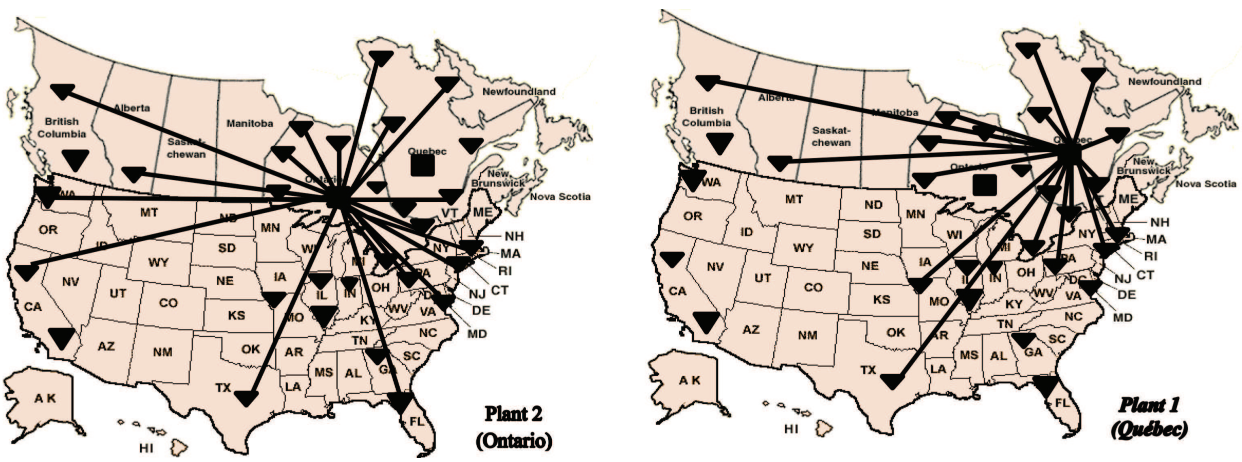


Figure 2. Supply chain set-up in the "Eco-optimal" scenario.

selected in each state/province shown in Table 6. Furthermore, Figure 2 displays potential distribution centers' locations and the flow of products from plants to selected DCs.

As shown in Figure 3, the production is set at a fixed rate using a fixed workforce size in some periods. However, additional (temporary) workers are deemed necessary in other periods to match the demand variations and save on the inventory holding cost. Following the model's production plans, the company can minimize the inventory at the expense of an increase in hiring and firing costs. A summary of the supply chain-related costs is depicted in Table 7. It turns out that more than half of the shipments from plants to DCs are carried out using big trucks (see Fig. 4). This could increase the network's transportation efficiency by increasing the shipment volumes while decreasing the number of shipments. However, since the size of shipments from DCs to retailers is

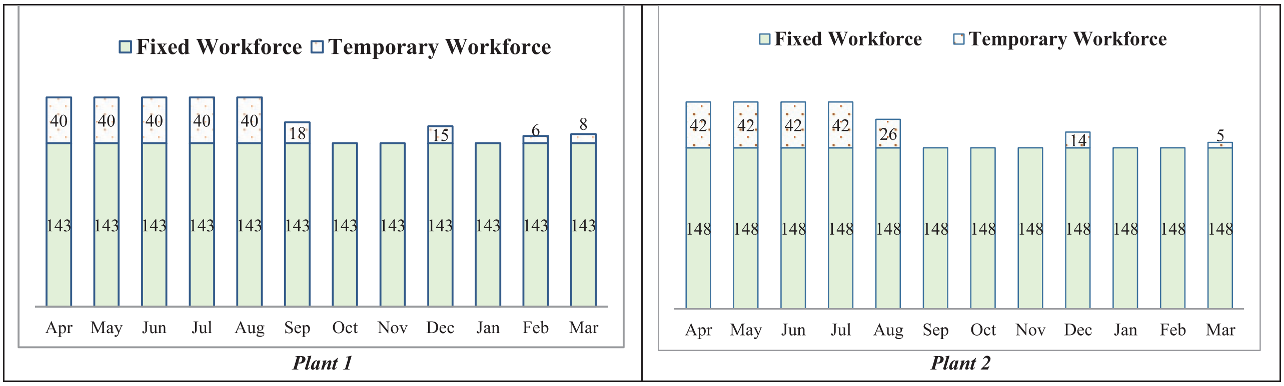


FIGURE 3. Number of workers at manufacturing plants in the "Eco-optimal" scenario.

TABLE 7. Breakdown of the supply chain cost in "Eco-optimal" scenario.

