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On the sustainable perishable food supply chain network design: A dairy products case to achieve sustainable development goals

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ABSTRACT

Perishable products require special handling measures that may have social and environmental impacts along with their well-known economic aspects. Therefore, the sustainability of food supply chains has gained ground; however, the sustainability of perishable food supply chains, is still not a fully explored field of study. Therefore, in this research, a multi-objective mathematical programming model is developed to optimize the cost, energy consumption, and the traffic congestion associated with such supply chain operations. In this study, product lifetime uncertainty is explicitly modeled as a Weibull random variable, and food perishability is assumed to be affected by vehicle refrigerator utilization, which is considered as a decision variable. In addition, multiple vehicle types and multiple product types are considered. A dairy supply chain case is investigated, and the interrelations and interactions of all three aspects of sustainability, also known as the three triple bottom lines (TBL) of sustainability, are studied. The results indicate that emphasizing the economic aspect, for highly perishable products, the environmental impact of the chain may increase by 120%, and for the highly congested road networks, the social impact may rise by 51%. However, a 15% economic compromise can improve the sustainability of the supply chain network design by 150%. It is also shown that road congestion and the uncertain perishability of the products are critical factors that can, although differently, affect the operation and the design of the supply chain. This study contributes to the sustainable development goals (SDG's) such as Zero Hunger (SDG 2); Affordable and Clean Energy (SDG 7); Decent Work and Economic Growth (SDG 8); Industry, Innovation, and Infrastructure (SDG 9); Responsible Consumption and Production (SDG 12); Climate Action (SDG 13) and Peace, Justice, and Strong Institutions (SDG 16). The results suggest that decision-makers can significantly reduce the environmental and social influences of the supply chain even without drastically compromising the economic aspect.

1. Introduction

Supply chains of food products are distinguished from the ones for other products due to their fundamental differences, such as the significant and constant variations in food product quality from the upper-hand side to the lower-hand side of the chain (Bloemhof and Soysal, 2017). In many cases, food product quality, especially for fresh food, is not constant and tends to decay over time until it reaches zero (Osvald and Stirn, 2008). A product is perishable if it has at least one of the conditions of 1) its quality of quantity noticeably deteriorates, 2) the reduction in its functionality has severe consequences, or 3) its value decreases over time (Amorim et al., 2013). Specifically, food products are usually considered perishable because the quality of the food product is known to decay rapidly, not only during the production and storage processes but also in the distribution (Govindan et al., 2014). The survival and success of food supply chains depend highly on delivering fresh products to their customers (Musavi and Bozorgi-Amiri, 2017). The design of a perishable food supply chain, like that of any other type of supply chain, plays a crucial role in this regard (Babazadeh and Sabbaghnia, 2018). Therefore, the "perishable food supply chain network design" (PFSCND) problem should be approached

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considering the specific features of the supply chains for perishable food. PFSCND encompasses a wide range of decisions including, but not limited to, facility location, production, storing, and transportation of food products with the property of diminishing quality. Due to the nature of these products and the operations required to produce, process, and distribute, perishable food supply chains have distinct and significant economic, social, and environmental aspects. PFSCND decisions affect not only the sustainability of the chain but also the quality of the products, which in turn affects customer satisfaction and business success (Yakavenka et al., 2019).

The increase in global rate of natural resource consumption along with the growth of population has put extra pressure on the environment (Kannan et al., 2020). However, with the global awareness about environmental and social impacts of such operations, decision-makers are forced to take all these aspects along with several other features into consideration (Meneghetti and Monti, 2015). In addition, researchers have been attracted and focused on the sustainability aspect of supply chains as a salient subject (Govindan et al., 2020). Therefore, “sustainable food supply chain network design” (SFSCND) is recognized as a significant problem. In this regard, several Sustainable Development Goals (SDGs) are defined (Wieben, 2016). This study can be a step toward achieving these SDGs. Specifically, it is known that energy consumption is one of the significant indicators for evaluating the sustainability of supply chains (Yakovleva et al., 2012). On the other hand, SDG 2 is focused on reducing food loss and waste. Perishable food products are very likely to be lost or wasted. Usually, in order to decrease the amount of perished food products, energy must be consumed. On the other hand, in SDG 7, it is stated that in developing countries, it is crucial to minimize the energy consumption for reducing food loss and waste. However, significant long-term investments may not be an option for many businesses in the fluctuating economic climate of developing countries. Therefore, this study provides a balanced trade-off between SDG2 and SDG 7 in perishable food distribution, especially for the developing countries. Therefore, energy efficiency should become a goal of food supply chain sustainability. In addition, with a significant portion of food products being transferred through road networks, food supply chain transportation activities are not only notable regarding fuel energy consumption, but are also significant concerning their social impacts. More specifically, costly, frequent, and yet vital road transportations in food supply chain networks contribute to traffic congestions to the extent of their frequency, which is usually substantial due to the food products’ specific characteristics (Jouzdani et al., 2013). By reducing the impact on traffic congestion, it is possible to ameliorate the burden on the transportation system. This not only decreases the social impact of the chain, which is the subject of SDG 16 but also frees up the capacity of the transportation system to be used for economic growth, i.e., SDG 8. Failing to consider salient aspects of food supply chains may have not only severe economic consequences but also social and environmental impacts (Jouzdani et al., 2018). Therefore, along with conspicuously important economic aspects, in food supply chains, energy consumption and traffic congestion impacts can be regarded as significant criteria for decision making in “sustainable food supply chain network” (SFSCN) design which in turn introduces the “sustainable perishable food supply chain network design” (SPFSCND) problem.

The perishable goods may not be stored away for a long time and may decay during their transportation from one echelon of the supply chain to another. The perishability of such products is time-dependent, i.e., the probability of perishing increases through time. Furthermore, the rates at which the products deteriorate depend on the conditions of the product and its environment. For example, the products may perish at a higher pace as the surrounding air temperature increases. On the other hand, the conditions under which the perishable products are kept are affected by the design and planning of the chain. More specifically, the time during which the products remain in each facility and in each vehicle is highly dependent on supply chain design. Therefore, the “perishable food supply chain network design” (PFSCND) under the inherent uncertainty is a prominent aspect of businesses working in the perishable food industry.

The main focus of the majority of studies on PFSCND is, in many cases, the total cost/benefit of the “supply chain network” (SCN), neglecting the environmental and social impacts of the problem. More specifically, Hasani et al. (2012) proposed a robust closed-loop “supply chain network design” (SCND) of perishable products considering uncertainty in costs. They modeled a multi-product multi-period multi-layer SCND problem; however, they did not consider the sustainability aspects of the problem. In a paper by de Keizer et al. (2015), a simulation-based optimization approach was proposed to minimize the total cost of the perishable goods SCND problem. In another research, de Keizer et al. (2017) considered the heterogeneous quality decay of the perishable products with the objective of maximizing the total profit of the supply chain network. Song and Ko (2016) proposed a model for routing of vehicles in a PFSCND problem considering refrigerated and general-type vehicles with the objective of maximizing total customer satisfaction.

According to a recent model-oriented review on SFSCNs by Zhu et al. (2018), the papers published considering all the aspects of sustainability, i.e., economic, environmental, and social, in food supply chains are rare. Obviously, when it comes to PFSCND, they are rare, still (Bloemhof and Soysal, 2017). Specifically, the papers addressing the SPFSCND problem have mostly considered the environmental and economic aspects neglecting the social impact. More specifically, Validi et al. (2014) considered the total cost and the CO_2 emission in a dairy SCND problem. In an article by Govindan et al. (2014), PFSCND problem with the aim of minimizing the cost associated with greenhouse gas emissions as well as the total cost of the network. Bortolini et al. (2016) studied the fresh food SCND problem considering three objectives of minimizing the total cost, carbon emission, and delivery time. Colicchia et al. (2016) proposed a bi-objective mathematical programming model for minimizing the total cost and CO_2 emissions of the supply chain network. Musavi and Bozorgi-Amiri (2017) addressed the hub location-scheduling in the context of PFSCND, minimizing the total transportation cost, maximizing the product quality, and minimizing the total CO_2 emission. In a paper by Yavari and Zaker (2019), resilience in green perishable products SCND was investigated. They considered two objectives of minimizing the total cost and carbon dioxide emission. In addition, uncertainty, especially the uncertainty of product lifetime, which plays a critical role in regarding the perishability and sustainability, and their interactions in FSCND, is seldom considered in the previously published papers (Jouzdani et al., 2013). Furthermore, none of the previously published papers has investigated the combination of uncertain perishability of products, the effects of traffic congestion, travel time, and temperature variability during different periods of time. Finally, few related articles have taken into account the time value of money to calculate the values in cash flow over multiple periods of time (Meneghetti and Monti, 2015).

Based on what was elaborated above, the main purpose of this paper is to study the suitability aspects of PFSCND, considering the most important practical features and most significant characteristics that are not investigated in previously published articles. Some of the major questions that are addressed in the current study are as follows.

1) How may a balance among all the three aspects of sustainability be reached in PFSCND?
2) How the perishability of food products affects the sustainability of PFSCND?

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3) What is the effect of traffic congestion on sustainable perishable food supply chains?

To this aim, a "multi-objective mixed integer programming" (MOMIP) model is proposed. The model aims at minimizing three objectives of 1) the net present value of supply chain total cost, 2) the total road traffic congestion, and 3) the total fuel consumption that represents the environmental, economic, and social aspects of the network, respectively. Although SDG 13 is not directly achieved by the objectives of the proposed model, it is addressed by minimizing the fleet energy consumption, which in turn minimizes the carbon footprint of the distribution system. It is known that energy consumption and emissions are among the most well-known and most widely-used environmental impact indicators. In addition, it is shown that there is a close relationship between energy consumption and CO_2 emissions (Soytas et al., 2007). Therefore, one may choose to use either. In this paper, the energy consumption is preferred because the reduction in energy consumption not only reduces the emissions but also can have wider social and global impacts such as moderating the price of energy, fleet utilization and maintenance, fuel availability, accessibility, and affordability, etc. Furthermore, 15% of total global energy consumption is attributed to cooling systems and cold chains (Coulomb, 2008). On the other hand, 40% of food products are transported using refrigerator-equipped vehicles (James et al., 2006). This, along with the increasing demand for food products, will signify the energy consumption in the food supply chains. From another perspective, it is known that travel time is significant in the transportation of perishable products, and is considered by other researchers in this context (Yakavenka et al., 2019). Here, we aim at studying the interrelations and interactions of perishability and sustainability. This research directly addresses SDG 12 by focusing on the design of perishable food supply chains which "adjusts" the "multi-dimensional" problem of the possible "structural changes" of the chain. In addition, the aforementioned trade-off is explicitly delineated in SDG 12 and is investigated in this study. Traffic congestion can take into account the travel time and social impacts, making it an appropriate social impact indicator. Therefore, in this paper, a two-echelon supply chain with multiple product types and different product perishability properties is considered, and it is assumed that the products are transported by means of different types of vehicles equipped with refrigerators that can be utilized. The products are assumed to be subject to perishability not only during the transport but also when stored. The vehicles are assumed to have different features, such as fuel consumption, depending on whether they utilize their refrigerator. In addition, the traffic congestion not only can represent the social aspect of the chain but also as a significant factor that affects the perishability of the products during transport depending on the utilization of the vehicle refrigerator and it becomes even more important when having the change of temperature during multiple periods of time. Having multiple time periods, the time value of money becomes significant and is incorporated in the calculations. In addition, to consider the inherent uncertainty in the perishable product lifetimes, a chance-constrained programming model is presented. These sustainability and product perishability interrelations and interactions are the main focus of our paper. Furthermore, a case of a dairy products producer firm in central Iran is studied, and analyses are conducted using "revised multi-choice goal programming" (RMCGP) to illustrate the implications of the model in practical situations.

To the best of authors' knowledge, this study is the first to incorporate all these features in SPFSCND. The contribution of this study is the combination of the following.

