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A Robust Optimisation Model for the Sustainable Design of a Dairy Supply Chain under Uncertain Environmental Conditions

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The production of dairy products in the relevant supply chains (SCs) is associated with the generation of significant amounts of pollutants in the wastewater and CO_2 emissions into the air, which released into the environment can cause a great risk of its pollution. The presence of uncertainties regarding the released amounts of pollutants further exacerbates the environmental problem. One of the ways to capture these uncertainties and control the environmental risk of pollution is by applying approaches to optimal design of sustainable supply chains operating under uncertainty conditions. The present study proposes a mixed integer non-linear programming approach to the optimal design of a sustainable SC for the production of two types of dairy products with a choice of technology, which includes models of economic, environmental and social impact as well as dairy production. The latter takes into account uncertainties regarding the environmental impact costs for treatment of the generated pollutants in terms of wastewater and CO_2 emissions related to the SC activities. The efficiency of the proposed approach has been proved in a real case from Bulgaria, which includes suppliers of two types of milk and dairy plants for the production of two types of dairy products and markets.

1. Introduction

Dairy production on a global scale is related to the generation of significant amounts of pollutants, which, released into the environment, lead to a great environmental risk. On the other hand, it is associated with a large consumption of water and energy at all stages of the dairy SC, which, in addition to the main production processes, also includes some auxiliary processes such as cleaning the equipment. It was found that cleaning operations are responsible for 70 % of the water requirements, while refrigerators, pasteurisation and packaging account for 70 % of the energy consumption in the dairy facility (Vasilaki et al., 2016).
One of the most effective ways to achieve the most complete and accurate assessment of the sustainability of respective productions in terms of their environmental and economic impact as well as the related water and energy consumption is the development and application of mathematical approaches for simulating and optimising activities in relevant dairy SCs. For example, the developed SC energy models can provide a complete overview of the energy demand and the energy mix of a dairy SC (Malliaroudaki et al., 2022). Additionally, they can highlight the most energy-consuming processes and allow the evaluation of alternative energy-saving operations that can lead towards the net-zero carbon target. On the other hand, the application of special models to simulate the greenhouse gas emissions generated under dairy production systems enables the identification of the effect of small management changes that would reduce pollutants and increase farm profitability (Lovett et al., 2008). Cecchini et al. (2016) have investigated the environmental and economic sustainability of dairy farms through the implementation of life cycle environmental assessment and economic assessment, including the direct and indirect costs related to the production process factors. The authors have performed a correlation analysis and a linear regression in order to study the relationship between the carbon footprint and operating income.
When applying mathematical approaches for the optimal design of dairy SCs, it is of utmost importance to take into account the presence of uncertainties that may arise regarding their main parameters, such as operational costs, prices of raw materials and products, product demands, energy consumption, transportation, the products

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lifetime and etc. Baghalian et al. (2013) have considered demand-side and supply-side uncertainties simultaneously in a stochastic mathematical formulation for the strategic design of multi-product SC involving capacitated production facilities, distribution centres and retailers. Jouzdani and Govindan (2021) have investigated the interrelations and interactions of the three aspects of sustainability through the development and implementation of a multi-objective stochastic mathematical programming model for optimisation of the costs, energy consumption, and the transport traffic associated with dairy SC operations. Ebrahimi et al. (2022) have proposed a multi-objective mixed-integer programming model for the design of sustainable economic dairy SC based on the triple bottom line strategy. Kalantari Khalil Abad et al. (2022) have developed a two-stage stochastic programming model for a strategic design of a green closed-loop SC. To control the uncertainty of strategic decisions, demand and the upper bound of emission capacity with three possible scenarios have been considered.

The presented above approaches aim to achieve sustainability or considered dairy SC concerning environmental impact, most often in terms of the greenhouse gas emissions related to the transport, minimisation of consumed energy by the production of the products, maximisation of the profit, minimisation of the total costs, products lifetime, social satisfaction and etc. The uncertainties which have been taken into consideration are regarding most often product demands, transport and production costs, facility capacity, transport traffic, etc.

Kirilova et al. (2022a) have proposed a deterministic approach for the optimal design of sustainable dairy SC for the production of different types of dairy products according to different technologies while satisfying economic, environmental and social criteria defined in terms of costs. The environmental criterion includes assessments of pollutant emissions in relation to two areas of impact - air and water. The model of Kirilova et al. (2022a) has been extended with a Robust Counterpart (RC) for uncertain product demands (Kirilova et al., 2022b) using the approach of Ben-Tal et al. (2005). It was solved considering only economic and environmental criteria for a case study consisting of two suppliers, two dairies and two markets.