Scenario	Inventory holding cost (in 1000$)	Transportation cost (in 1000$)	Production cost (in 1000$)	Total cost (in 1000$)
Eco-optimal	792	11 517	11 549	23 858

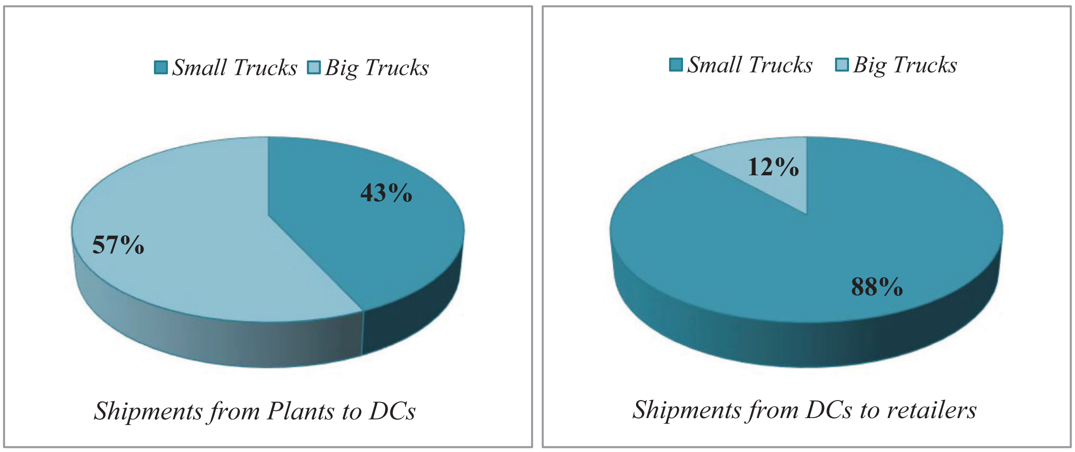
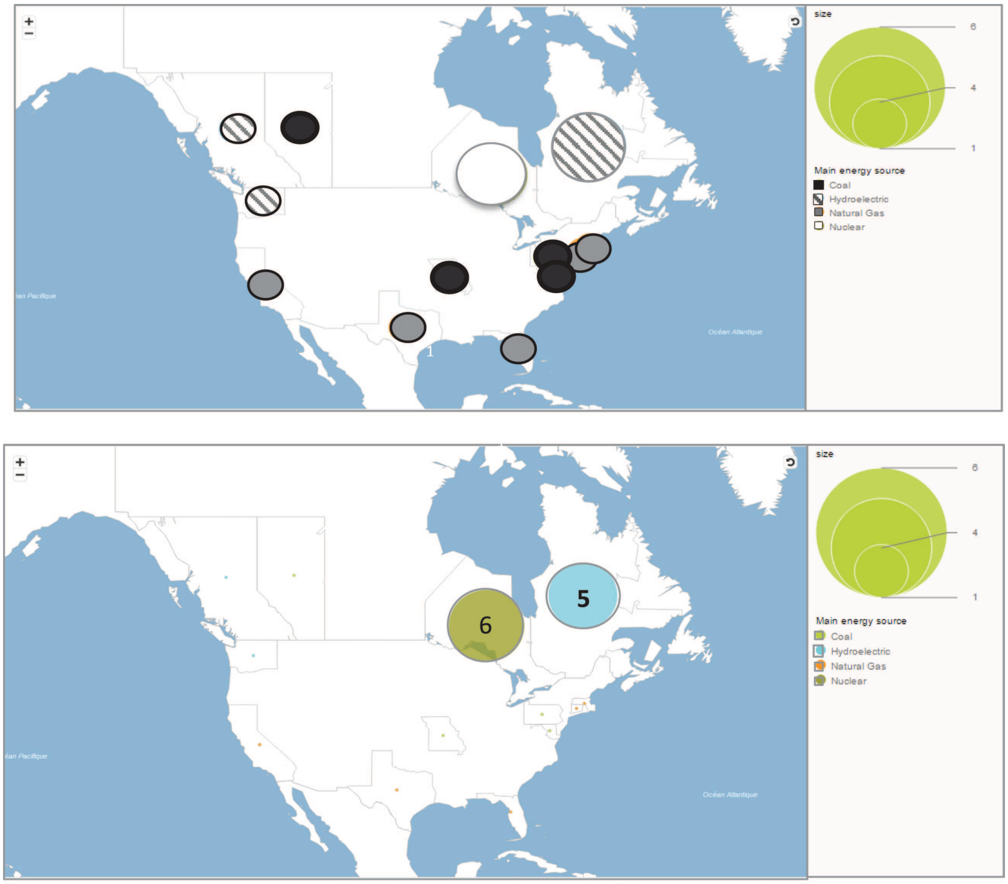


FIGURE 4. Transportation using small and big trucks (Eco-optimal scenario).

usually small relative to those between plants and DCs, only 12% of the downstream shipments are transported using big trucks.