1) Explicitly modeling the uncertainty of perishable products lifetime as a random variable through chance-constraint programming, and considering the time-varying perishability, allowing for modeling the problem for temperature changes in different seasons in the case of products such as dairy
2) Assuming multiple types of products with different properties including perishability, weight and sales price, and considering multiple vehicle types with different capacities, fuel consumption and traffic congestion impacts
3) Incorporation of the decision on the utilization of each vehicle's refrigerator and its effect on product perishability and total fuel consumption
4) Studying the effects of traffic congestion on the travel time and in turn on the perishability of the products during transportation considering the uncertain nature of perishability
5) Considering multiple planning periods and incorporating the time value of money impact in the form of interest rates into calculations of the total cost net present value

6) Providing a means to achieving the sustainable development goals (SDG's) such as Zero Hunger (SDG 2); Affordable and Clean Energy (SDG 7); Decent Work and Economic Growth (SDG 8); Industry, Innovation, and Infrastructure (SDG 9); Responsible Consumption and Production (SDG 12); Climate Action (SDG 13) and Peace, Justice, and Strong Institutions (SDG 16).

The exposition of the remainder of this paper is as follows. A review of the most related and recent articles in the literature is presented in the next section. Section 3 addresses the problem assumptions and the mathematical model. Section 4 discusses the solution approach, and a dairy industry case is studied, and the analyses are in Section 5. Finally, Section 6 provides the conclusion of the paper and provides suggestions to extend this study.

2. Review of literature

Govindan et al. (2017) reviewed the literature on SCND under uncertainty. Earlier, Melo et al. (2009) presented a review of the problem. These, along with several other published articles, show that the literature on SCND is quite rich, and numerous papers are published in the area of research. Within this field of study, sustainability has also gained ground, with several researchers addressing the subject. Specifically, Eskandarpour et al. (2015) reviewed the literature on sustainable supply chain network design (SSCND) investigating different aspects of a considerable number of published papers in this regard. A more narrowed down topic of research is the sustainable food supply chain network design (SFSCND) problem on which a detailed review of the literature can be found in a book chapter by Bloemhof and Soysal (2017), and a review by Zhu et al. (2018). Since the literature on SCND, SSCND, and SFSCND have already been thoroughly addressed in the aforementioned review articles, in this paper, we limit the literature review to the focus on perishability, addressing the PFSCND and SPFSCND. In this Section, the related recently published papers are presented in chronological order, and a summary of the features of the most related articles on PFSCND is presented in Table 1.

2.1. Literature on PFSCND

Food supply chains usually deal with perishable products. The quality characteristics of such food products make the PFSCND difficult (Ghezavati et al., 2017). Different PFSCNDs result in different ways of production, storage, and transport, which in turn affects all the aspects of the supply chain. Although SCND is a well-explored area of research, few papers are published on PFSCND. In this section, the most relevant papers published on the subject are reviewed.

The performance of food supply chains regarding the total cost, total revenue, and the quality of the delivered food is affected by

Table 1
Summary of the features of articles on perishable food supply chain network design.

Article	Sustainability Dimension		Number of Objectives	Time Value of Money Consideration	Decision Variables				Uncertainty				Multi-vehicle	Multi-Period	Multi-Product	Number of Echelons	Uncertainty Modelling	Solution Method	Case Study
	Environmental	Social			Location	Transportation	Routing	Inventory	Perishability	Demand	Costs	Other							
Jouzdani et al. (2013)		✓	1	✓	✓	✓				✓				✓		4	FP	LINGO MINLP	Dairy
Costa et al. (2014)	✓		1			✓		✓		✓				✓	✓	2	TSSP	CG	–
Govindan et al. (2014)	✓		2		✓		✓	✓					✓	✓		2	N/A	MOPSO and AMOVNS	–
Validi et al. (2014)	✓		2				✓									3	N/A	MOGA-II and NSGA-II	Dairy
Khalili-Damghani et al. (2015)			2		✓		✓						✓			2	N/A	NSGA-II	–
Kovačić et al. (2015)			1	✓	✓											2	N/A	Unspecified	Baby Food
Meneghetti and Monti (2015)	✓		1	✓	✓											2	N/A	CP	Frozen Food
Bortolini et al. (2016)	✓		3			✓							✓		✓	4	N/A	Expert System	Fruit and Vegetables
Colicchia et al. (2016)	✓		2			✓										3	N/A	LINDO	Chocolate
Saif and Elhedhli (2016)	✓		2		✓	✓		✓					✓			3	N/A	LD, SBO	Meat and Vaccine
Musavi and Bozorgi-Amiri (2017)	✓		3			✓							✓			2	N/A	NSGA-II	–
Banasik et al. (2017)	✓		2		✓									✓		2	N/A	Xpress-IVE	Mushroom
Behzadi et al. (2017)			1			✓		✓				✓		✓	✓	2	SSP	CNC Solver	Kiwifruit
de Keizer et al. (2017)			1		✓	✓									✓	3	N/A	CPLEX Solver	Flower
Sazvar et al. (2018)	✓	✓	3			✓		✓						✓	✓	2	N/A	AUGMECON	–
Singh et al. (2018)			1		✓	✓									✓	2	N/A	CPLEX Solver	–
Darestani and Hemmati (2019)	✓		2		✓	✓		✓	✓	✓	✓			✓	✓	8	RO	CCM, WSM, TH	–
Yakavenka et al. (2019)	✓	✓	3			✓							✓			2	N/A	Excel Solver	Fruit
Yavari and Zaker (2019)	✓		2		✓	✓		✓						✓	✓	4	N/A	LP-Metric	Dairy
Biuki et al. (2020)	✓	✓	3		✓	✓	✓	✓		✓				✓	✓	4	Fuzzy	PSO, GA	–
Dutta and Shrivastava (2020)			1		✓	✓						✓				3		SSP	Milk
Manouchehri et al. (2020)			1			✓	✓	✓					✓	✓	✓	2	N/A	CPLEX Solver, VNS	Poultry
Current Paper	✓	✓	**3**	✓	✓	✓		✓	✓				✓	✓	✓	**2**	**CSP**	**RMCGP**	**Dairy**

Abbreviations: FP: Fuzzy Programming, TSSP: Two-Stage Stochastic Programming, CG: Column Generation, SSP: Scenario-based Stochastic Programming, CP: Compromise Programming, LD: Lagrangian Decomposition, SBO: Simulation-based Optimization, MINLP: Mixed Integer Non-Linear Programming, MOPSO: Multi-Objective Particle Swarm Optimization, AMOVNS: Multi-Objective Variable Neighborhood Search, NSGA: Non-dominated Sorting Genetic Algorithm, AUGMECON: Augmented ε-constraint Method, RO: Robust Optimization, CCM: Comprehensive Criterion Method, WSM: Weighted Sum Method, TH: Torabi-Hassini, PSO: Particle Swarm Optimization, CSP: Chance-constrained Stochastic Programming, RMCGP: Revised Multi-Choice Goal Programming, VNS: Variable Neighborhood Search.

the degree of the perishability of the products. A single-objective MILP was proposed by de Keizer et al. (2017) to model the quality decay of perishable products. They considered heterogeneity in quality and studied the results of several related test problem instances to investigate the effects of different decay levels and rates. They studied the case of a floricultural supply chain in Europe. Pointing out the similarity between the flower distribution network and food supply chains, they conducted several analyses. One of their findings was that the increase in the number of distribution centers leads to an increase in revenue due to a 3.25% increase in product quality. Dutta and Shrivastava (2020) proposed a non-linear mathematical programming model for the PFSCND problem. They followed a scenario-based approach to model uncertainty due to disruption. They studied the case of a milk supply chain and showed the impacts of disruption on the PFSCND through statistical analysis of simulation results on the value at risk.

Product perishability is known to play a significant role in the strategies and decisions regarding the PFSCND (Hasani et al., 2018). Behzadi et al. (2017) investigated the robustness and resilience of agricultural supply chains. They developed a two-stage stochastic programming model to study the perishability of the products as an exponential random variable. They aimed at maximizing the profit of the chain and studied a case of the kiwifruit supply chain. They illustrated the impacts of risk management strategies and perishability on the total profit of the chain. They showed that as perishability surpasses 30%, the robust strategy loses its effectiveness, and instead, a risk management strategy yields a better result. Singh et al. (2018) studied the location-allocation problem for the design of cold chains. In their paper, perishability was represented by the deterioration of product value. They proposed a single-objective model for cost minimizations and used big data approximations for distance calculation. They solved a hypothetical problem using the data from China and found out that institutional innovation among supply chain members is essential for demand satisfaction and quality requirements fulfillment.

Temperature is one of the most important features of PFSCND. Kovačić et al. (2015) studied the impacts of deciding the locations of facilities and, thus, the transportation lead time on the perishability of products. They investigated the role of Extended Material Requirement Planning in lead-time and temperature perturbation evaluations. They considered a four-echelon supply chain presenting the case of a perishable baby food supply chain in Spain. Their research was among the very few to incorporate the interest rate into the calculations of PFSCND. They showed that for highly perishable ingredients of baby food, with a perishability rate above 10%, the net present value of the chain may become negative, showing an economic loss. In a paper by Manouchehri et al. (2020), a single-objective mathematical programming model for the production-routing of perishable products was presented. They assumed deterministic parameters and solved their model using a hybrid meta-heuristic algorithm. Their results from a poultry supply chain case in Iran showed the significant potential for cost reduction considering the optimized inventory levels and temperatures in different periods. Their results showed that the optimized temperature varies from 4 to 15 °C in different time periods.

The review of literature on PFSCND shows that the high perishability of products significantly affects decision-making in this regard. In addition, interest rate and perishability uncertainty are the two concepts that are rarely considered in the previous studies in this area of research. Considering the significance of temperature, the uncertainty in perishability is a crucial modeling feature. In addition, the previously published papers indicate that temperature plays a critical role in the design and planning of perishable food supply chain design.

2.2. Sustainability in PFSCND

As revealed from the review of literature on PFSCND, the perishable food supply chains have several aspects that impact the environment and society. For instance, providing low temperature for storage and handling of such products require higher levels of energy consumption and different transportation from the case of conventional supply chains. Therefore, in this section, the most relevant papers on the sustainability of the PFSCND are reviewed.

Some of the articles focus on proposing efficient solution methods for SPFSCND problem. Validi et al. (2014) presented a case study of a dairy distribution network aiming at total cost minimization and carbon dioxide emission reduction. However, they did not explicitly consider the perishability of the products in their model. They solved their model using a hybrid method based on Genetic Algorithm (GA) and compared their performance of their algorithm with two other multi-objective methods. The result showed the superiority of the hybrid method over the other two. In a paper by Khalili-Damghani et al. (2015), a bi-objective mixed integer mathematical programming (BOMIP) model for minimizing the total cost and balancing the workload of distribution centers in an SCN was proposed. They considered the delivery due dates of a single perishable product. They utilized a customized "Non-Dominated Sorting Genetic Algorithm-II" (NSGA-II) to solve their deterministic model, and the results show that their proposed algorithm performs better than the ε-constraint method. Darestani and Hemmati (2019) followed robust optimization and queue theory approaches to present a bi-objective model for PFSCND. They considered the uncertainty of some parameters, including operational and transportation costs, product lifetime, demand, and capacity. Their objective was the minimization of the total greenhouse gas emission and the total supply chain network cost. They studied numerical experimental problems in order to investigate three methods in solving the model in terms of the performance of each method. The results of their analysis showed the superiority of Torabi-Hassani method over other implemented algorithms.