The present study is an implementation of the approach developed by Kirilova et al. (2022b) to a different case study for the SC consisting of three suppliers, two dairies and three markets, taking into account the three criteria of sustainability - economic, environmental and social. As an uncertain parameter, the environmental impact costs for treatment of the generated CO_2 emissions related to the transportation and consumed energy by production facilities and wastewater generated during the production of the dairy products and these ones associated with used raw materials are considered.

2. General formulation of the optimisation problem for the design of a sustainable dairy SC under uncertain environmental costs

The considered approach has been developed to plan the activities in a SC, including milk suppliers, dairies and markets, to satisfy given consumer demands (short-term) for the production of two types of cottage cheese - low-fat content and high-fat content according to different technologies using as raw materials standardised whole milk and skimmed condensed milk. As a result of its implementation, the optimal sustainable production portfolios of the dairies, satisfying the trade-off between environmental, economic and social objectives, are found. The approach includes three interconnected models for (i) the production of the products according to different recipes; (ii) SC design; (iii) the environmental impact assessment of the SC, and (iv) the social impact assessment related to the employees to be hired by suppliers, dairies and markets. The latter depends on the average quantities of raw materials/products processed by these employees.

The environmental impact is assessed in terms of two areas:

1). Wastewater generated at each processing task of the production technologies, including those related to pre-processing of used raw materials. As an environmental impact indicator of generated wastewater Biological Oxygen Demand for 5 days (BOD_5) is used.

2). CO_2 emissions related to the energy consumption by the dairies and CO_2 emissions produced during the transportation of raw materials and products between suppliers, dairies and markets when vehicles with different payload capacities and fuel engines are used.

Wastewater produced in the dairies is treated in Wastewater Treatment Plants (WWTPs) at a given cost. The expenses to be paid to the WWTPs, associated with the considered products are limited for each dairy.

Air Pollution Tax (APT) is also imposed concerning the CO_2 emissions associated with the production of the products and transportation of raw materials and products. It aims to maintain the quantity of the emitted CO_2 below an acceptable level.

The used optimisation criterion is represented by the income from the market sale of products after the deduction of all costs - production costs, raw materials costs, transportation costs, and environmental and social costs.

The robust optimisation framework includes four groups of data: 1). Data about the contents of used raw materials and dairy products; 2). Data about the SC structure. The latter involves data about the used production system, the capacities of milk supply centres, 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). The environmental impact related to pollutants generated in air and water, and 4). Data about the costs related to the employees (job positions) to be hired by suppliers, dairies and markets. They include costs for salaries, social benefits, working clothes, medical care and insurance and the average quantities of raw materials/products processed by employees in suppliers, dairies and markets.

In addition, the following decision variables are defined: 1). Binary variables for the SC structuring; 2). Continuous variables for the raw materials and product flows between suppliers, dairies and markets. The latter accounts for the quantities of both types of raw materials and the quantities of dairy products; 3). Continuous variables for the milk fat content in the used milk; 4). Integer variables for the employees (job positions) to be hired by suppliers, dairies and markets. The latter depends on the processed amounts of raw materials/products.

The proposed optimisation framework includes the constraints related to 1). Conducting production of the products in the dairies in the predefined time horizon; 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 air and water emissions of pollutants. The latter are considered uncertain parameters.

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 to produce 1 kg of product. Information about size factors, production units, production tasks, processing times, etc., is given in Kirilova and Vaklieva-Bancheva (2017).

Several optimisation problems have been formulated and solved at different realisations of the nominal values for the environmental costs regarding wastewater and CO_2 emission of pollutants generated randomly with uniform distribution under two levels in specified uncertainty sets. A detailed description of formulated optimisation problems, including needed data, all mathematical models, constraints and optimisation criteria is provided in Kirilova et al. (2022a). A mathematical formulation of the robust model is given in Kirilova et al. (2022b).

3. Case study

The presented above robust optimisation approach is applied in a real case study from Bulgaria, including the production of two types of cottage cheese according to two production technologies using standardised 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 to three markets. The product's production is realised over the time horizon of one month. Used production units (UNEP, 2000) for conducting the production tasks and their summarised volumes are listed in Table 1.

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

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

Capacities of the three suppliers (kg) and milk prices (BGN/kg) are presented in Table 2 (EU PRICES of COW's RAW MILK, 2023). Table 3 lists product demands and product prices in the markets. Distances (km) between suppliers, dairies and markets are listed in Table 4.