6.2. Environmental objective optimization

This section analyzes how the environmental sustainability objective affects the production/distribution plan and the structural change in the distribution pattern *via* selecting different 3PLs. As mentioned earlier, DCs and retailers are located in different provinces across the U.S. and Canada. As such, various sources of power



a) Eco-optimal *b) Env-optimal*

Figure 5. Location of the DCs under optimized economic and environmental scenarios. (a) Eco-optimal. (b) Env-optimal.

generation are used in these provinces. The respective province's energy mix data are retrieved from EIA (U.S. Energy Information Administration)[2] and CEA (Canadian Electricity Association)[3] databases. The Ontario's energy mix is made up of 24% hydroelectricity, 42% nuclear, 30% coal, and 4% coal. Furthermore, the various energy sources' emission factors are determined based on IPCC (2011). Figures 5a and 5b provide a comparison between "Eco-optimal" and "Env-optimal" scenarios in terms of 3PL selection. They depict the number and the locations of the selected DCs in each province and their corresponding primary energy source. In particular, it can be seen that only 11 out of the available 30 DCs are selected in the "Env-optimal" scenario.

Therefore, the CO_2 emissions due to transportation and warehousing activities are substantially reduced once compared to the "Eco-optimal" scenario. To facilitate such comparison, the CO_2 emissions in the "Eco-optimal" scenario are calculated by substituting the values of the decision variables obtained from this scenario in the environmental objective function, and the results are seen in Figure 6. The same approach is also adopted to calculate the "Env-optimal" costs reported in Table 8. It is noted that in the latter scenario, DCs naturally make use of more environmentally friendly energy sources. In particular, the model suggests that contracts

[2] http://www.eia.gov/.

[3] http://www.electricity.ca/.

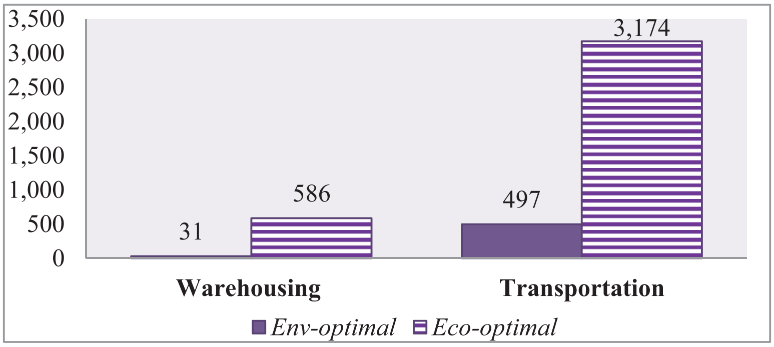


FIGURE 6. Carbon emissions (tons of CO_2) from inventory and transportation activities.

TABLE 8. "Env-optimal" *vs.* "Eco-optimal" scenarios (in thousand dollars).

Supply chain costs	Env-optimal	Eco-optimal	Difference
Production	11 554	11 549	0.04%
Inventory (warehousing)	1724	792	54%
Transportation	42 179	11 517	73%
Total	55 457	23 858	57%

are established with 3PLs located in the two Canadian provinces, where the primary sources of energy are hydroelectric (Quebec) and nuclear (Ontario). This selection occurs even though the inventory costs for some of the DCs located in these provinces are higher than other DCs, explaining the increased inventory cost in this scenario (see Tab. 8). Also, reducing the on-hand inventory levels helps mitigate inventory induced CO_2 emissions. In addition to this reduction, workers are hired and laid-off in different periods to absorb the variation in demand and better match the resulting production plan to the demand pattern.

Since the tactical planning model considers the relation between the energy sources used at each location, the selection of 3PL is now sensitive to the type of energy used by each DC (country/province/state). Therefore, supply chain managers ought to revise their distribution plans on a periodic basis and decide on establishing contracts with 3PLs that are greener to improve the supply chain's environmental performance. Furthermore, for the "Env-optimal" scenario, the DCs are located closer to the plants to reduce CO_2 emissions generated from transportation activities. The use of large trucks to carry out about 96% of shipments is another reason justifying the considerable reduction in the carbon footprint generated due to transportation (see Fig. 6). However, as reported in Table 8, this would trigger a significant increase in transportation costs.

6.3. Social objective minimization

In this section, the developed model is optimized solely based on the social objective (Z_3), where the goal is to minimize the job instability at the manufacturing sites, referred to hereafter as the "Soc-optimal" scenario. The obtained results indicate that a total of thirty DCs are selected. As anticipated, the production rates remain unchanged *via* a fixed number of workers throughout the planning horizon: 143 workers in Quebec's plant and 148 workers at Ontario's plant. Since these values are also the average number of workers at the respective plants (μ_i), the objective function optimal value is equal to zero. The obtained results of this scenario are also compared to those of the "Eco-optimal" scenario. Supply chain costs for the "Soc-optimal" scenario are calculated by substituting the values of the decision variables obtained from this scenario in the economic objective function. As shown in Table 9, the production cost is slightly lower in the "Soc-optimal" scenario due

TABLE 9. "Soc-optimal" *vs.* "Eco-optimal" scenario (in thousand dollars).

