Robust Optimization of Sustainable Dairy Supply Chain with Products Demands Uncertainty and Environmental Impact Consideration

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Milk and milk products are an important part of the daily menu of millions of people around the world. Increasing the efficiency and competitiveness of this type of production is related to the implementation of the strategy of sustainable management of supply chains, which cover all processes from raw materials, through production to end users. The presence of fluctuations in the product demands on the markets also influences the sustainable operation of considered supply chain activities. The present study proposes an application of already developed robust optimization approach for optimal design of a sustainable dairy supply chain operating under uncertain products demands on a new case study from Bulgaria which include three milk suppliers, two dairies and three markets. The considered supply chain is related with a production of different dairy products according to different recipes while satisfying environmental and economic criteria defined in terms of costs. The latter is associated with the generated wastewater from dairy production and CO_2 emissions due to the energy consumed and transportation. Several optimization problems have been formulated and solved under nominal data for the product demands and four uncertainties levels - 0.25, 0.5, 0.75 and 1.

The obtained optimal values of the economic and environmental costs show that the optimization approach implementation results in sustainable solutions that do not change significantly with an increase in the uncertainty level of consideration of the product demands.

1. Introduction

Dairy products are one of the most consumed food all over the world. Today global dairy industry is worth over $400 billion representing around 14 % of global agricultural trade with milk being the third most produced agri-commodity (Berman and Swani, 2010). Similar to other sectors of the food industry, this sector also faces many challenges mainly related to the uncertainties that can arise regarding the parameters of the processes that are involved in the whole life cycle of the products – from the raw materials, through the production itself to the final customers. Most often, these uncertainties are related to the dynamically changing prices of raw materials and products, production capacities, transportation costs, short shelf life of raw materials and products, etc. This requires decision-makers to apply more reliable methods to mitigate the risk of uncertainties in dairy supply chains and improve the sustainability of production in this sector (Tüzemen and Yapraklı, 2022). In this order, Drofenik et al. (2021) have identified the scenarios in food production and consumption that would lead to a more balanced supply of locally produced food and a reduction in the environmental impact of agricultural production.

One of the most effective ways to solve these problems is by formulating and solving optimization models of dairy supply chains in the presence of uncertainties regarding their parameters. Recently, many approaches to deal with these uncertainties have been developed. Yang et al., (2015) have developed a two-stage optimization method for two-objective supply chain design problem with uncertain transportation costs and uncertain

customer demands has been shown. The authors have proposed two solution concepts to define the multi-objective value of fuzzy solution. They have implemented an approximation approach for finding out the values of the both objective functions. Stefansdottir and Grunow (2018) have proposed a two-stage stochastic mixed integer linear programming model for determination of both, product designs and processing technologies of dairy supply chain under uncertain product demands consideration. Gao and You (2018) have shown a stochastic bi-level mixed integer non-linear programming model for optimal design of decentralized dairy supply chain considering multiple stakeholders. Yavari and Geraeli (2019) have provided a deterministic mixed-integer linear programming model with a robust counterpart for the uncertain products demands, returns, transportation costs and the quality of returned products satisfying economic and environmental criteria. Touil et al., (2019) have proposed a credibility-based fuzzy mathematical programming model with the Hurwicz criterion or integrating the production and distribution in milk supply chain under uncertainty has been shown. The latter has been defined in terms of mixed integer linear programming with optimization criterion - maximizing the total profit which include the total costs such as production, storage, and distribution. As fuzzy numbers the objective function coefficients (e.g. production cost, inventory holding and transport costs) and other parameters (e.g., demand, production capacity, and safety stock level) have been defined. Dutta and Shrivastava (2020) have developed a scenario-based approach for optimal transportation routes in dairy supply chain operating under uncertain processes, supply operations and products demand. Jouzdani et al., (2020) have proposed a robust supply chain design problem considering multiple products, multiple transportation modes, monetary value of time and uncertainty in transportation costs, demand and supply. The approach has been applied on a case study of dairy products packaging and distribution network. Kaviyani-Charati et al. (2022) have developed a three-objective two-stage stochastic optimization model for design of non-profit food bank supply chain which include the following objectives: 1) minimizing costs of food collection, storage, distribution or transportation, and food banks establishment, 2) minimizing carbon emissions of food waste and transportation as well as incrementing carbon emissions saving through preserving surplus food and 3) optimizing social performance including demand satisfaction, job creation, and unpleasant odor of food waste. Foroozesh et al. (2022) have proposed a novel robust possibilistic programming (RPP) approach is presented using credibility measure and membership functions of generalized interval-valued type-2 fuzzy variables to face the epistemic uncertainties, such as supply capacity of facilities, customer demand, transportation cost, and emission factor, in the proposed mathematical model.