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

In Table 5 are presented the data about vehicles used for transportation of raw materials and products. They are used for calculation of the CO_2 emissions associated with transportation and transportation costs. The latter in BGN/kg.km are calculated by multiplication of the vehicle's fuel consumption (L/100 km), the vehicle's fuel price (BGN/L) and the number of vehicles' courses. The latter is divided by the total quantities of raw materials or products produced (kg).

Table 3: Products demands (kg) and products prices (BGN)

	Product demand (kg)		Products prices (BGN)	
	Product 1	Product 2	Product 1	Product 2
Market 1	32,730	30,830	10.8	12.1
Market 2	17,830	20,300	12.3	11.4
Market 3	20,000	19,500	12.7	12.5

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	75

Table 5: Data about used vehicles for transportation of raw materials and products

Vehicles used for transportation	Payload capacity, (L/kg)	Energy of fuel, (kWh/L)	CO_2 emissions generated from fuel combustion, (kg CO_2/kWh)	Fuel consumption, (L/100 km)	Fuel price, (BGN/L)
Milk tanker truck with petrol engine	2,500	8.056	0.249	32	2.22
Refrigerator truck with diesel engine	4,000	9.583	0.267	23	2.27

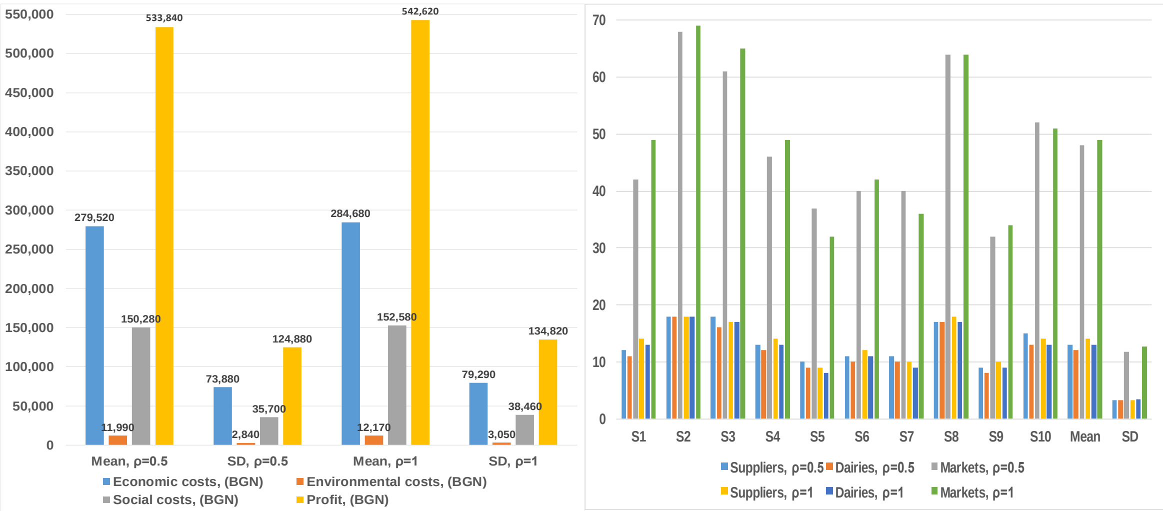
The environmental costs associated with transportation are obtained using data listed in Table 5 and the price of CO_2 emissions, which is 0.174 BGN/kg CO_2. The energy consumed in both recipes for heating of 1 kg milk is 8.333×10^{-3} kWh/kg milk, and for cooling is 6.333×10^{-2} kWh/kg milk (Maslarski and Tomova, 1980). The CO_2 emissions associated with both processes is 0.46 kg CO_2/kWh (Covenant of Mayors and Joint Research Centre of the European Commission, 2014). The costs of CO_2 are 0.00998 BGN/kg CO_2. The price of BOD_5 paid to wastewater treatment plants from Dairy 1 is 2.9 BGN/kg, while from Dairy 2 it is 3.5 BGN/kg. The production costs are obtained based on the energy used for production of the products using the price of energy, which is 0.14072 BGN/kWh. In Table 6 the average costs (BGN), related to the number of employees (job positions) to be hired by the suppliers, dairies and markets are presented (Living and working conditions: Bulgaria, 2023). They include costs for salaries (BGN) (Salaries in the category: Agriculture, food industry, 2023), working clothes (BGN), social benefits (BGN) and medical insurance (BGN). The same table also shows the average quantities (kg) of raw materials or products that employees can process per day in the different echelons of the SC.