Network costs	Soc-optimal	Eco-optimal	Difference
Production	11 521	11 549	−0.24%
Inventory	2018	792	154.80%
Transportation	45 698	11 517	296.79%
Total	59 237	23 858	148.29%

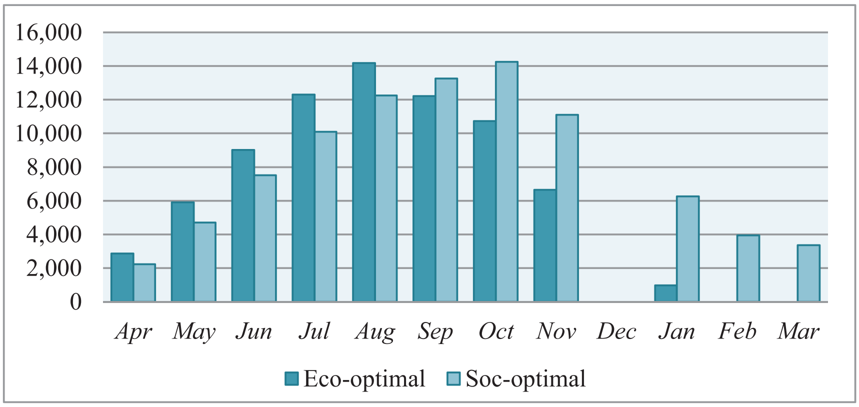


FIGURE 7. Inventory level (# pallets) at the DCs.

to the savings attained from the hiring and firing costs. However, inventory and transportation activities are drastically increased as seen in the table. Figure 7 shows the inventory levels at the DCs under both scenarios throughout the planning horizon. As may be noted, the inventory levels are increased in low demand periods when following the "Soc-optimal" scenario due to the assumed stable production rates.

6.4. Multi-objective optimization

The results obtained in the previous sub-sections for the stand-alone "Eco-optimal", "Env-optimal", and "Soc-optimal" scenarios clearly demonstrate the trade-offs that exist between the three dimensions of sustainability. Therefore, it is essential to find an optimal integrated production-distribution-inventory plan that is aligned with the company's preference while adhering to sustainability objectives. A comprehensive study of techniques applicable to solving multi-objective optimization models for supply chain management problems can be found in Aslam and Amos [7]. In this study, the multi-objective optimization model is solved by combining the three objectives into a single objective using a scalar function known as the weighted sum method or scalarization method [18, 38]. This method provides a single solution that reflects preferences incorporated in selecting a single set of weights. It can also provide multiple solution points by varying the weights. Given that the interaction with the decision-makers in sustainable supply chain design is essential, the weighted sum method can help them decide how much additional cost to bear for reduced carbon emissions and increased social responsibilities. Following this approach, the new single objective mathematical model is given as follows:

$$\begin{aligned} &\text{Min } X = w_1 X_1 + w_2 X_2 + w_3 X_3 \\ &\text{s.t.} \\ &\qquad \text{Equations (4.20)–(4.39)} \end{aligned}$$

where $w_1, w_2, w_3 \geq 0$ and $w_1 + w_2 + w_3 = 1$. In order to obtain a uniform expression for the objective function X, the different objective functions (Z_i) need to be normalized first. A normalized vector for the objective function

TABLE 10. Payoff table.

Performance	Economic (Eco) (Thousand dollars)	Environmental (Env) (Tons of CO_2)	Social (Soc) (#Worker variation)
Economic (Eco) (Thousand dollar)	23 858	3,760	406
Environmental (Env) (Tons CO_2)	55 457	527	413
Social (Soc)	59 237	6021	0

TABLE 11. Trade-off between economic, environmental, and social objectives.

Scenario	Weights			Z_1 (Thousand $)		Z_2 (Tons of CO_2)		Z_3 (# Worker variation)	
	w_1	w_2	w_3	Value	Δ *vs.* Baseline	Value	Δ *vs.* Baseline	Value	Δ *vs.* Baseline
S1 (Baseline)	1	0	0	23 858	–	3760		406	
S2	0	1	0	55 457	132.45%	527	–85.98%	413	1.72%
S3	0	0	1	59 237	148.29%	6021	60.13%	0	–100%
S4	0.7	0.3	0	24 416	2.34%	1121	–70.19%	410	0.99%
S5	0.6	0.2	0.2	26 015	9.04%	4034	7.29%	55	−86.45%
S6	0.5	0.5	0	30 146	26.36%	3015	−19.81%	387	−4.68%
S7	0.33	0.33	0.33	24 925	4.47%	1083	−71.20%	150	−63.05%
S8	0.5	0.25	0.25	24 633	3.25%	1080	–71.28%	404	−0.49%
S9	0.6	0.3	0.1	26 116	9.46%	3,948	5.00%	370	−8.87%
S10	0.5	0	0.5	24 394	2.25%	5000	32.98%	*0*	−100%
S11	0.3	0.7	0	34 555	44.84%	2507	−33.32%	387	−4.68%
S12	0	0.8	0.2	54 815	129.76%	559	−85.13%	250	−38.42%

of the following form, suggested by Atrek [8], has been applied:

$$X_i = \frac{Z_i - \min Z_i}{\max Z_i - \min Z_i} \quad \text{for } i = 1, 2, 3.$$