Storage of perishable products in SPFSCND has been a subject on which several researchers have focused. In a paper by Costa et al. (2014) a supply chain of perishable vegetables assuming sustainability of the chain was studied. They presented a mathematical programming model and solved their mode using a two-stage stochastic programming approach. The uncertainty was incorporated into their model, and they illustrated the performance of their model through some numerical test problems. The results show that when inventories are allowed, an 8% improvement in demand fulfillment is achievable when the planting area is large (4,000 m^2) for their problem. Meneghetti and Monti (2015) proposed a model for optimizing the design of an "automated storage and retrieval" (ASR) system for refrigerated items. They considered several factors, including the energy requirements of the facilities and the equipment along with total carbon dioxide emission and the total supply chain cost, and solved their model by using constraint programming. They analyzed the effects of storage facilities on the environmental impacts and the total cost and presented numerical results, including that when the storage temperature decreases from −21 °C to −29, the energy consumption and the total cost soar up to 53.5% and 12.2%, respectively.

As one of the most important analyses, researchers have addressed the interrelation and the trade-off among the aspects of the sustainability in SPFSCND. Colicchia et al. (2016) proposed a bi-objective mathematical programming model of a PFSCN. Their objectives were minimizing the CO_2 emissions and the distribution cost. They combined these two objectives into a single one comprised of a weighted average of the two objective functions. The results from the case study indicate that there exists a design for the chocolate supply chain to decrease the total cost and the total emission by 3.1% and

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0.73%, respectively. Moreover, a 15.1% decrease in CO_2 emission was illustrated to be achievable at the cost of a 3.5% increase in the total cost. Bortolini et al. (2016) presented an expert system to optimize three objectives of cost, delivery time, and carbon emission of a perishable product distribution network and provided a case of Italian fresh fruit and vegetable distribution. The outcomes of their analysis on the case suggested a solution that, although increased the total cost by 2.7%, could decrease the carbon footprint by 9.6%. Saif and Elhedhli (2016) proposed a simulation-based optimization approach for an eco-friendly cold chain supply chain design. They presented a mixed-integer programming model considering the total cost and the total emission. They studied two cases of perishable products in Canada: meat and vaccine. The results from their cases showed that the environmental impacts of the chain by about 1% could be reduced even without an increase in the total cost. Banasik et al. (2017) studied the design of an agricultural supply chain, presenting a bi-objective model. They specifically studied the case of a two-echelon mushroom supply chain. They did not explicitly address the perishability of the products. Their results indicate that the chain can increase its profitability by 11% while decreasing the environmental impact by 28%. In an article, Sazvar et al. (2018) also presented a multi-objective linear program considering all three aspects of the SFSCND. They optimized their deterministic three objectives of the total cost, total greenhouse gas emission, and the social health using AUGMECON. They found out that as supply chains move toward more organic food products, the social impact of the chain may be four times better than that of a conventional chain. Similar patterns were observed for environmental aspects of the chains, emphasizing the significance of organic food products.

Research by Yavari and Zaker (2019) addressed the green PFSCND. Their model considered the resilience of the integrated two-echelon chain under power disruption. They presented a bi-objective model to minimize the chain's total cost and the total CO_2 emission and solved the proposed model using the LP-metric method. They studied a four-echelon supply network of dairy products in Iran, and comprehensive analyses of the results depicted the effects of the integration of chain and product lifetime. They showed that integration could improve the chain's total cost and total emission by 21% and 25%, respectively. In an article by Yakavenka et al. (2019), an SSCND model with multiple objectives, for all three aspects of sustainability, was proposed. They presented a case of fresh fruit in order to study the perishability of products. They also considered the transportation of the products by means of refrigerated containers and proposed the model assuming deterministic parameters. In their research, the environmental and social impacts are represented by total CO_2 emissions and total transportation time. They studied a case of Eastern Europe and analyzed the effects of objective weight factors. The analysis of the problem revealed that optimizing the total cost may lead to a 111% increase in delivery time while optimizing the delivery time not only increases the total cost by 22.62% but also worsens the total emission objective by 34.52%. In addition, they showed that optimizing the CO_2 emissions increases the cost and delivery time objectives by 22.33% and 70.37%, respectively. Zanoni et al. (2019) proposed a model for green cold chain network design. They considered the perishability of products, as well as the impact of transportation and storage processes. They analyzed some numerical examples and showed the impact of the number of opened DCs on the total cost and the total emission. They found out that temperature is a significant factor in the chain's performance, while the impact of shipment lot size is limited. Their results indicate that opening new distribution centers increases the total cost when holding temperature is 273K while this is the opposite at 263K and 253K temperature. They attributed this to the decay of perishable products at higher temperatures. Biuki et al. (2020) proposed a multi-objective mixed-integer programming model for the location-routing-inventory problem in an SSCND of perishable products considering demand uncertainty. They proposed a hybrid of Genetic Algorithm and Particle Swarm Optimization to solving several randomly generated test problems to analyze the impact of different parameters of their model. Their results showed that facility location decisions, and especially that of manufacturing centers, play a crucial role in the sustainability of the chain. In addition, the analyses indicated that moving toward a more sustainable supply chain translates to decentralization, and sustainability can be reached at the cost of slightly compromising the economic aspect of the supply network.

The subject of sustainability in PFSCND is confined to the environmental aspect of the problem in many previously published papers. Specifically, the environmental impact is measured through CO_2 emissions. However, perishable food supply chains may affect the environment in several other ways, and their impacts may be measured by other indicators such as energy consumption. This can be justified, as discussed in the Introduction. In addition, sustainability urges us to consider social impacts as a salient aspect of the PFSCND. This has been rarely addressed in the literature. Specifically, as discussed in the Introduction, traffic congestion as an important social impact of those chains needs to be more thoroughly studied. As mentioned before, incorporating the interest rate into the calculations of PFSCND is rare. Obviously, for the SPFSCND, it is rare still. Although perishability has been addressed in the literature, the uncertainty, which is an inherent nature of the products in this context, is seldom explicitly considered. Furthermore, although the storage of perishable products has been studied in previously published papers, transportation using refrigerated vehicles needs to be more thoroughly explored. More specifically, no paper could be found to consider the use of the refrigerator as a decision variable.

2.3. Literature review summary

According to the review of the papers published on the subject, the literature on PFSCND and SPFSCND is still developing and needs to be more fully explored. Some of the findings of this review are as follows.

The perishability of food products is inherently a stochastic process; however, the uncertainty of the perish process is explicitly considered in a few previous studies. Furthermore, the deterioration of the products depends highly on the conditions under which they are transported; however, the papers published on the perishable supply chain networks are not addressed in the literature. More specifically, time-varying perishability which allows for modeling the problem for the impact of temperature changes in different time periods, e.g., seasons in the case of perishable products considering refrigerator-equipped vehicles with the decision on the utilization of refrigerators is not addressed in previously published papers.

While some previously published papers have considered multiple periods of time in the planning horizon, a few have addressed the time value of money, which has a prominent role in making the cash flow calculations closer to reality. In addition, all three important decision variables in SCND, i.e., location, transportation, and inventory, are present in the proposed model in order to provide the possibility of further and deeper analyses of perishable products SCND while this is not the case for the published papers on the subject.

In terms of modeling technique and solution method, the current research follows less explored approaches. More specifically, CSP has not been applied to the problems in SFSCND. Accordingly, RMCGP, a relatively new solution method, has not been utilized to solve the problems in this domain. Finally, as a significant area of application, this study addresses the dairy industry, which deals with some of the most perishable products.

Furthermore, multiple vehicles, multiple products, and multiple periods of planning are not simultaneously considered in any of the previously published articles in the field of SPFSCND. The review of

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the related literature reveals that the papers addressing all three aspects of the sustainability of such chains, i.e., the triple bottom lines (TBL) of sustainability (Darbari et al., 2019; Govindan et al., 2020) are rare, and when it comes to the sustainability of perishable food products, they are rare still. This is in agreement with the results from a recent review by Rashidi et al. (2020). In addition, it is clear that a multi-objective approach to model the three dimensions is not fully explored and only a few papers are published in this regard.

The contributions of this paper are in accordance with a review by Sel and Bilgen (2015). Especially, they suggested the incorporation of perishability and uncertainty into multi-objective models for dairy supply chains. In addition, our findings are in agreement with a recent review paper by Zhu et al. (2018), and the reader is referred to their review for a comprehensive review of the papers published on SFSCNs.

3. Mathematical formulation

A set of assumptions under which the model is constructed is presented. The sets, indices, variables, and parameters are introduced, and finally, the mathematical model is discussed.

3.1. Assumptions

The proposed model is constructed considering the assumptions delineated in what follows:

1) All parameters are deterministic except the lifetime of each product type in each time period that follows Weibull distribution because the decay of perishable products is a stochastic process, and their lifetime can be suitably modeled by well-known random distributions such as Weibull (Pahl and Voβ, 2014). More specifically, Weibull distribution has been shown to be able to suitably model the perishability of dairy products (Sel et al., 2017). In addition, this is in agreement with the opinions of the experts from the case study.
2) As some of the previously published papers proposed considering the use of refrigerators in perishable product transportation (Song and Ko, 2016), in this paper, it is assumed that all the vehicle types are equipped with refrigerators which are decided to be utilized for transportation of products from each "distribution center" (DC) to each retailer.
3) Following the previous assumption, the perishability of the product during transport depends on whether it is transported with the refrigerator utilized or not.
4) Similar to what assumed in a paper by Jouzdani et al. (2018) on dairy products, here, it is assumed that there are multiple products with different perishability properties, i.e., the products perish at different rates.
5) The total cost comprises the fixed facility location, purchase, transportation, and holding costs. These are some of the most commonly addressed, and the most essential components of the total cost in SCND (Govindan et al., 2017).
6) Similar to Dayhim et al. (2014), in this paper, the supply chain operations' environmental impact is evaluated by calculating the total amount of energy consumed by the fleet.
7) The social influence of the chain operations is evaluated by calculating the total traffic congestion impact of the fleet. This is also assumed by Jouzdani et al. (2013).
8) Fleet energy consumption is influenced by several factors, including the load, road conditions, vehicle type, weather conditions, driver profile, speed, etc. (Murphy, 1999). In this paper, it is assumed that the fuel consumption of vehicles depends only on the travel distance and refrigerator utilization, as two of the most important factors (Song and Ko, 2016).

3.2. Mathematical model

Having the model elements defined as presented in Appendix 1, the mathematical model is discussed in this Section. In what follows, the three objective functions optimizing the environmental, economic, and social impacts of the chain are presented following the constraints.

$$\min\ z_{eco} = \sum_{i=1}^{D} f_i \times y_i + \sum_{i=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{V}\sum_{t=1}^{T} \frac{(b_k + c_{kt}s_{ir}) \times z_{ikrt}}{\prod_{j=1}^{t}\left(1+\rho_j\right)} + \sum_{p=1}^{P}\sum_{t=1}^{T}\sum_{i=1}^{D} \frac{\eta_{pt} \times H_{ipt}}{\prod_{j=1}^{t}\left(1+\rho_j\right)} + \sum_{i=1}^{D}\sum_{p=1}^{P}\sum_{t=1}^{T} \frac{h_{ipt} \times I_{ipt}}{\prod_{j=1}^{t}(1+\rho_j)} \tag{1}$$

$$\min z_{env} = \sum_{i=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{V}\sum_{t=1}^{T} \gamma_{ikrt} \times v \times s_{ir} \times u_k^R \times z_{ikrt} + \sum_{i=1}^{D}\sum_{r=1}^{R}\sum_{k=1}^{V}\sum_{t=1}^{T} (1-\gamma_{ikrt}) \times v \times s_{ir} \times u_k^O \times z_{ikrt} \tag{2}$$

$$\min z_{soc} = \sum_{i=1}^{D}\sum_{r=1}^{R}\sum_{t=1}^{T} \phi_{irt} \times \tau_{irt} \tag{3}$$