Table 6: Data related with employees

Employees	Costs for salaries, (BGN)	Working clothes, (BGN)	Social benefits, (BGN)	Medical insurance, (BGN)	Average quantities of raw materials/products that employees can process per day, (kg)
Suppliers	1,300	50	100	90	500
Dairies	2,300	50	200	90	150
Markets	1,700	50	100	90	40

4. Results and discussion

The proposed robust optimisation approach has been implemented in a real case study from Bulgaria. The dairy SC includes three suppliers, two dairies and three markets. As uncertain parameters the environmental costs for treatment of the generated CO_2 emissions related with transportation and energy consumed by product facilities and wastewater generated at each processing task of the production recipes, including those related with pre-processing of used raw materials, are considered. Several robust optimisation problems were formulated and solved under nominal product requirement data and two different uncertainty levels (UL) (ρ = 0.5 and 1). Under each uncertainty level, ten random realisations (scenarios) have been uniformly generated in the following uncertainty set: $[nominal\ value \pm \rho * SD]$, where SD is the standard deviation (SD) of the obtained results. The optimisation models have been solved using GAMS® optimisation software-BARON solver as all calculations have been carried out on an AMD 7 3700X 8-CORE (3.6/4.4. GHz, 32 MB, AM4) CPU with 16 GB DDR4 3600 MHz RAM. Two performance measures have been used to evaluate the models: the mean and standard deviation of the obtained results. The optimisation problems have been formulated and solved at given boundaries of varying of the environmental costs, as follows: cost for treatment of wastewater generated in both dairies - 1,500 ÷ 5,000 BGN and costs for treatment of CO_2 emissions of pollutants associated with transportation of raw materials and products between suppliers, dairies and markets and energy consumed by production facilities - 5,000 ÷ 15,000 BGN. The obtained results for model solutions are shown in Figure 1 (a) and Figure 1 (b). From Figure 1 (a), it can be seen that the higher level of uncertainty (ρ=1) is associated with greater environmental impact cost values for treating air and water generated pollutant emissions, economic, environmental, social cost values, and profit. The increase in the standard deviation values of the economic, environmental, social costs, and the profit obtained at the higher uncertainty level are 6.8 %, 6.8 %, 7.2 %, and 7.4 %. One can see that large variations in the level of uncertainty do not lead to a large difference in the standard deviations of the abovementioned values.



(a) (b)

Figure 1 (a): Optimal solutions for the SC for economic, environmental, social costs and profit, at two UL levels *(b) Optimal solutions for the number of employees to be hired from the suppliers, dairies and markets, at two UL levels for 10 scenarios S1÷S10*

The same conclusion can be made for the results presented in Figure 1 (b). In this case, the number of employees to be hired by suppliers, dairies and markets is kept constant at the different uncertainty levels, except for the case of the markets. In this case at the higher uncertainty level, the standard deviation values of the obtained results are about 7 %. From the resulting products portfolios of the dairies under the different scenarios, it can be concluded that imposing strict restrictions on the environmental costs for treatment of the generated emissions of pollutants in air and water result in solutions that do not satisfy predefined product demands.

5. Conclusions

The research represents an implementation of the robust optimisation approach for optimal design of sustainable dairy SC for production of two types of cottage cheese using two technologies at uncertain environmental costs. The considered SC comprises three milk suppliers, two dairies and three markets, operating under uncertain environmental costs for treatment of the generated CO_2 emissions related to transportation and energy consumed by product facilities and wastewater generated at each processing task of the production recipes, including those related with pre-processing of used raw materials. Several robust optimisation problems have been formulated and solved under different random realisations of the uncertain parameters taking into account economic, environmental and social considerations. The nominal data for the environmental costs were randomly generated at two levels using uniform distribution in a specified uncertainty set. Two performance measures were used to evaluate the optimisation models: the mean and SD of the objective function values under random realisations.

The obtained results show that a higher level of uncertainty is associated with greater environmental impact costs for treating pollutants released in air and wastewater, economic, environmental, and social costs, and profit. At the higher level of uncertainty, there is an increase in the values of the standard deviation of the obtained results by 6.8 % for economic and environmental costs and 7.2 % and 7.4 % for social costs and profit. Similar is the case with the results obtained for employees to be hired by the suppliers, dairies and markets. In them, at the higher level of uncertainty, the largest increase in the values of the standard deviation of the obtained results of 7 % is related to employees hired by the markets. On the other hand, imposing strict restrictions on the environmental costs for treatment of the generated emissions of pollutants in air and water result in solutions that do not satisfy predefined product demands. The obtained optimal values of the economic, environmental and social costs show that the optimisation approach implementation results in sustainable solutions that do not change significantly with an increase in the uncertainty level of consideration of the environmental costs. The developed optimisation model takes into consideration environmental assessments of pollutants that are released only into air and water. For the future can be extended with including an assessment of the environmental impact of pollutants released in soil.