For this study, some scenarios have been designed using various weights to find different solutions and the trade-offs between economic, environmental, and social objectives. To that end, the payoff table, seen in Table 10, is obtained by solving each objective function separately to determine the nadir values and generate the range for the respective objective functions.

The existing trade-offs between economic, environmental, and social objectives are better exemplified upon using different weights, as seen in Table 11. It can be concluded from the conducted analysis that improvement in one objective may not be attained without degrading the performance of another objective due to the conflicting nature of these objectives. The table also displays the percentage increase or decrease in the three objectives for the different scenarios as compared to the benchmark scenario that solely optimizes the economic objective (Baseline).

However, it can be observed in Figure 8 that for scenarios S4, **S7**, and S8, it is possible to achieve more than 70% reduction in CO_2 emissions with a maximum cost increase of 4.47% compared to the Baseline case. Yet, if the company decides to implement a fully green environmental policy ($w_2 = 1$), it is possible to achieve approximately 86% CO_2 reduction with scenario S2 at the expense of a much higher increase in the chain-wide total cost.

A graphical illustration of the trade-off analysis between economic and social objectives is depicted in Figure 9. One can observe the possibility of achieving improved jobs' stability levels for scenarios S5, **S7**, and S10, with a maximum cost increase of 9.04%. However, if the company seeks to implement a stable environment for workers by offering only permanent jobs, it is possible to achieve this goal with scenarios S3 ($w_3 = 1$) and S10 ($w_1 = w_3 = 0.5$). For S10, this result is attainable with only 2.25% increase in the total cost.

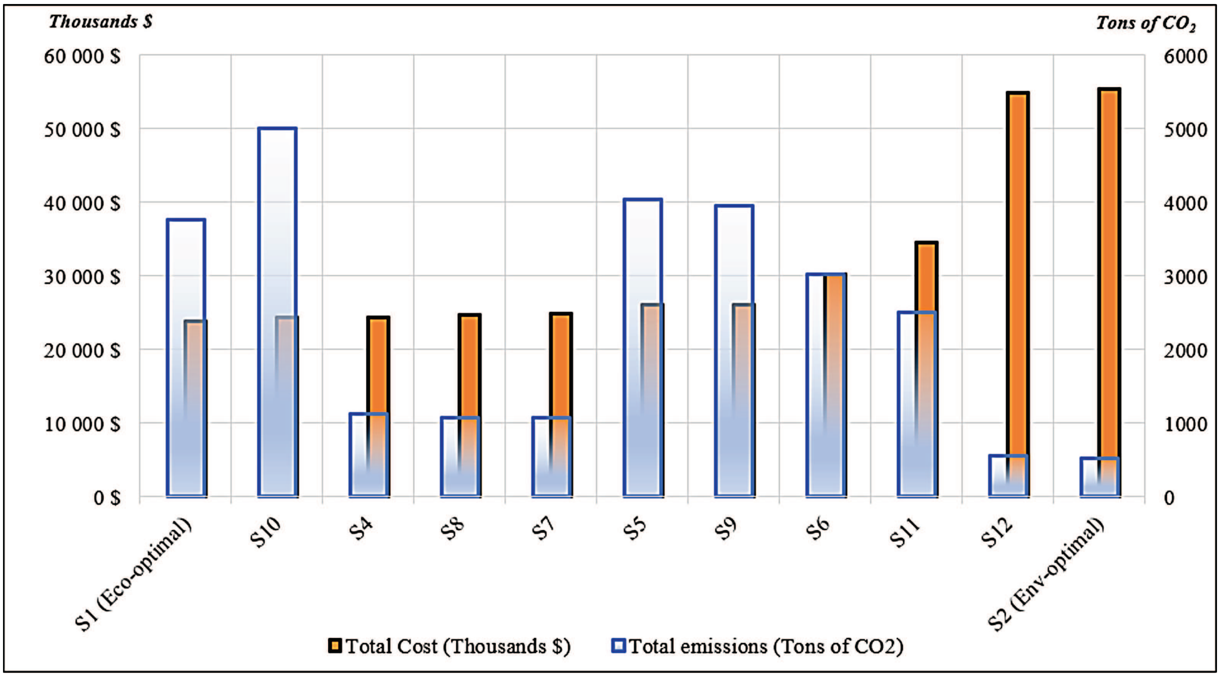


FIGURE 8. Trade-off analysis between the economic and the environmental objectives.