Subject to

$$\sum_{k=1}^{V}\sum_{i=1}^{D}\left(1-\alpha_p^O-\alpha_p^R\right) \times x_{ipkrt} = d_{rpt} \quad \forall r \in \Upsilon, \forall p \in \Pi, \forall t \in \Psi \tag{4}$$

$$\tau_{irt} \times q_{ipkrt} \le \delta_{pt}^R \times \sqrt[\beta_{pt}^R]{-\ln\left(1-\alpha_p^R\right)} \times \gamma_{ikrt} + \forall r \in \Upsilon, \forall p \in \Pi, \forall t \in \Psi, \delta_{pt}^O \times \sqrt[\beta_{pt}^O]{-\ln\left(1-\alpha_p^O\right)} \times (1-\gamma_{ikrt}) \quad \forall k \in \Phi, \forall i \in \Delta \tag{5}$$

$$\sum_{p=1}^{P} I_{ipt} + \sum_{r=1}^{R}\sum_{k=1}^{V} x_{ipkrt} \le y_i \times m_i \quad \forall t \in \Psi, \forall i \in \Delta \tag{6}$$

$$I_{ipt} = (1-\pi_p) \times I_{ip(t-1)} + H_{ipt} - \sum_{r=1}^{R} \times \sum_{k=1}^{V} x_{ipkrt} \quad \forall p \in \Pi, \forall t \in \Psi, t \ge 2, \forall i \in \Delta \tag{7}$$

$$I_{ip1} = H_{ip1} - \sum_{r=1}^{R}\sum_{k=1}^{V} x_{ipkr1} \quad \forall p \in \Pi, \forall i \in \Delta \tag{8}$$

$$I_{ipT} = 0 \quad \forall p \in \Pi, \forall i \in \Delta \tag{9}$$

$$q_{ipkrt} \le M \times x_{ipkrt} \quad \forall r \in \Upsilon, \forall p \in \Pi, \forall t \in \Psi, \forall k \in \Phi, \forall i \in \Delta \tag{10}$$

$$\gamma_{ikrt} \le \sum_{p=1}^{P} q_{ipkrt} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall k \in \Phi, \forall i \in \Delta \tag{11}$$

$$I_{ipt}, H_{ipt}, x_{ipkrt} \ge 0, y_i, \gamma_{ikrt}, q_{ipkrt} \in \{0,1\} \forall r \in \Upsilon, \forall p \in \Pi, \forall t \in \Psi, \forall k \in \Phi, \forall i \in \Delta \tag{12}$$

Eq. (1) calculate the total supply chain cost's present value. More specifically, in the first term of Eq. (1), the total facility location cost is formulated. In the other sentences of Eq. (1), the present worth factor is utilized to convert the future costs to their corresponding present values. The present worth factor is defined as $1/(1+\rho_t)$ where ρ_t is the interest rate in period t and is used to convert the cash flow in time period t to its present value (Park et al., 2007). Therefore, the second term is the present value of transportation costs, the third sentence calculates the present equivalent worth of the DC purchase cost, and the fourth term is the total inventory cost present worth.

An important aspect of food supply chain operations is energy consumption, especially fossil fuel consumption of transport vehicles. This is crucial because of the frequency of transports and the environmental and social impacts of fuel consumption. Therefore, the fuel consumption of vehicles when utilizing and not utilizing their refrigerators is minimized in the second objective, which is presented in Eq. (2).

The third objective minimizes the SCN social influence. Because of the high frequency of transports in food supply chains, traffic congestion caused by such activities is significant compared to other industries. Therefore, the total traffic congestion impact of the supply chain is minimized in Eq. (3) where we have the following definitions.

$$\tau_{irt} = \tau_{irt}^{0} \times \left(1 + 0.15 \times \left(\frac{\phi_{irt}}{\kappa_{ir}}\right)^{\beta}\right) \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta \tag{13}$$

$$\phi_{irt} = \phi_{irt}^{0} + \sum_{k=1}^{V} \omega_k \times z_{ikrt} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta \tag{14}$$

$$z_{ikrt} = \left\lceil \frac{\sum_{p=1}^{P} w_p \times x_{ipkrt}}{a_k} \right\rceil \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall k \in \Phi, \forall i \in \Delta \tag{15}$$

In Eq. (13), τ_{irt} is the US Bureau of Public Roads (BPR) link performance function (Sheffi, 1985). In Eq. (15) $\lceil x \rceil$ for a real number, x, is the smallest integer number greater than x.

Eq. (4) expresses the fact that the net amount of products transported to retailers must be equal to the corresponding demand. The net amount is calculated by subtracting the amount of perished products from the total transported amount.

Eq. (5) imposes the transportation time constraint considering the amount of product perished during transport. Let $t_{ipkrt} = \tau_{irt} \times q_{ipkrt} \le \tilde{l}_{pt}^{R} \times \gamma_{ikrt} + \tilde{l}_{pt}^{O} \times (1-\gamma_{ikrt})$ be the time constraint for product lifetimes. Now, following the chance-constrained approach, the aim is to impose a constraint to have at least a specific chance for a product in a time period transported by vehicles reaches its destination before the lifetime of the product. Obviously, if the refrigerator is not utilized, i.e., $\gamma_{ikrt} = 0$, we have $t_{ipkrt} \le \tilde{l}_{pt}^{O}$ and the corresponding constraint is $p(t_{ipkrt} \le \tilde{l}_{pt}^{O}) \ge 1 - \alpha_p^{O}$ which can be written as the following constraint considering the Weibull probability density function (Montgomery and Runger, 2010).

$$p\left(t_{ipkrt} \le \tilde{l}_{pt}^{O}\right) = \int_{t_{ipkrt}}^{\infty} \frac{\beta_{pt}^{O}}{\delta_{pt}^{O}}\left(\frac{x}{\delta_{pt}^{O}}\right)^{\beta_{pt}^{O}-1} \exp\left(-\left(\frac{x}{\delta_{pt}^{O}}\right)^{\beta_{pt}^{O}}\right)dx = \exp\left(-\left(\frac{t_{ipkrt}}{\delta_{pt}^{O}}\right)^{\beta_{pt}^{O}}\right) \ge 1 - \alpha_p^{O} \tag{16}$$

Similarly, if the refrigerator is utilized, i.e., $\gamma_{ikrt} = 1$, we have

$$p\left(t_{ipkrt} \le \tilde{l}_{pt}^{R}\right) = \int_{t_{ipkrt}}^{\infty} \frac{\beta_{pt}^{R}}{\delta_{pt}^{R}}\left(\frac{x}{\delta_{pt}^{R}}\right)^{\beta_{pt}^{R}-1} \exp\left(-\left(\frac{x}{\delta_{pt}^{R}}\right)^{\beta_{pt}^{R}}\right)dx = \exp\left(-\left(\frac{t_{ipkrt}}{\delta_{pt}^{R}}\right)^{\beta_{pt}^{R}}\right) \ge 1 - \alpha_p^{R} \tag{17}$$

From Eq. (16) and Eq. (17) we have $t_{ipkrt} \le \delta_{pt}^{O} \times \sqrt[\beta_{pt}^{O}]{-\ln(1-\alpha_p^{O})}$, and $t_{ipkrt} \le \delta_{pt}^{R} \times \sqrt[\beta_{pt}^{R}]{-\ln(1-\alpha_p^{R})}$, respectively. The left hand side of Eq. (5) is $\tau_{irt} \times q_{ipkrt}$ to ensure the fact that if x_{ipkrt} is zero, the constraint in Eq. (5) is not applied. In other words, considering Eq. (10), if no units of product p is transported using vehicle k from DC i to retailer r in time period t, then q_{ipkrt} is zero, and no constraint of the time spent for transportation, τ_{irt}, is imposed.

Eq. (6) defines the limit for the capacities of the DCs. Inventory balance control for the DCs for the second planning period up to the last one is implemented through Eq. (7). This constraint considers the amounts of perished products in the warehouse as well as the amounts purchased and transported to the retailers. The inventory balance equation for the initial period is expressed through Eq. (8). We assume that no inventories can be stored in the final time period; this is modeled through Eq. (9). Eq. (10) is for defining the auxiliary variable q_{ipkrt} which is a binary variable that equals 1 if the x_{ipkrt} is positive and is 0 otherwise. This variable is also used in Eq.

(11) imposing the fact that a decision regarding the use of the refrigerator on any vehicle can be made only if a vehicle is used correspondingly; and finally, Eq. (12) determines the type of the variables.

The proposed model is obviously non-linear in the second term of the objective function in Eq. (1), and in Eq. (2), Eq. (3), and Eq. (5). For complexity reduction, and to prepare the model for the application of the RMCGP method possible, linearization techniques are implemented to linearize the non-linear terms. This linearization process of the model is described in Appendix 2.

4. Solution approach

Several multi-objective approaches have already been suggested for tackling the problems of multi-objective optimization. As one of the most widely utilized methods, goal programming (GP) was originally introduced by Charnes and Cooper (1957), who aimed to obtain compromised solutions in multi-objective optimization. In GP, for each of the objectives, the decision-maker defines an aspiration level (target value). The aim is minimizing the deviation of each objective function value from its corresponding aspiration level. The deviations may be caused either by underachievement of a goal or by its overachievement. Incorporating the opinions of the experts may improve model efficiency. Therefore, a solution method, such as the goal programming approach, that can consider their opinions is preferable, especially when the method is meant to be applied in a real-world situation. According to Rezaei et al. (2020), simultaneous consideration of various goals provides flexibility in the decision-making process in comparison to other methods of multi-objective optimization. In addition, goal programming is more flexible and direct regarding manipulating the different scenarios through adjustment of the target values and/or weights (Rezaei et al., 2020). Furthermore, in many cases, managers are not multi-objective optimization experts. Therefore, a set of Pareto-optimal solutions may confuse them. Therefore, it may be more applicable if they are provided with single preferable solutions instead of a set of Pareto-optimal solutions set. Therefore, it can be considered as a practical advantage of goal programming approach over its counterparts.

Constraints in a GP model are of two categories: systems constraints and goal constraints. The former are those of the original multi-objective model and the latter are added to obtain the solution at which the deviations from the aspiration levels are minimized. In the standard GP approach, the focus is on finding a solution that minimizes the deviations from the aspiration levels. However, in practice, the decision-makers may have several target values in mind for each of the goals. Therefore, Chang (2007) proposed the multi-choice goal programming (MCGP) approach, in which for each objective, several aspiration levels are imaginable. The MCGP model includes a multiplication of binary variables, making it a non-linear model. Hence, Chang (2008) revised his model and proposed the revised multi-choice goal programming, which can be expressed as a linear model. In the MCGP approach, the aspiration level of each objective is defined based on the experts' opinion. An important advantage of this method is its capability of incorporating decision-maker's preference (Chang, 2011).

In what follows, a model for the case in which the aim is to minimize multiple objective functions is presented.

$$\min \sum_{i=1}^{n} \left(W_i\left(d_i^+ + d_i^-\right) + \alpha_i\left(e_i^+ + e_i^-\right)\right) \tag{18}$$

Subject to

$$h_k(X) = (\le or \ge) 0 \quad k \in \{1, 2, \ldots, q\} \tag{19}$$

$$y_i - e_i^+ + e_i^- = g_{i.\min} \quad i \in \{1, 2, \ldots, n\} \tag{20}$$

$$f_i(X) - d_i^+ + d_i^- = y_i \quad i \in \{1, 2, \ldots, n\} \tag{21}$$

$$g_{i.\min} \le y_i \le g_{i.\max} \quad i \in \{1, 2, \ldots, n\} \tag{22}$$

$$d_i^+, d_i^-, e_i^+, e_i^- \ge 0 \quad i \in \{1, 2, \ldots, n\} \tag{23}$$

In the above model, W_i is the important factor for the deviation of goal i from the corresponding aspiration level. Also, the positive and negative deviations of the objective function $f_i(X)$ from the aspiration level for goal i are denoted by d_i^+ and d_i^-, respectively. Constraints (31) are the constraints of the original model and Constraints (32) are the goal constraints in which y_i is the aspiration level for the objective $f_i(X)$. Furthermore, the bounds of y_i are denoted by $g_{i.\min}$ and $g_{i.\max}$. Correspondingly, the positive and negative deviations of y_i from $g_{i.\min}$ (for the case of minimization problems) are presented by e_i^+ and e_i^-, respectively. In maximization problems, the deviations are calculated from $g_{i.\max}$. Finally, α_i determines the weight of the summation of the aforementioned deviations. For a concise discussion on GP, MCGP, and RMCGP models, one may refer to a paper by Habibi-Kouchaksaraei et al. (2018).