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References

Baghalian A., Rezapour S., Farahani R.Z., 2013, Robust supply chain network design with service level against disruptions and demand uncertainties: A real-life case, European Journal of Operational Research, 227(1), 199-215.

Ben-Tal A. Golany B., Nemirovski A., Vial J.P., 2005, Retailer-supplier flexible commitments contracts: A robust optimisation approach, Manufacturing and Service Operations Management, 7(3), 248-271.

Cecchini L., Torquati B., Paffarini C., Barbanera M., Foschini D., Chiorri M., 2016, The milk supply chain in Italy's Umbria region: Environmental and economic sustainability, Sustainability, 8(8), 728.

Covenant of Mayors and Joint Research Centre of the European Commission, Reporting Guidelines on Sustainable Energy Action Plan and Monitoring, 2014, <eumayors.eu/IMG/pdf/Reporting_Guidelines_SEAP_and_Monitoring.pdf >, accessed 13.04.2023.

Ebrahimi E., Shirazi B., Mahdavi I., Arshadi Khamseh A., 2022, Toward a sustainable economic production quantity model employing triple bottom line strategy: Uncertain multi-objective optimisation with lost sales and full back-order, Scientia Iranica, DOI: 10.24200/sci.2022.59478.6267.

EU PRICES of COW's RAW MILK, 2023, <agriculture.ec.europa.eu/system/files/2023-07/eu-raw-milk-prices_en.pdf> accessed 06.05.2023.

Jouzdani J., Govindan K., 2021, On the sustainable perishable food supply chain network design: A dairy products case to achieve sustainable development goals, Journal of Cleaner Production, 278, 123060.

Kalantari Khalil Abad A. R., Pasandideh S. H. R., 2022, Green closed-loop supply chain network design with stochastic demand: A novel accelerated benders decomposition method, Scientia Iranica, 29(5), 2578-2592.

Kirilova E. G., Vaklieva-Bancheva N. G., 2017, Environmentally friendly management of dairy supply chain for designing a green products' portfolio, Journal of Cleaner Production, 167, 493-504.

Kirilova E., Vaklieva-Bancheva N., Vladova R., Petrova T., Ivanov B., Nikolova D., Dzhelil Y., 2022a, An approach for a sustainable decision-making in product portfolio design of dairy supply chain in terms of environmental, economic and social criteria, Clean Technologies and Environmental Policy, 24(1), 213-227.

Kirilova E. G., Vaklieva-Bancheva N. G., Vladova R. K., Petrova T. S., Nikolova D. S., Ganev E. I., Dzhelil Y. R., 2022b, Impact of Product Demand uncertainties on the Optimal Design of a Sustainable Dairy Supply Chain: A Case Study of Bulgaria, Chemical Engineering Transactions, 94, 547-552.

Living and working conditions: Bulgaria, 2023, <eures.ec.europa.eu/living-and-working/living-and-working-conditions/living-and-working-conditions-bulgaria_en> accessed 11.04.2023.

Lovett D. K., Shalloo L., Dillon P., O'Mara F. P., 2008, Greenhouse gas emissions from pastoral based dairying systems: The effect of uncertainty and management change under two contrasting production systems, Livestock Science, 116, 260–274.

Malliaroudaki M. I., Watson N. J., Ferrari R., Nchari L. N., Gomes R. L., 2022, Energy management for a net zero dairy supply chain under climate change, Trends in Food Science and Technology, 126, 153–167.

Maslarski D., Tomova V., 1980, Technological Equipment of Dairy Industry, "Hristo Danov", Plovdiv, Bulgaria (in Bulgarian).

Salaries in the category: Agriculture, food industry, 2023, <www.zaplatomer.bg/en/salaryinfo/agriculture-food-industry > accessed 13.04.2023.

UNEP 2000, Overview of Dairy Processing. A report by COWI Consulting Engineers and Planners AS, Denmark for the United Nations Environment Programme (UNEP) and the Danish Environmental Protection Agency, 7-11, <wedocs.unep.org/rest/bitstreams/17331/retrieve>, accessed 27.07.2023.

Vasilaki V., Katsou E., Ponsá S., Colón J., 2016, Water and carbon footprint of selected dairy products: A case study in Catalonia. Journal of Cleaner Production, 139, 504-516.