Kirilova et al., (2022a) have created a deterministic optimization model for design of dairy supply chain with economic, environmental and social consideration. The model includes environmental impact assessments for the pollutants released in air and water. These are related with CO_2 emissions generated due to transportation and energy consumed and wastewater from the production of dairy products.

The present study represents an application of already developed robust optimization approach (Kirilova et al., 2022b) for optimal design of a sustainable dairy supply chain operating under uncertain products demands. The approach is based on formulation and solution of several optimization problems at different realizations of the nominal values for the products demands generated randomly with uniform probability distribution under four uncertainty levels in specified uncertainty set (Ben-Tal et al., 2005). The proposed approach has been implemented on a new case study form Bulgaria including three suppliers, two dairies and three markets.

2. Robust optimization approach

The proposed robust optimization model for designing a sustainable dairy supply chain operating under conditions of product demand uncertainties includes four types of mathematical models of production of dairy products according different production recipes; dairy supply chain design; environmental impact performance of the considered dairy supply chain and economic performance of the considered dairy supply chain. The optimization framework additionally includes model constraints and The optimization framework includes model constraints and optimization criterion. Detailed description of formulated optimization problems including needed data, all mathematical models, constraints and optimization criterions is given in (Kirilova et al., 2022a) and (Kirilova and Vaklieva-Bancheva, 2017).

2.1 Supply chain optimization problem description

The research proposes a robust optimization model of sustainable three-echelon dairy supply chain operating under uncertainty conditions regarding product demands. The dairy supply chain includes suppliers of different raw materials (milks), dairies for production of different type of products according two production technologies (recipes) and markets for delivering of the produced products. The products should be produced in given quantities in the dairies for a given time horizon. The latter should satisfy predefined product demands for the markets. The aim of the study is formulation and solution of several robust optimization problems under different random realizations for the product demands while meeting environmental and economic criteria defined in

terms of costs. The environmental impact of the considered dairy supply chain is accounting through both, BOD_5 (biochemical oxygen demand for 5 days) related with generated wastewater during the production of the products in the dairies and CO_2 emissions related with the consumed energy by the production units' and those generated during transportation of raw materials and products between suppliers, dairies and markets. The economic impact of the dairy supply chain is considered in terms of production costs, the costs for purchasing the required quantities of raw materials and those of transporting the milk and products.

2.2 Data needed for mathematical model formulation

The mathematical model for optimal design of the dairy supply chain includes three sets of data:
1). Data related to the composition of the raw materials used and the products produced.
2). Data on the production system, capacity of milk suppliers, selling prices of milk and products, production costs, distances between milk suppliers, dairies and markets, transporting costs and payload capacity of used transportation trucks.
3). Environmental impact data related to pollutants generated in air and water.

2.3 Mathematical model of production of dairy products according production recipes

The proposed approach involves four mathematical models:
1). Mathematical models of the used production recipes for the production of the different products.
The production of two types of cottage cheese - low-fat content and high-fat content according to two different recipes, each of which uses standardized whole milk and skimmed condensed milk as raw materials is considered. Production recipes include different production tasks performed in units of different types.
The first production recipe includes three production tasks: pasteurization of standardized whole milk; acidification to obtain both dairy products; draining to produce the target dairy products, while the second involves four production tasks: dilution of skimmed condensed milk; pasteurization of milk; acidification and draining. The amount of products produced depends on the milk fat content of milk used, which also determines the environment impact.
The mathematical models of the production recipes include equations for determination of the concentrations of main components such as protein, casein and lactose of used raw materials – different types of milk.
2). Equations of the products yield as functions of the fat content in the used raw materials.
3). Equations for determination of specific indicator accounting for the quality of the produced products.

2.4 Mathematical model of dairy supply chain portfolio

Mathematical model of considered three-echelons dairy supply chain includes equations determining the quantities of raw materials provided by all suppliers and products delivered on the markets.