5. The case study

According to Yin (2011), a case study approach is applicable in at least three situations. The first and most important one is when the study is conducted to answer "how" and "why" questions. The second is when the emphasis is on studying the phenomenon within the real-context. The third one is utilizing the case study as a tool for evaluation. In this paper, we chose to study a case because we are interested in studying "how" the different parameters affect the design of a perishable food supply chain in its "real-context."

The study of this case is worth studying for a number of reasons. The global dairy products production and demand are expected to rise in the future, and the consumption of dairy products is predicted to increase faster than their production in the Middle East, and this will create supply chain investment opportunities (Organisation for Economic Co-operation and Development (OECD) and the Food and Agriculture Organization (FAO), 2019). However, these opportunities need to be carefully planned if it is to be sustainable. One of the major drivers for the increase in animal-origin food products in developing countries is urbanization and industrial growth (Delgado et al., 2001). Therefore, an area with a high rate of urbanization and industrial growth (Jouzdani et al., 2018) in central Iran, as a developing country, is studied in this paper. In addition, a dairy product supply chain is already established in this region; therefore, experts are available to help through various steps of the study, including determining the parameters, interpreting the results, and analyzing the combinations of the three objective function values. The region under investigation in this paper covers the cities Golpayegan, Khomein, Mahalat, Delijan, Arak, and Khansar, and is depicted in Fig. 1 to provide an overview of their geographical positions.

In this area, weather conditions under which the dairy products are transported may fluctuate widely. This makes this study more meaningful because it can shed light on the effects of temperature variations in different seasons on the perishability of the products, and in turn, on the decision variables. For example, in Golpayegan, the difference between the lowest and the highest temperature in

2017 is 25.7 °C varying from 2.9 °C to 27.8 °C (Iran Meteorological Organization, 2017). In addition, the traffic flow of the roads connecting these cities vary from season to season. For instance, the number of daily commuters from Golpayegan to Khansar vary by 64% from season to season (National Road Management Center, 2018). This, along with temperature fluctuations, can affect the lifetime of the dairy products and calls for a careful plan for storage and transportation of the perishable products.

In this region, Pegah Golpayegan Dairy Company, a well-established dairy factory, has been working in Golpayegan since 1973. The company produces milk and other dairy products, such as different types of cheese, yogurt, butter, and cream. Four types of vehicles, namely heavy pickup, light truck, heavy truck, and trailer, are available to transport the milk packaged in two types of packages: ordinary packages and aseptic packages. The former type, shown in Fig. 2(a), is a plastic bag containing pasteurized milk, more sensitive to transportation and storage conditions, has a lower price, and consequently a higher demand and has a shorter lifetime. The latter type, shown in Fig. 2(b), is a paperboard sterilized container of thermally sterilized milk, produced through an aseptic process. This type is shelf-stable, has a longer lifetime, higher price, and consequently a lower demand. The experts provide the data regarding the features of the products.

It should be noted that in each city in this region, there is one potential location for establishing a DC, and there is already a representative retailer. Four seasons of the year are considered as four time periods. The data are collected by querying the databases and experts of the company as well as other data sources provided by private and governmental organizations, including Iran Meteorological Organization and National Road Management Center. It is assumed that all the products can be stored and shipped from any DC. The weather conditions are assumed from one time period to another. This is reflected in the parameters of the randomly distributed variable associated with the lifetimes of the products for different seasons. The traffic flow is assumed to change from a time period to another. The change in traffic flow is reflected in the basic flow of the routes.

The data regarding the links between each pair of nodes in the network, including the free flow travel time, the basic traffic flow, the capacity, and the distance are obtained from The National Roads Management Center (2019). For all other parameters, the data are gathered from the experts, the documents, and the databases of Pegah Golpayegan Dairy Company. In order to determine the value of $g_{i.\min}$ for each of the objectives, the model is run considering each objective individually, and for obtaining $g_{i.\max}$, for each objective, the decision-maker was asked to determine the maximum tolerable percent deviation from the optimal value for achieving a better result for other objectives. Based on that, Table 2 was set up to perform the numerical analysis of the case.

The collected data were used to run a LINGO 12 model using a computer equipped with 4 GB of RAM and an Intel® Core™ i3-3210 CPU @ 3.20 GHz running Microsoft Windows™ 7 Basic. The results were obtained in 9 s. The results show the SPFSCND to achieve the SDG 12 in the enterprise-scale, and depict the trade-off among the conflicting goals mentioned in SDG 12. More specifically, the solution presents a balance in the economic aspect, including food loss and waste (SDG2), energy consumption (SDG 7), and the social impacts (SDG 16).

5.1. The values of the objective functions

Considering the weights of 0.80, 0.15, and 0.05 for the economic, environmental, and social objectives, respectively, the values for the three objectives are calculated as, 1,333,847.49 (USD), 815,904.00 (Mega Joules), and 279,791,904.58 (Vehicle-Hours). In addition, d_i^-, e_i^+, and e_i^- for the three objectives, and $d_{env}^+$are zero. d_{eco}^+ and d_{soc}^+ are 89,052.89 and 77,041.55, respectively. It is evident that all the three objectives have satisfied the lower and upper limits conditions; however, expectedly, they deviate from their corresponding lower bounds. In the obtained solution, a DC is established in Golpayegan. The cost components that comprise the total cost, i.e., facility location cost, transportation cost, purchase cost, and holding cost, are $533,333.0, $1,346.2, $799,168.3, and $0, respectively. One can obviously see that in this solution, no inventory is held.

5.2. Transportation of the products

Table 3 depicts the amounts of products transported by different vehicle types through the four seasons of the year. Table 4 depicts the purchased amounts of products in different seasons of the year.

5.3. The fleet composition and the utilization of vehicles' refrigerators

The bold entires in Table 3 represent the utilization of the refrigerator of the vehicles transporting the products. It is interesting to observe that the vehicles that transport the products from the DC in Golpayegan to deliver the products to the retailer in Golpayegan and Khomein do not utilize their refrigerators while this is the opposite for the vehicle departing from the Golpayegan DC to cities other than Golpayegan and Khomein.

In total, 64% of the vehicles use their refrigerators. This can be explained by the short travel distances and relatively low temperatures in these two cities throughout the year. From this point on, the term "refrigerator utilization" refers to the proportion of vehicles that utilize their refrigerators on different routes. This is simply calculated by dividing the number of entries in bold for one of the products to the total number of entries for that product in Table 3. In addition, vehicles with higher capacities, i.e., the trucks, do not use their refrigerators in the obtained solution. This is because if they do so, they may contribute a considerable amount to the increase of the total consumed energy.

It is assumed that if a refrigerator is set to be ON or OFF in a season, it is the plan to be so during all the daily transports. This can be considered as the default refrigerator condition, which can be overruled according to the more specific situation, including the daily temperature and shipment load weight. This is in agreement with the current policy of Pegah Golpayegan Company in which the refrigerators are always ON except otherwise is permitted by the transportation department of the company. Considering the fact that the same vehicles can be used in different seasons, the number of vehicles are 6, 2, 1, and 1 for heavy pickup, light truck, heavy truck, and trailer, respectively.

6. Analyses and discussions

To clarify the significance of this research, a series of analyses and discussions are presented with a focus on the main features of the proposed model. In what follows, a series of analyses are conducted to show the impacts of the weights of the objective functions, the perishability of the products, and the traffic congestion, and the results are summarized in Table 5 and Table 6.

In order to clarify the structure and organization of the analyses, Fig. 3 depicts the scenarios. As the diagram shows, the focus of the analyses is on sustainability and product perishability.

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Fig. 1. The map view of the cities considered in the case study (Google Maps, 2018).

6.1. The analysis of the weights

To create an insight on the effects of the relative significance of the objectives, providing the decision-maker with an overview of the interactions of the objective functions, and determining the preferred weights for the objectives, a sensitivity analysis is done on the weights of the objectives. It is worth noting that based on the opinions of the decision-makers of the company we assume that the economic objective is of more significance compared with the environmental objective which in turn is more important than the social objective, i.e., $W_{eco} > W_{env} > W_{soc}$ which are the weight of the economic, environmental, and social objectives, respectively. Considering that, the weights of the objectives are changed to provide a bed for the decision-makers to select the best-suited among a range of available solutions.

In this experiment, the weights of the objectives are changed by 0.05 in the interval [0.05, 0.95] assuming $W_{eco} > W_{env} > W_{soc}$ as depicted in Table 7. In this Table, the weight tuples are presented as $(W_{eco}, W_{env}, W_{soc})$. The criteria, based on which the solutions are compared, are calculated by Eq. (42) for each of the objectives. The weights of the objectives provide an insight into the multiple dimensions of structural changes to achieve SDG 12. The analysis of weights enlights the trade-off between every two pairs of the objectives in SDG 2, SDG 7, and SDG 16. Since a business owner is normally focused on economic aspects of the supply chain, the incentives to achieving SDG 2 are already strong. Similarly, since energy is costly and SDG 7 promotes the reduction of its consumption, supply chain decision-makers are more easily convinced to achieve this SDG. However, since there is little incentive to reduce the social impact, SDG 16 is harder to achieve.

$$score_i^{obj} = \frac{\max\limits_{j\in\{1,2,\ldots,E\}}\left\{Z_j^{obj}\right\} - Z_i^{obj}}{\max\limits_{j\in\{1,2,\ldots,E\}}\left\{Z_j^{obj}\right\} - \min\limits_{j\in\{1,2,\ldots,E\}}\left\{Z_j^{obj}\right\}} obj\in\{eco, env, soc\}, i\in\{1,2,\ldots,E\} \tag{24}$$

In Eq. (42), Z_i^{obj} is the objective function value, *obj*, for the solution obtained in *i*th experiment, and *E* is the total number of experiments. With these definitions, $score_i^{obj}$ calculates the relative closeness of the objective function value Z_i^{obj} to the lowest obtained in the experiment.

From Table 7, it can be seen that the weight tuples (0.80, 0.15, 0.05) and (0.45, 0.40, 0.15) result in non-dominated solutions. The scores for these two are illustrated in Fig. 4. Since the primary objective of any business is profitability, which is directly related to the total cost, business decision-makers would expectedly express their preference for the (0.80, 0.15, 0.05) tuple.

However, the weight tuple (0.45, 0.40, 0.15) is worth considering. In this solution, 4 DCs are established in Golpayegan,

(a) ordinary package *(b) aseptic package*

Fig. 2. The two types of milk packages.

Table 2
The weight intervals and the corresponding bounds of the objective functions.

Objective	Weight Interval	$g_{i.\min}$	$g_{i.\max}$
z_{eco} (USD)	$W_{eco} \in [0, 1]$	1,244,794.6	1,369,274.1
z_{env} (Mega Joules)	$W_{env} \in [0, W_{eco}]$	815,904.0	938,289.6
z_{soc} (Vehicle-Hours)	$W_{soc} \in [0, W_{env}]$	279,714,863.0	335,657,835.6

Khomein, Arak, and Khansar, and 44,050 kg of aseptic package milk and 23,818 kg of ordinary package milk are stored in Golpayegan DC in winter and spring, respectively, to be distributed during the next seasons. The fact that the more sustainable SCND calls for establishing more DCs is in agreement with the results obtained by Souza et al. (2019). increase in the At the DC in Arak, the inventory levels for the aseptic package milk are 248,283 kg, 187,505 kg, and 120,892 kg for winter, spring, and summer, respectively. For the ordinary packages, the amount at this DC is 9,811 kg in winter. In other DCs, the inventory levels are 0. With more DCs established and the inventories held at these facilities, the traveled distances are shorter. This indicates the significance of considering the perishability of products during transport and its effect on SCND. The values of the objective functions are presented and compared for the two non-dominated solutions in the first three rows of Table 5. The results show that in our case, the supply chain has to pay a very high price to be slightly more sustainable. However, as discussed in what follows, for highly perishable products, this is not the case. In addition, consider the local and global impacts of these seemingly small improvements in environmental and social dimensions of supply chain activities, the sacrifice may be worth the result. This should be a highly noticeable result for major local, national, and global policymakers. More specifically, the policymakers are expected to facilitate such enhancements in order to move towards sustainability on a larger scale because these improvements, when compounded, can make sustainability more achievable.The fleet composition under different importance weight factors is presented in the first row of Table 5. This shows that for preserving the and environmental and social values, the SCN has to increase the number of established DCs, inventory levels, and even fleet size, which in turn signifies the interactions of the three dimensions of sustainability in SPFSCND. To provide more details on the influence of the weights on the cost components, the first four rows of Table 5.