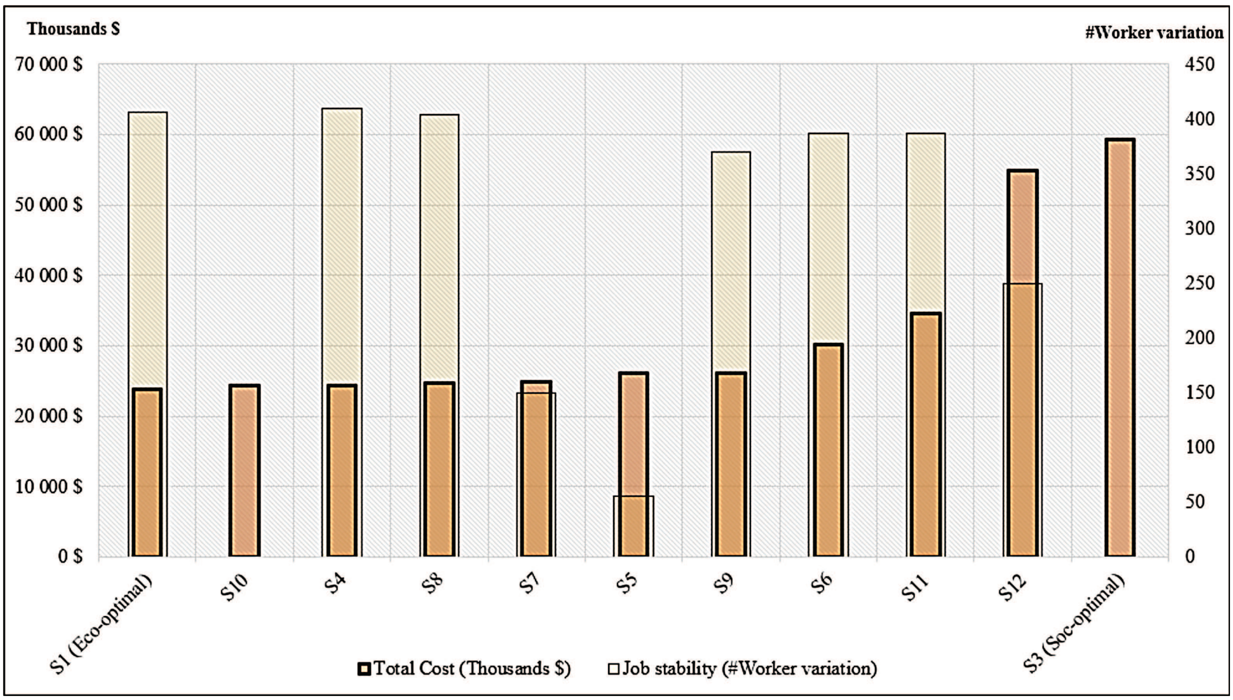


FIGURE 9. Trade-off analysis between the economic and the social objectives.