2.5 Mathematical model of environmental impact performance of the considered dairy supply chain

This model includes equations for: 1). BOD_5 related with wastewater generated during conducting production tasks for the production of both products according both recipes as well as those related with pre-processing of used raw materials – different types of milk. 2). Equations for determination of the quantities of CO_2 emissions related with energy consumed by the dairies for the production of the products. 3). Equations for determination of the CO_2 emissions generated by the trucks used for transporting the raw materials and products.

2.6 Model of economic performance of the considered dairy supply chain

The mathematical model of economic performance of the considered dairy supply chain includes equations for all costs related with: the production of the products in the dairies; purchasing the required quantities of milks by the suppliers; transporting of raw materials and products between milk suppliers, dairies and markets.

2.7 Dairy supply chain model constraints

In order to obtain feasible solutions during solution of formulated optimization problems several constraints should be formulated and included in the optimization framework. They are related to: 1). Conducting production of the products in the dairies in the predefined time horizon (for their calculation, size factors, the quantities of the produced products and the production tasks are used) 2). Capacities of considered milk suppliers; 3). Capacities of the markets to deliver the produced products and 4). Environmental impact costs for treatment of the generated in air and water emissions of pollutants.
All equations are referred to 1 kg milk and 1 kg target product. The connection between the production tasks is provided by so called size factors. They determine the quantities of processed in each production unit materials so as 1 kg product to be produced.
Information about size factors, production units, production tasks, processing times, etc. is provided in Kirilova and Vaklieva-Bancheva, (2017).

2.8 Optimization criterion formulation

The used optimization criterion represents the optimal profit obtained after reduction of the revenue from the sale of the products on the markets with all economic and environmental costs.

Detailed description of formulated optimization problems including needed data, all mathematical models, constraints and optimization criterions is given in (Kirilova et al., 2022a) and (Kirilova and Vaklieva-Bancheva, 2017).

3. Description of robust counterpart for uncertain product demands

Represented above optimization model for optimal design of sustainable dairy supply chain is extended with a robust counterpart for determination of the uncertain products demands using the approach of Ben-Tal et al., (2005). It is based on formulation and solution of robust optimization problems at different realizations of the nominal values for the products demands generated randomly with probability distribution under certain uncertainty levels in specified uncertainty set. More detailed description of the robust counterpart for determination of the uncertain products demands is provided in (Kirilova et al., 2022b).

4. Case study

The presented above robust optimization approach is applied in a real case study from Bulgaria including production of two types of cottage cheese according two production technologies using standardized whole milk and skimmed condensed milk as raw materials. The production of both types of products is conducted in two dairies. Three suppliers provide dairies with the raw materials. The produced products deliver on three markets. The products production is realized over time horizon of one month. The considered dairy supply chain is represented in Figure 1. Used production units for conducting the production tasks and theirs summarized volumes are listed in Table 1. Capacities of the three suppliers (kg), milk prices (BGN/kg) are presented in Table 2. Products prices (BGN/kg) are represented in Table 3. The exchange rate of BGN (Bulgarian lev)/EUR is 1.95583 BGN per 1 EUR. Distances (km) between suppliers, dairies and markets are listed in Table 4.

Data about the type of the used trucks as payload capacity, energy of fuel, CO_2 generated from fuel combustion, fuel consumption, fuel price, CO_2 emissions price, energy consumed in both recipes, BOD_5 price paid to wastewater treatment plants from Dairy 1 and Dairy 2 are provided in (Kirilova et al., 2022a). These data are needed for calculation of the environmental costs related to the pollutants released in air and water.

Figure 1: Dairy Supply Chain

Table 1: Equipment units with summarized volumes (m^3)

	Milk tanks	Pasteurizers	Curd vats	Drainers
Dairy 1	1,450	800	950	300
Dairy 2	1,450	950	1,050	340

Table 2: Capacities of suppliers (kg) and milk prices (BGN)

	Capacity (kg)		Milk price (BGN)	
	Milk 1	Milk 2	Milk 1	Milk 2
Supplier 1	97,000	57,000	0.90	2.7
Supplier 2	100,540	54,500	0.80	2.4
Supplier 3	113,000	78,000	1	3

Table 3: Products prices (BGN)

	Market 1	Market 2	Market 3
Product 1	14.00	14.30	14.50
Product 2	15.60	14.90	14.70

Table 4: Distances between suppliers, dairies and markets (km)

	Supplier 1	Supplier 2	Supplier 3	Market 1	Market 2	Market 3
Dairy 1	10	15	20	98	136	46
Dairy 2	20	10	15	22	23	71