Table 6 presents the components, assuming the weights 0.45, 0.40, and 0.15 for the economic, environmental, and social objectives, respectively. This shows the costs of sustainability for the chain and its significance in SPFSCND. It is interesting to note that the considerable increase in the total cost is mostly due to the increase in the number of established DCs. This is significant in terms of SDG 9. Specifically, it should be noted that although the total cost is significantly increased to achieve an almost negligible improvement in sustainability, the cost may be a means to achieve SDG 9.

6.2. Sustainability and the impact of perishability

In the results presented in what discussed above, the lifetime of the products is assumed to follow a Weibull distribution. The lifetime probability density functions of the two types of packaged milk when transported utilizing or not utilizing the vehicle refrigerator in summer are presented in Fig. 5. As shown in this figure, when the refrigerator is utilized, the lifetime of the ordinary and aseptic packages are the same, while when the refrigerator is not used, the lifetime of the aseptic package remains unaffected and the ordinary package will last considerably shorter. These are expressed as the probability of perishing. In other words, the utilization of refrigerator has no significant impact on the probability of perishing for the aseptic package while that of the ordinary package significantly increases. The aseptic type has a long life and is almost not influenced by temperature changes, while this is not the case for ordinary packages.

Now, consider the situation in which one or more products are highly perishable if not refrigerated; for example, suppose that the milk in the ordinary packages has 10% of the average lifetime of the original product in this study. Assuming the same data used to solve the original problem with the weight tuple (0.80, 0.15, 0.05), a different solution with a considerably higher environmental cost is obtained (see the second three row of Table 5). In this situation, as for the original problem, a DC is opened in Golpayegan where no inventory is held (see the second row of Table 5), and the change in the economic objective is relatively small. However, the increase in environmental cost is significant and can mainly be attributed to the excess amount of energy needed to preserve highly perishable products (see the second four rows of Table 6). More specifically, 75.0% of the vehicles utilized their refrigerators (see the second row of Table 5). This depicts the significance of sustainability regarding the uncertain perishability in PFSCND.

Moving toward sustainability is more significant for highly

Table 3
The amount of products (in kilograms) shipped using different vehicle types.

To	From	Golpayegan							
	Milk Package Type	Aseptic				Ordinary			
	Vehicle Type/Season	Heavy Pickup	Light Truck	Heavy Truck	Trailer	Heavy Pickup	Light Truck	Heavy Truck	Trailer
Golpayegan	Winter	78,136	–	–	–	87,495	–	–	–
	Spring	87,955	–	–	–	98,443	–	–	–
	Summer	77,845	19,825	–	–	109,299	–	–	–
	Fall	–	–	–	107,489	–	–	–	120,247
Khomein	Winter	91,125	–	–	–	101,969	–	–	–
	Spring	–	–	102,477	–	–	–	114,680	–
	Summer	–	113,829	–	–	–	127,485	–	–
	Fall	–	–	125,284	–	–	–	140,196	–
Mahalat	Winter	**47,966**	–	–	–	**53,722**	–	–	–
	Spring	**54,000**	–	–	–	**60,495**	–	–	–
	Summer	**60,034**	–	–	–	**67,175**	–	–	–
	Fall	**65,966**	–	–	–	**73,856**	–	–	–
Delijan	Winter	**44,795**	–	–	–	**50,103**	–	–	–
	Spring	**50,420**	–	–	–	**56,412**	–	–	–
	Summer	**55,943**	–	–	–	**62,629**	–	–	–
	Fall	**61,568**	–	–	–	**68,938**	–	–	–
Arak	Winter	**51,852**	–	–	–	**57,990**	–	–	–
	Spring	**58,295**	–	–	–	**65,227**	–	–	–
	Summer	**64,739**	–	–	–	**72,464**	–	–	–
	Fall	**71,284**	–	–	–	**79,794**	–	–	–
Khansar	Winter	**28,636**	–	–	–	**32,103**	–	–	–
	Spring	**32,216**	–	–	–	**36,093**	–	–	–
	Summer	**35,795**	–	–	–	**40,082**	–	–	–
	Fall	**39,375**	–	–	–	**44,165**	–	–	–

Table 4
Purchase amounts (in kilograms).

DC	Milk Package Type/Season	Winter	Spring	Summer	Fall
Golpayegan	Aseptic	342,511	385,364	428,011	470,966
	Ordinary	383,381	431,351	479,134	527,196

perishable products food supply chains (see the fourth three rows in Table 5). Especially, when having highly perishable products, moving toward a more sustainable supply chain may be worth the economic sacrifice. As depicted in Table 5, a 149.225% increase in the total cost, fruits a 105.894% decrease in the environmental impact of the chain. Compared to the results reported in previously published papers, e.g., Colicchia et al. (2016), Bortolini et al. (2016), Yakavenka et al. (2019), the numbers are considerably higher, showing the significant role of perishability. Following our previous discussions, the policymakers should put even more emphasis on facilitating this movement in supply chains with high perishable products. The results indicate that for the case of highly perishable products, the trade-off between SDG 2 and SDG 7 is much more significant compared to conventional perishable products. Based on what discussed earlier regarding the financial incentives of business owners in achieving the SDGs, in the case of highly perishable food products, the high cost of sustainability may be a strong barrier. The results are also significant in terms of SDG 9. Specifically, in the case of highly perishable products a sustainable design of perishable food supply chain implicates the establishment of more DCs, which in turn, can be translated to the industrialization of the region in which the chain operates.

Having a large gap in the total supply chain cost, it is worth inspecting the components of cost to have a deeper insight. These differences can be more easily justified considering the information presented in Table 6, which sheds light on the reason behind the significant increase in the total supply chain cost and fleet energy consumption. In the fourth row of Table 5, it is interesting to note that a larger fleet is used, and the products are transported in a shorter distance because of the large number of DCs. Also, only 6.3% of the vehicles in the fleet utilize their refrigerators, accordingly. This results in a considerable reduction in the environmental footprint of the chain at the cost of an increase in the total cost.

6.3. *Traffic congestion and its relation to sustainability*

In this section, the effect of traffic congestion is investigated by assuming that both the basic flow and the capacity of the paths between each pair of DC and retailer are 10% of those of the original problem. One may expect that this would only increase the social cost of the chain; however, the results presented in the third three rows of Table 5 show that the traffic congestion has a significant impact also on other aspects of the supply chain as well. This illustrates that considering the social aspect of perishable food supply chain operations is crucial for not only it affects the environmental dimension but also the economic aspect of the chain.

With such limited relative road capacity, the average travel time soars from 1.164 h to 12.525 h. This forces the supply chain to have DCs in 4 of the cities. In addition, 2 light trucks, 2 heavy trucks, and 3 trailers are needed to transport the goods, while 27.3% of this fleet utilizes their refrigerators. These facts justify the significant increase in the objective functions (see the third row of Table 5 and the third four rows in Table 6).

When dealing with highly perishable products, the heavily congested roads become more significant. As depicted in the fifth three rows of Table 5, assuming the weight of the objective functions as those of the original problem, the concurrent effect of traffic congestion and high perishability of products may lead to a different result. More specifically, the results indicate that with a fleet of 1 light truck, 3 heavy pickups, 5 heavy pickups, and 3 trailers, out of

Table 5
Summary of the analyses of the variables and objectives considering highly perishable products, highly congested roads, and promoted sustainability, and a comparison with the original problem.

Scenario	Objective	Objective Value	Gap with the Original Problem	Number of Opened DCs	Total Inventory (kilograms)	Vehicle Type				Refrigerator Utilization
						Heavy Pickup	Light Truck	Heavy Truck	Trailer	
Promoted Sustainability	z_{eco} (USD)	2,825,113.39	111.802%	4	634,358	11	6	1	1	60.0%
	z_{env} (Mega Joules)	827,208.00	1.385%							
	z_{soc} (Vehicle-Hours)	279,781,292.10	0.004%							
Highly Perishable Products	z_{eco} (USD)	1,333,908.60	0.005%	1	473,645	6	1	0	1	75.0%
	z_{env} (Mega Joules)	1,804,680.00	121.188%							
	z_{soc} (Vehicle-Hours)	279,714,863.04	0.028%							
Highly Congested Roads	z_{eco} (USD)	2,855,955.4	114.114%	4	0	0	2	2	3	27.3%
	z_{env} (Mega Joules)	770,760.0	5.533%							
	z_{soc} (Vehicle-Hours)	423,847,075.8	51.487%							
Highly Perishable Products and Promoted Sustainability	z_{eco} (USD)	3,324,285.21	149.225%	5	0	10	6	5	7	6.3%
	z_{env} (Mega Joules)	963,216.00	15.294%							
	z_{soc} (Vehicle-Hours)	279,810,659.63	0.007%							
Highly Perishable Products and Highly Congested Roads	z_{eco} (USD)	2,412,107.0	80.838%	3	0	1	3	5	3	22.2%
	z_{env} (Mega Joules)	1,102,320.0	35.104%							
	z_{soc} (Vehicle-Hours)	423,894,605.3	51.504%							
Highly Perishable Products, Highly Congested Roads, and Promoted Sustainability	z_{eco} (USD)	2,411,599.5	80.800%	3	0	1	1	2	3	0.0%
	z_{env} (Mega Joules)	860,112.0	5.418%							
	z_{soc} (Vehicle-Hours)	423,894,946.4	51.504%							

Table 6
Summary of the analyses of the cost components considering highly perishable products, highly congested roads, and promoted sustainability, and a comparison with the original problem.

Scenario	Cost Component (USD)	Value	Gap (percent) with the Original Problem
Promoted Sustainability	Facility Location Cost	1,977,777.0	270.8%
	Transportation Cost	1,407.2	4.5%
	Purchase Cost	818,533.9	2.4%
	Holding Cost	27,395.3	Indefinite
Highly Perishable Products	Facility Location Cost	533,333.0	0.000%
	Transportation Cost	1407.289	4.538%
	Purchase Cost	799,168.3	0.000%
	Holding Cost	–	0.000%
Highly Congested Roads	Facility Location Cost	2,000,000.0	285.417%
	Transportation Cost	1,356.6	8.480%
	Purchase Cost	799,168.3	0.000%
	Holding Cost	–	0.000%
Highly Perishable Products and Promoted Sustainability	Facility Location Cost	2,522,222.0	372.917%
	Transportation Cost	2,894.9	115.042%
	Purchase Cost	799,168.3	0.000%
	Holding Cost	–	0.000%
Highly Perishable Products and Highly Congested Roads	Facility Location Cost	1,611,111.0	202.084%
	Transportation Cost	1,827.7	35.769%
	Purchase Cost	799,168.3	0.000%
	Holding Cost	–	0.000%
Highly Perishable Products, Highly Congested Roads, and Promoted Sustainability	Facility Location Cost	1,988,889.0	272.917%
	Transportation Cost	1,457.9	8.295%
	Purchase Cost	799,168.3	0.000%
	Holding Cost	–	0.000%

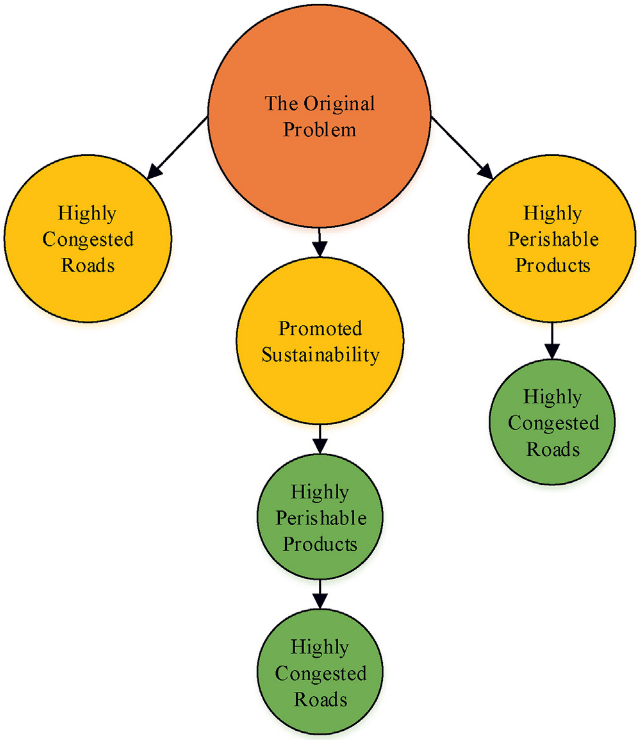

Fig. 3. The organization of the analyzed scenarios.

which 22.2% use their refrigerators (see the fifth row of Table 5).