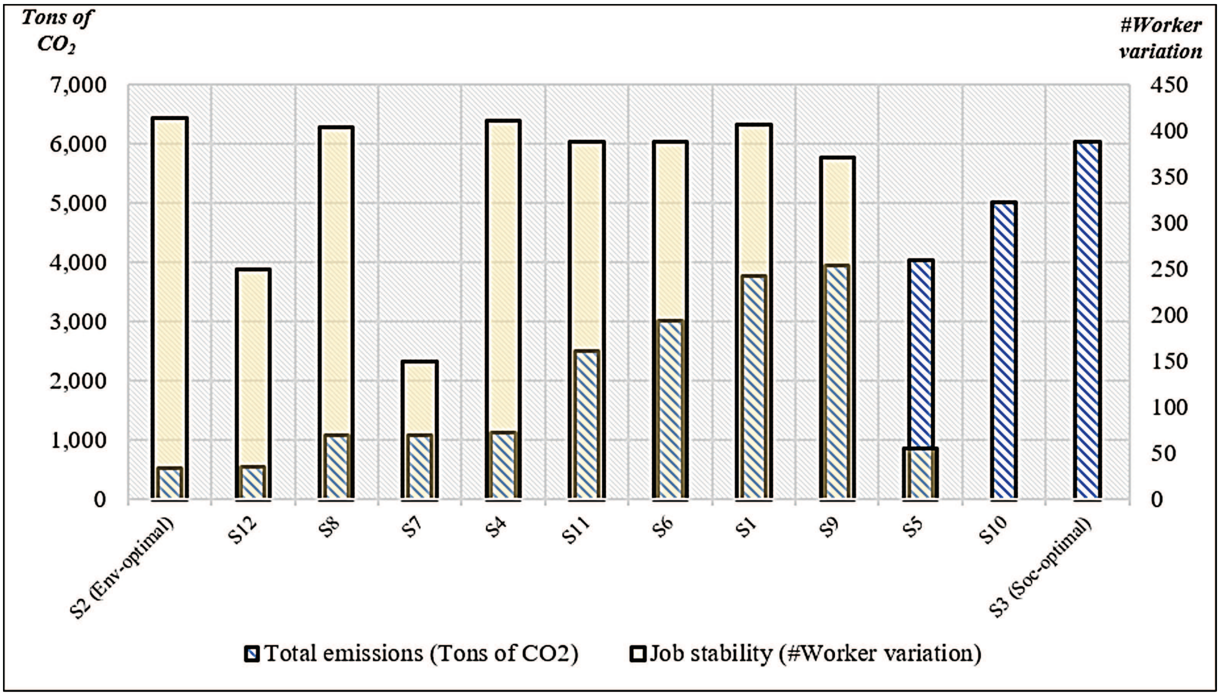


Figure 10. Trade-off analysis between environmental and the social objectives.

7. Managerial insights

The increase in environmental related concerns worldwide has forced many governments to implement stringent regulations endorsing healthy and ecological practices. These policy changes affect all sectors and are applicable across all industries, including the energy industry, specifically, renewable energy sources. For instance, in North America and Europe, it is required in some cases that Renewable Energy Certificates (RECs) are provided as proof that a particular energy used has been generated from renewable sources such as solar or wind power [29]. Such certificates can be purchased on trading platforms. The deployment of energy-sensitive and global CSCs operations under environmental and social objectives provides a better chance of adhering to long-term sustainability goals while avoiding significant cost increases. Due to the fast-paced energy transition taking place in many countries, the 3PL selection process ought to be flexible enough where the model developed herein helps the decision-makers react in a timely fashion to such dynamic change as 3PLs embrace greener energy sources. With the centralization of 3PLs in some regions, it is possible to rely heavily on the less polluting DCs with valid RECs and reduce supply chain GHG emissions from inventory and transportation accordingly. However, the massive centralization will significantly increase transportation costs due to lower efficiency in using the trucks' capacity, especially between DCs and retailers, coupled with an increase in the supply chain response time as 3PLs are located distant from the retailers. Therefore, to maintain a minimum service level, it is possible to set a cap on the response time of each retailer, introduce a lead time crashing cost towards minimizing the lead time [47] or adopt a smart supply chain system with controllable lead time [27]. Since adopting a fully green production and distribution plan (centralization of 3PLs) increases the risk of global supply chain disruption, this model helps the decision-makers with the timely implementation of an appropriate response strategy whenever such disruption occurs. In essence, it provides industrial practitioners with a tool to evaluate various production/distribution scenarios, develop contingency plans, assess inherent relations between interdependent decisions (*e.g.*, inventory and backorder levels, workers hiring and firing, etc.) in a sustainability conscious manner.

Based on the computational results reported in Section 6 and the in-depth analysis of additional results obtained from this study, one can draw the following insights to operationalize sustainability aspects at the tactical level of cold chains operations. Firstly, the trade-off analysis between social and environmental performance demonstrates that job stability is better attained *via* hiring permanent workers to maintain constant production levels. Combining such production policy and selecting the appropriate number of 3PLs contributes significantly to generating the right balance between inventory levels and transportation efficiency. Consequently, with the optimal number and location of 3PLs, the proposed sustainable solution plays a pivotal role in achieving supply chain decarbonization targets set by legislative authorities without a considerable increase in total cost. Secondly, using the marginal abatement cost (MAC) calculation for different scenarios, supply chain decision-makers can decide if they wish to implement the new sustainable production-distribution plan or acquire carbon allowances from the carbon trading markets [61]. According to Table 11, scenario 7 ($w_i = 1/3$) provides a compromise solution that strikes a balance between the three sustainability objectives with a potential reduction of approximately 71% in CO_2 emissions along with a 63% reduction in the number of worker variations (see Fig. 10). The MAC per ton of CO_2 for this scenario is approximately \$0.4 $\left(\text{MAC} = \frac{24\,925-23\,858}{3760-1083}\right)$. The weighted-sum method adopted in this work allows policymakers to sway the solution towards whichever sustainability dimension they deem more important through subjectively assigning weights that reflect such importance.