5. Results and discussions

Several robust optimization problems were formulated and solved under nominal products demands data and four different uncertainty levels (UL) (ρ = 0.25; 0.5; 0.75; 1). Under each uncertainty level, ten random realizations of products demands θ have been generated with uniform distribution in the following uncertainty set: $[\bar{\theta} \pm \rho * G]$. Where $\bar{\theta}$ is the nominal value of uncertain parameter. G and ρ, $\rho \in (0,1)$ are positive numbers representing so called "uncertainty scale" and "uncertainty level". The "uncertain scale" represents the standard deviation of the variable. The "uncertainty level" represents the upper limit of uncertainty. Table 5 represents the results obtained from solving the optimization problems in terms of supply chain profit under 10 scenarios (S). The highest profit is obtained at the highest uncertainty level 1. The obtained results show that increasing the uncertainty levels leads to a decrease in the supply chain profit with a relatively small standard deviation (SD). At an uncertainty level of 0.75, the lowest average value of supply chain's profit of 531,877 BGN was calculated. In general, we can say that the obtained results are comparable at all levels of uncertainty.

Table 6 presents the results obtained from the solution of the optimization problems for the supply chain environmental costs under 10 scenarios. It can be concluded that regardless of the levels of uncertainty, there are no large deviations in the supply chain environmental costs, respectively environmental pollution. The results for the obtained solutions for the supply chain total costs are listed in Table 7. One can see, that these data also do not change significantly with an increase in uncertainty level.

Table 5: Obtained results from the optimization problem solutions for the dairy supply chain profit

UL	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Mean	SD
ρ=0.25	520,118	570,839	551,404	528,392	520,924	520,662	526,033	568,495	507,893	541,504	535,626	20,489
ρ=0.5	520,119	567,893	552,720	527,424	513,232	518,390	518,649	562,152	505,932	537,056	532,357	20,514
ρ=0.75	514,182	568,707	557,796	530,216	509,301	519,878	515,024	559,569	507,730	536,368	531,877	21,568
ρ=1	532,269	569,521	562,872	533,008	505,369	521,365	511,399	556,986	509,529	535,679	533,800	21,723

Table 6: Obtained results from the optimization problems solutions for the supply chain environmental costs

UL	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Mean	SD
ρ=0.25	20,487	21,956	21,162	20,623	20,500	20,496	20,584	21,860	20,286	20,839	20,879	561
ρ=0.5	20,487	21,852	21,232	20,531	20,298	20,383	20,387	21,617	20,177	20,690	20,765	558
ρ=0.75	20,056	21,885	21,439	20,577	20,233	20,407	20,327	21,512	20,207	20,679	20,732	610
ρ=1	20,611	21,918	21,647	20,623	20,168	20,432	20,268	21,406	20,237	20,667	20,798	596

Table 7: Obtained results from the optimization problems solutions for the supply chains total costs

UL	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Mean	SD
ρ=0.25	489,823	529,590	507,901	493,418	490,173	490,059	492,394	526,973	484,509	499,117	500,396	15,182
ρ=0.5	489,823	527,008	510,075	491,142	484,974	487,216	487,328	520,601	481,801	495,328	497,530	15,097
ρ=0.75	479,076	527,916	515,739	492,355	483,265	487,862	485,752	517,718	482,582	495,029	496,729	16,397
ρ=1	493,247	528,824	521,404	493,569	481,556	488,509	484,177	514,836	483,364	494,730	498,422	16,119

6. Conclusions

The research represents an application of already developed robust optimization approach (Kirilova et al., 2022b) for optimal design of a sustainable dairy supply chain operating under uncertain products demands. A new case study is considered, which involves the production of two products according two recipes in a production complex comprising three milk suppliers, two dairies and three markets. Several robust optimization problems have been formulated and solved under different random realizations of products demands taking into

account economic and environmental considerations. The nominal data for the product demands were randomly generated at four uncertainty levels using uniform distribution in a specified uncertainty set. Two performance measures were used to evaluate the optimization models: the mean and standard deviation of the objective function values under random realizations. The obtained results show that the increase in the uncertainty level leads to a decrease in the supply chain profit with a relatively small standard deviation. At the uncertainty level of 0.75, the lowest mean value of the supply chain profit of 531,877 BGN was obtained. The results for the supply chain total costs show that they also do not change significantly with an increase in the uncertainty level.

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