In addition, the concurrent impact of these two phenomena on the cost components of the chain may more deeply explain the increase in the total cost (see the fifth four rows in Table 6). Finally, we investigate the effect of moving towards a more sustainable PFSCND through considering the weights of the objective functions as (0.45, 0.40, 0.15) while assuming highly congested roads and highly perishable products. The results show that a notably satisfying solution exists. The supply chain decision-makers may achieve much more sustainable design, especially regarding the environmental dimension, by putting more importance weight on social and economic aspects without significantly increasing the total cost. This is in agreement with the results reported by previously conducted studies, e.g., Banasik et al. (2017) and Yavari and Zaker (2019), presenting a solution to reach a satisfying balance among the objectives. According to the last three rows of Table 5, such attention may reduce the environmental impact by 30.351% in comparison with the case of neglecting sustainability with highly perishable products highly congested roads. The last row of Table 5 shows that with three DCs and a fleet composed of 1 heavy pickup, 1 light truck, 2 heavy trucks, and 3 trailers, and without utilizing the refrigerators, the supply chain can achieve a satisfying result regarding sustainability. The cost components of a more sustainable PFSCND are presented in the last four rows of Table 7. These components are justified by the data presented in Table 5.

In the case of highly perishable products in highly congested roads, finding a sustainable design is more prominent because a considerable improvement in the environmental impact is achievable at a negligible cost. In other words, SDG 7 can be achieved without significantly compromising other SDGs. In addition, with highly congested roads, the facility location cost component is significantly higher than that of the original problem, indicating the establishment of a larger number of DCs. This is significant regarding SDG 9.

7. Conclusions and future works

This research proposed a chance-constrained mathematical programming model for the sustainable multi-period design of a perishable food supply chain, and a dairy product case was studied. The initial non-linear model was linearized, and the linear model was solved using the revised multi-choice goal programming method.

According to the review of the related literature, the subject of sustainability in the design of perishable food supply chains needs to be more thoroughly explored. This paper is among the few papers that consider the subject, and stands out in the literature by considering some specific aspects of the sustainable perishable food supply chain network design. In this paper, the uncertainty in perishability is explicitly modeled using chance-constraint programming. Multiple products with different properties, including perishability, weight, and price, are considered. Vehicles equipped with refrigerators with the decision of their utilization is the feature that is not studied in the previous studies. In addition, several properties of the vehicles, including the fuel consumption and traffic congestion effects, are considered to study their environmental and social impacts. A rarely studied feature, which is addressed in this paper, is considering multiple planning periods and incorporating the time value of money into the calculations. This paper presents a case study through which the interrelation and interactions of all three aspects of sustainability are exhaustively studied. Finally, this study contributes to the sustainable development goals (SDG's) such as Zero Hunger (SDG 2); Affordable and Clean Energy (SDG 7); Decent Work and Economic Growth (SDG 8); Industry, Innovation, and Infrastructure (SDG 9); Responsible Consumption and Production (SDG 12); Climate Action (SDG 13) and Peace, Justice, and Strong Institutions (SDG 16).

Table 7
The comparison of the solutions obtained by varying the objective weights.

i	Weights	$score_i^{eco}$	$score_i^{env}$	$score_i^{soc}$	i	Weights	$score_i^{eco}$	$score_i^{env}$	$score_i^{soc}$
1	(0.85,0.10,0.05)	99.97%	69.98%	71.55%	12	(0.60,0.35,0.05)	71.76%	66.80%	64.73%
2	***(0.80,0.15,0.05)***	***100.00%***	***100.00%***	***94.33%***	13	(0.55,0.25,0.20)	49.14%	50.25%	57.17%
3	(0.75,0.20,0.05)	49.17%	75.20%	64.64%	14	(0.55,0.30,0.15)	53.63%	16.41%	29.63%
4	(0.75,0.15,0.10)	76.26%	56.23%	45.00%	15	(0.55,0.35,0.10)	22.59%	19.42%	12.60%
5	(0.70,0.20,0.10)	71.77%	84.03%	77.94%	16	(0.55,0.40,0.05)	3.37%	0.00%	0.00%
6	(0.70,0.25,0.05)	48.04%	81.53%	67.68%	17	(0.50,0.30,0.20)	0.00%	13.35%	10.64%
7	(0.65,0.20,0.15)	71.77%	86.59%	78.84%	18	(0.50,0.35,0.15)	99.99%	94.25%	86.42%
8	(0.65,0.25,0.10)	27.16%	91.46%	93.75%	19	(0.50,0.40,0.10)	2.85%	42.94%	37.61%
9	(0.65,0.30,0.05)	77.41%	88.02%	80.42%	20	(0.50,0.45,0.05)	2.86%	75.02%	75.74%
10	(0.60,0.25,0.15)	0.07%	96.38%	99.30%	***21***	***(0.45,0.40,0.15)***	***24.23%***	***98.92%***	***100.00%***
11	(0.60,0.30,0.10)	71.74%	68.70%	44.01%	22	(0.45,0.35,0.20)	25.44%	71.84%	54.51%

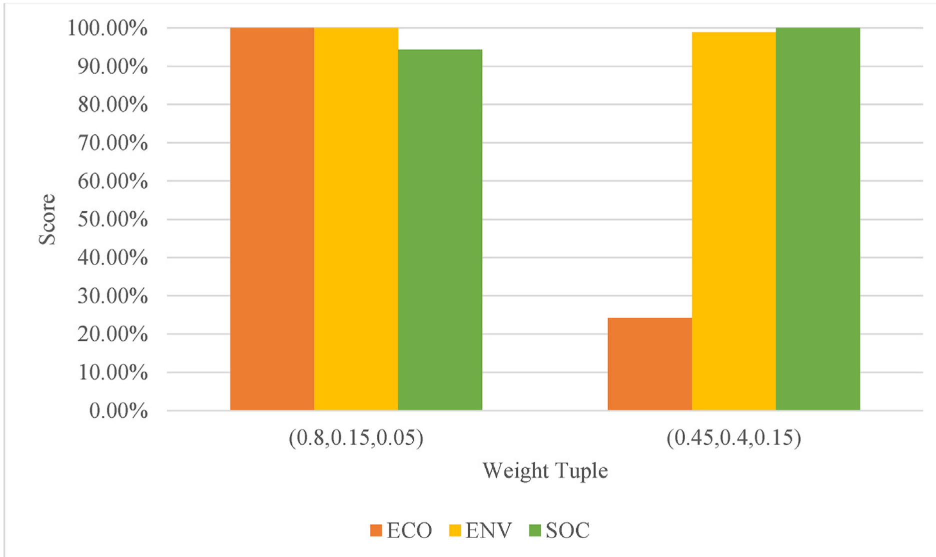

Fig. 4. Comparison of the scores for the two non-dominated weight tuples.

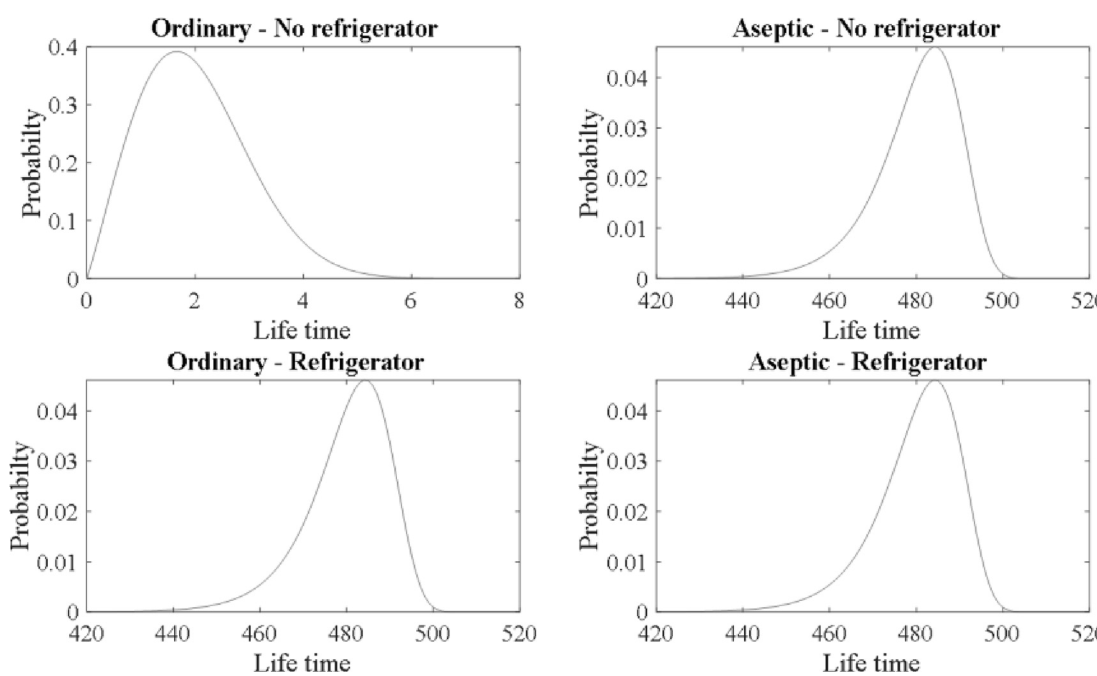

Fig. 5. The lifetime (in hours) probability density functions of the two types of products transported with or without refrigerator in summer.

7.1. Practical implications

The case study results showed that the perishability of the products plays a crucial role, and can drastically influence the cost as well as the social and environmental aspects of the supply chain. Specifically, in our case, it was shown that when dealing with highly perishable products, the environmental impact may soar to more than 120%. However, if the perishable food supply chain decision-makers decide to move towards a more sustainable chain, they can reduce this amount to near 15% at the cost of an about 150% increase in the chain's total cost. From a government point of view, a business owner is very unlikely to accept such loss in favor of the environment; therefore, they should be inspired to shoulder this burden through manipulating the environmental taxes or tax incentives. Another way is to educate the consumers regarding the environmental impacts of the supply chain operations.

In addition, the analysis of the effects of traffic congestion showed that this phenomenon can be a crucial factor in the design of the perishable food dynamic supply chains, and can influence not only the social impact of the chain but also may affect and be affected by other aspects. More specifically, in our case, the results indicate that in a highly congested road network, the economic, environmental and social impacts may rise to about 114%, 5.5%, and 51.5%, respectively. However, if the products are highly perishable, the numbers may change to about 81% and 35% for the economic and environmental aspects. Interestingly, the environmental impact of the chain may be considerably reduced to about 5% by slightly compromising the other two objectives. This shows that even with highly congested road networks and highly perishable products, there still exist some sustainably satisfying solutions.