Finally, a crucial finding in this research is that a drastic alteration in the 3PL locations and material flow patterns between supply chain members is observed once more stringent environmental and social policies are put in place for the global supply chain. Therefore, coordination of the best-fit environmental policy to adopt for transboundary transportation through international agreements is necessary to avoid problems shifting from one country to another. The proposed multi-objective optimization model lends itself to being an instrumental tool for supply chain managers in the spirit of finding a balanced plan for the production and distribution of multiple products based on the three pillars of sustainability. For instance, policymakers can use this tool to select new 3PLs depending on their geographic location and the energy source used to operate their warehouses towards attaining a substantial reduction in the amount of carbon footprint generated, as proposed in Singh *et al.* [50]. The integration of this criterion (use of clean energy source by the 3PLs as supported by RECs) could be amended to the selection process, which shall provide a new incentive for supply chain collaboration allowing for the attainment of sustainability targets set by legislative entities. Moreover, given the rapid technological advancement and the fast-paced transition to clean energy sources, adjusting the production/distribution network settings is an activity that can be carried out and continuously revisited dynamically.

8. Conclusion and future research avenues

This work has devised a planning model that aids toward managing sustainable global supply chain operations at the tactical level. In essence, the proposed formulation utilizes cross-border energy transition to drive sustainability in CSCs and periodically (dynamically) adjusts the configuration of the 3PLs network used for products' transportation and distribution. The developed multi-objective optimization problem is solved using the weighted sum method, which revealed that improvement in one objective may not be attained without degrading another objective's performance due to the conflicting nature of these objectives. From an organizational perspective, it was shown that there are certain areas across the supply chain where small investments can lead to a significant reduction in emissions and increased social responsibilities. In particular, the trade-off analysis indicates the possibility of reducing 71% of CO_2 emissions while attaining 63% reduction in worker variations at the expense of only 4.47% cost increase once compared to solely optimizing the economic objective. The analysis also points out the possibility of attaining a substantial improvement of 86% in social measure, as reflected by the jobs' stability levels, at the expense of a maximum cost increase of around 9% as compared to the economic measure. In essence, investment in sustainability may attract more customers who are willing to pay higher prices for products when made aware that they have been produced in an environmentally and socially friendly manner.

While the case study presented in this work addressed the frozen food industry, it is essential to note that the proposed model is also applicable to other FSCs, especially for products exhibiting high seasonality. The model is generic and accounts for situations where backorder might occur due to excessive demand in specific periods.

In reality, a shortage in the form of backorder can be a viable alternative for food companies at some periods when there is insufficient inventory to fulfill an order and the hiring of skilled workers is not feasible on a short notice. Therefore, the impact of demand variation and backorder options on the economic, environmental, and social pillars of sustainability can also be investigated through the proposed model.

In terms of limitations, the conducted analysis does not consider hazards associated with energy generation from nuclear power, such as the risks and costs of treating and disposing of radioactive materials. This contributed to a biased solution towards the use of nuclear energy, as seen in Figure 5b. Furthermore, it shall be noted that the proposed model overlooks sourcing and production activities. To provide a generic model that integrates tactical decisions of sustainable FSCs, it is essential to include the procurement process of raw materials and considerations related to the production process, such as bill-of-material constraints, along with the remaining objectives. These extensions will be subject to future research, with particular emphasis on existing supply chains that better reflect various sectors' industrial reality. The consideration of uncertainty and risk factors applicable to FSCs specifically also poses a promising research avenue that would help identify the relationship between sustainability and resiliency. Moreover, the incorporation of relevant issues pertaining to partial, rather than complete, backordering in conjunction with multi-period delay-in-payments allowance (*e.g.*, [4]) in the context of global CSCs addressed in this work presents another potential extension. Finally, the weighted sum solution method provided compromised solutions, which is vital for a large-scale optimization problem where the objectives are conflicting. The efficiency of other multi-objective solution methodologies, such as metaheuristic for multi-objective optimization [56], should be explored when tackling such problems in future works.

Appendix A. Holding costs at the DCs per month

Country	Province	City	Holding cost ($/unit)
Canada	British-Columbia	Delta	18.42
	British-Columbia	Surrey	34
	Alberta	Calgary	16.75
	Ontario	Kitchener	16.5
	Ontario	Concord (1)	9.5
	Ontario	Concord (2)	9.5
	Ontario	Concord (3)	9.5
	Ontario	Vaughan	19.98
	Ontario	Concord (4)	9.5
	Ontario	Mississauga	16.5
	Quebec	Dorval	18.42
	Quebec	Saint-laurent (1)	34
	Quebec	Lachine	14.25
	Quebec	Montreal	11
	Quebec	Saint-laurent (2)	14.25
	Quebec	Anjou	13.75
United-States	California	Riverside	18.42
	California	Anaheim	17.17
	Illinois	Belvidere	17
	Illinois	Rochelle	18.42
	Indiana	Indianapolis	9.55
	Washington	Fife	3.69
	Texas	Fort Worth	15.67
	Georgia	Atlanta	15.13
	Maryland	Elkton	12.04
	Florida	Orlando	5.40
	Pennsylvania	Fogelsville	13.65
	Missouri	Carthage	14.69
	Massachusetts	Tewksbury	8.87
	Connecticut	Rocky Hill	4.10

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