From the supply chain's viewpoint, these results provide a bed for negotiations for receiving public benefits. As shown in the case of highly perishable products and highly congested roads, the environmental and social impacts may be drastic, and moving towards sustainability may require large investments. Such a movement can significantly reduce the social and environmental impacts of the chain without considerably increasing the total chain. Therefore, supply chain decision-makers may find the results of this study a way to fund the projects through the government and other non-government organization that work to protect the society and the environment. This may be attractive for both parties because the supply chain restructures its design with a negligible increase in the total cost using the external financial resources, the environmental and social activists observe the considerable improvement, and the society and the environment benefit from the outcomes.

In general, this study provides a means to achieve several sustainable development goals (SDGs). Specifically, it sheds light on the interactions and interrelation of SDG 2, SDG 7, and SDG 16. By proposing a multi-objective model, this paper studied the trade-offs among the SDGs and proposed a model for the multidimensional structural changes in perishable food supply chains. According to the close relationship between energy consumption and emissions, this paper indirectly addressed SDG 13. As shown by the results, the roads' capacity can be freed to help achieving SDG 8. In addition, this study is a general step towards SDG 9 by specifically providing a bed for SFPSCND.

7.2. Limitations and future research guidelines

This research is limited and can be expanded in several ways. In this research, the focus was on food products, whereas other perishable products may be addressed by accordingly modifying the proposed model. In this paper, the lifetimes of the products are modeled using a Weibull distribution, while other lifetime modeling methods may be utilized for other perishable products. Moreover, the social and environmental footprints of the chain operations can be evaluated through other means such as public health, greenhouse gas emission, etc. An assumption in this research, which is a limitation of the study, is that in real-world situations, the problem parameters other than the product's lifetime may be subject to uncertainty; therefore, they can be considered in the future development of the model. In addition, it is interesting to investigate the impacts of vehicle load on the environmental and social and environmental influences of these supply chains. In this study, a comprehensive analysis of the impacts of perishability and traffic congestion are conducted. For future works, several other analyses on various model parameters, including the demand, features of the fleet such as fuel consumption with or without a refrigerator, along with other parameters, can be conducted to shed more light on the performance of the model. Furthermore, in this study, each time period is considered to be a season. Therefore, some decisions that can be detailed to a day-by-day or even hour-by-hour basis are lumped into season-by-season. Specifically, operational-level planning needs to be developed to determine the utilization of the refrigerators on a daily basis according to the conditions under which the products are transported. In addition, a comprehensive comparison of the performance of RMCGP with other multi-objective solution approaches regarding computing time and solution quality is an interesting subject of future research. Finally, although our proposed model is general, the results of our analyses are limited to the time, location, and the specific features of the studied case and may not be generalized to other cases. Therefore, a series of comprehensive real-world experiments with the model may shed more light on the model and the results in future research.

CRediT authorship contribution statement

Javid Jouzdani: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Investigation, Data curation. **Kannan Govindan:** Validation, Writing - review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

The following sets are defined and used in constructing the mathematical model:

$i \in \Delta = \{1,\ldots,D\}$	Index for the potential locations for DCs
$r \in \Upsilon = \{1,\ldots,R\}$	Index for the retailers
$k \in \Phi = \{1,\ldots,V\}$	Index for the vehicle types
$p \in \Pi = \{1,\ldots,P\}$	Index for the products
$t \in \Psi = \{1,\ldots,T\}$	Index for the time periods

x_{ipkrt}	The number of units of product p transferred using vehicle k from DC i to retailer r in time period t
y_i	Is 1 if a DC is established in location i and is 0 otherwise
I_{ipt}	The inventory in units of product p at DC i in period t
H_{ipt}	The number of units of product p purchased in time period t by DC i
γ_{ikrt}	Equals 1 if vehicle type k which transports goods from DC i to retailer r in time period t utilizes its refrigerator, and is 0 otherwise

z_{ikrt}	The number of vehicles type k to transport goods from DC i to retailer r in period t
ϕ_{irt}	Total traffic from DC i to retailer r in time period t
q_{ipkrt}	Is 1 if x_{ipkrt} is strictly greater than 0, and is 0 otherwise

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f_i	The fixed cost of opening a DC at location i
d_{rpt}	The number of units of product p demanded by retailer r in period t
τ^0_{irt}	The travel time assuming free flow from DC i to retailer r in period t
$\tilde{l}^R_{pt}$	The lifetime of product p in period t if transported by a vehicle with its refrigerator on; follows Weibull distribution with parameters β^R_{pt} and δ^R_{pt}
$\tilde{l}^O_{pt}$	The lifetime of product p in time period t if transported by a vehicle with its refrigerator off; follows Weibull distribution with parameters β^O_{pt} and δ^O_{pt}
c_{kt}	The per unit of distance transport cost of a vehicle type k in time period t
w_p	The weight for a unit of product p
a_k	Total vehicle type k capacity in terms of load weight
b_k	The fixed transportation cost of vehicle type k
m_i	Maximum capacity of DC i
ρ_t	The interest rate in time period t
ϕ^0_{irt}	The basic flow in time period t from DC i to retailer r
κ_{ir}	The capacity of the route from DC i to retailer r
ω_k	Traffic congestion weight of vehicles of type k
s_{ir}	The distance from DC i to retailer r
u^O_k	Per distance unit fuel consumption of vehicle of type k if the refrigerator is turned off
u^R_k	Per distance unit fuel consumption of vehicle of type k if the refrigerator is utilized
α^R_p	The maximum allowable portion of product p perished utilizing the refrigerator
α^O_p	The maximum allowable portion of product p perished not utilizing the refrigerator
ν	Fuel conversion factor
π_p	The portion of product p perished in a DC
Λ_p	The maximum acceptable portion of deteriorated product p
η_{pt}	The unit sale price in period t for product p
h_{ipt}	The unit cost for holding product p in period t at DC i
M	A sufficiently large number

The followings are the variables of the proposed model. Some of the variables are utilized to simplify the presentation of the model. These variables are defined as auxiliary variables.

Auxiliary variables are:

The model parameters are introduced in what follows.

Appendix 2

The non-linearity in the second part of the objective function in Eq. (1) is due to the use of ceiling function utilized for calculating the variable z_{ikrt}. Defining this variable as an integer and adding the following auxiliary constraints can resolve the non-linearity caused by the ceiling function.

$$z_{ikrt} \geq \frac{\sum_{p=1}^{P} w_p \times x_{ipkrt}}{a_k} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{25}$$

$$z_{ikrt} < \frac{\sum_{p=1}^{P} w_p \times x_{ipkrt}}{a_k} + 1 \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{26}$$

Another source of non-linearity is the multiplications of z_{ikrt} by the binary variable γ_{ikrt} in the second sentence of the objective function in Eq. (1), which can be linearized by introducing two variables, ζ_{ikrt} and ζ'_{ikrt}, and adding the following constraints to the model.

$$\zeta_{ikrt} \leq M\gamma_{ikrt} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{27}$$

$$\zeta_{ikrt} \leq z_{ikrt} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{28}$$

$$\zeta_{ikrt} \geq z_{ikrt} - (1-\gamma_{ikrt})M \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{29}$$

$$\zeta'_{ikrt} \leq M(1-\gamma_{ikrt}) \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{30}$$

$$\zeta'_{ikrt} \leq z_{ikrt} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{31}$$

$$\zeta'_{ikrt} \geq z_{ikrt} - \gamma_{ikrt}M \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{32}$$

Similarly, the non-linearity caused by the multiplication of $\tau_{irt}(\phi_{irt})$ and q_{ipkrt} in Eq. (5) can be resolved by adding Eq. (26), Eq. (27), and Eq. (28) to the model and defining a variable θ_{ipkrt}.

$$\theta_{ipkrt} \leq Mq_{ipkrt} \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{33}$$

$$\theta_{ipkrt} \leq \tau_{irt}(\phi_{irt}) \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{34}$$

$$\theta_{ipkrt} \geq \tau_{irt}(\phi_{irt}) - \left(1 - q_{ipkrt}\right)M \quad \forall r \in \Upsilon, \forall t \in \Psi, \forall i \in \Delta, \forall k \in \Phi \tag{35}$$

According to the definitions provided in Eq. (13) and Eq. (14), the term in Eq. (3) is polynomial and obviously non-linear. Stefanello et al. (2017) addressed the traffic congestion function in Eq. (3) and investigated two piecewise-linear approximations, one of which presents an over-approximation and the other an under-approximation. Following their approach, the piecewise-linear overestimation of the function in Eq. (3) can be delineated as

$$\min \sum_{i=1}^{D} \sum_{r=1}^{R} \sum_{t=1}^{T} \Phi^{over}_{irt} \tag{36}$$

Subject to

$$\mu^l_{irt}\phi_{irt} + \sigma^l_{irt} \leq \Phi^{over}_{irt} \quad \forall r \in \Upsilon, \forall i \in \Delta, \forall t \in \Psi, \forall l \in \Lambda \tag{37}$$

$$\Phi^{over}_{irt} \geq 0 \quad \forall r \in \Upsilon, \forall i \in \Delta, \forall t \in \Psi, \forall l \in \Lambda \tag{38}$$

where

$$\mu^l_{irt}=(\Phi_{irt}(X_l)-\Phi_{irt}(X_{l-1}))/(X_l-X_{l-1})\forall r\in\Upsilon,\forall i\in\Delta,\forall t\in\Psi,\forall l\in\Lambda \tag{39}$$

$$\sigma^l_{irt}=\Phi_{irt}(X_l)-X_l\mu^l_{irt}\quad\forall r\in\Upsilon,\forall i\in\Delta,\forall t\in\Psi,\forall l\in\Lambda \tag{40}$$

and

$$\Phi_{irt}(X_l)=X_l\times\tau^0_{irt}\times\left(1+0.15\times\left(\frac{X_l}{\kappa_{ir}}\right)^\beta\right)\forall r\in\Upsilon,\forall i\in\Delta,\forall t\in\Psi,\forall l\in\Lambda \tag{41}$$

The objective function in Eq. (29) is to minimize the approximation of average user travel time. In the model presented in Eq. (29) to Eq. (31), the slope and the displacement of the linear approximation, μ^l_{irt} and σ^l_{irt}, are calculated by Eq. (32) and Eq. (33), respectively. Eq. (30) is calculates the partial cost for the route from DC i to retailer r in time period t by determining the approximate value Φ^{over}_{irt} for Φ_{irt} according to ϕ_{irt}. We define $\Lambda=\{0,1,\ldots,L-1\}$ as the set representing the index for the points determining the linear pieces. The congestion cost link between every two nodes is comprised of line segments that sequentially connect the coordinates $(X_l,\Phi_{irt}(X_l))$ for $l\in\Lambda$ where $X_l>X_{l-1}$ and $X_l\in R$. The slope of the line connecting two points of $(X_{l-1},\Phi_{irt}(X_{l-1}))$ and $(X_l,\Phi_{irt}(X_l))$ is denoted by μ^l_{irt} and is calculated by Eq. (32) while the displacement of the line is represented by σ^l_{irt} and is obtained by Eq. (33).

The piecewise-linear under-approximation, Φ^{under}_{irt}, can be derived by replacing Eq. (32) by Eq. (35). In this paper, an average of the over-approximation and the under-approximation is used as the linear approximation of the function. For further reading and an illustration of these two approximations, one is referred to a paper authored by Stefanello et al. (2017).

$$\mu^l_{irt}=\tau^0_{irt}\left(1+0.15\times(\beta+1)\times\left(\frac{(X_{l-1}+X_l)/2}{\kappa_{ir}}\right)^\beta\right)$$
$$\forall r\in\Upsilon,\forall i\in\Delta,\forall t\in\Psi,\forall l\in\Lambda \tag{42}$$

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