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A multi-objective robust optimization to design a sustainable dairy supply chain under uncertain product demands, economic and social consideration. A real case study from Bulgaria

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The operation of dairy supply chains (DSCs) is associated with the generation of significant amounts of wastewater pollutants and CO_2 emissions. The presence of uncertainty regarding various parameters of the considered DSCs has an additional impact on their sustainability. The most efficient way to improve the sustainability of DSCs is by applying mathematical modeling approaches for optimal design of sustainable DSCs operating under uncertain conditions. The present study proposes an optimal model for design of a sustainable DSC for the production of two types of dairy products with a technology selection, which includes economic, environmental and social impact models, as well as dairy production model. The optimization model takes into account uncertainty in products demands, raw materials and products prices and social costs. The effectiveness of the proposed approach is proved in a real case of a DSC from Bulgaria, which includes suppliers of two types of milk and dairy plants for the production of two types of dairy products and markets. The obtained optimal values of the economic, environmental and social costs show that the application of the optimization approach results in sustainable solutions that do not significantly change with an increase in the uncertainty level of consideration of the uncertain parameters.

Keywords: robust optimization; optimal design; uncertain conditions; economic, environmental and social sustainability improvement; dairy supply chain

INTRODUCTION

Increasing dairy products production, population growth and changing consumer habits lead to an increased market volume for dairy products, which rises concerns about possible environmental impacts, increased dairy production costs and negative social impact [1]. The latter requires the implementation of the strategy of sustainable management of the DSCs, which takes into account all activities across the network - from the supply of raw materials, through the production itself, products transportation and their delivery to customers. The design of sustainable SCs is directly related to making important decisions that can be taken into account at different levels such as strategic, tactical and operational of the design and management of SCs activities. This includes: choosing suppliers, determining the purpose and location of facilities, allocating production capacity, choosing technologies for manufacturing products, creating a transportation network for supplies, purchasing raw materials, planning production, planning supplies and stocks, etc. On the other hand, to get an overall advantage for the DSCs efficiency, it is important to consider all aspects of sustainability - economic, environmental and social - in the decision-making process. The uncertainties regarding various parameters of the considered DSCs such as products demands, raw materials and products prices, operating costs, transportation costs, etc., has an additional impact on their sustainability. It is very important to predict how these uncertainties affect the overall sustainability of DSCs to avoid potential risks. They can be: generation of large amounts of pollutants with a harmful impact on the environment, loss of raw materials and products along the supply chain, high energy consumption, lowering of economic indicators (profit from productions, losses in markets for selling the products), social dissatisfaction (spoilage of dairy products due to their perishable nature), etc. Therefore, dealing with uncertainty plays a crucial role in supply chain design and management. One of the most effective ways to improve the sustainability of the considered DSCs operating under uncertain conditions is to optimize all network activities while satisfying economic,

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environmental and social aspects [2]. A large part of the developed mathematical approaches for optimal DSCs design are based on robust [3-6], fuzzy [7-9], chance-constrained [10] and stochastic optimization [11] models. The researchers have chosen to satisfy economic [3, 7, 9], environmental and social criteria, or most often a combination of economic and environmental [4, 12] or the three dimensions of sustainability –economic, environmental and social [6, 13]. The developed approaches aim optimization of material, energy and waste flows and include as optimization criteria - maximization of production profit, minimization of total costs, reduction of energy consumption, reduction of greenhouse gas emissions due to transport, storage and packaging, achievement of maximum social satisfaction, etc. Some of the developed approaches have taken into account the impact of uncertainty on products demands, transport, production and storage costs, capacity of facilities, life (durability) of products. There are no approaches in the literature that consider three aspects of sustainability in the design of optimal DSCs operating under uncertainty, which produce different products according to different technologies and to include not only the impact of CO_2 emissions but also of industrial wastewater.

This paper is organized as follows. A literature review positioning the research in the field is given. In the next sections the proposed robust multi-objective optimization approach is described, an illustrative case study is presented and the obtained results are described and discussed. Finally, the main conclusions are given.

LITERATURE REVIEW

The literature review part of this study is divided into two sections. Methods for sustainable supply chain management under uncertainties found in the literature are presented. Then, approaches for wastes reduction in dairy supply chain operating under uncertain conditions are given.

Sustainable DSCs management under uncertainties

The dairy market occupies a significant share in the global food sector. This necessitates the application of effective optimization techniques to improve production efficiency and sustainability in the dairy industry. The varied parameters of the considered DSCs complicate their implementation. The latter requires the creation and application of special methods for the optimization of DSCs operating under uncertain conditions. Jouzdani *et al.* [7] applied a fuzzy mixed-integer programming approach to solve an optimization problem for dynamic optimal dairy facility location and supply chain planning under uncertain products demands. The formulated optimization problem includes as an objective function: minimization of costs of traffic congestion, facility location, transportation of raw/processed milk and dairy products. Sel *et al.* [10] considered a planning and scheduling problem in the dairy industry and proposed a chance-constrained programming model accounting for uncertainty in quality deterioration of intermediate mixture. The lifetime of intermediate products and the quality deterioration of perishable intermediate mixture are considered as uncertain parameters and Weibull distribution is used to determine the waste generated in two-stage semi-continuous production and packaging set of the yogurt production process. Jouzdani *et al.* [3] addressed a robust supply chain network design optimization problem considering multiple products, multiple transportation modes, monetary value of time and uncertainty in transportation costs, demand and supply. The approach is implemented on a case study from Iran of a dairy packaging and distribution network. Jouzdani and Govindan [13] developed a multi-objective mathematical programming model to optimize the cost, energy consumption, and the traffic congestion associated with such supply chain operations. The uncertainty of product lifetime is modeled as a Weibull random variable, and food perishability is assumed to be affected by vehicle refrigerator utilization. The three aspects of sustainability are explored. The weighted multi-objective function is defined by minimizing the net present value of SC total cost, total road traffic congestion, and the total fuel consumption in the considered multi –period multi-product DSC. Yavari and Geraeli [14] investigated a green closed-loop multi-period and multi-product supply chain network design for perishable products under uncertain products demands, rate of return and the quality of returned products. They proposed a mixed-integer linear programming (MILP) model to minimize the total cost of the supply chain and the amount of environmental pollution along the supply chain. Furthermore, they developed a robust approach for the considered problem to deal with uncertainty. Gitinavard *et al.* [15] applied several approaches for optimal allocation of distribution centers in a dairy company under uncertain parameters such as products demands and transportation time. They are: mixed-integer programming model for the distribution center location problem solution; a fuzzy method for ranking the resulting Pareto optimal solutions and chance-constrained programming technique for dealing with uncertain parameters. The minimization of the transportation costs and the deviation of delivered products for important customers and candidate customers with respect to their demands to increase their satisfaction are considered as optimization criteria. Guarnaschelli *et al.* [11] used a two-stage hierarchical stochastic and decomposition approach for optimal planning and distribution of multi-product two-echelon supply chain under uncertain products demands and supply aiming maximizing the expected net benefit. Roa *et al.* [4] proposed an effective methodology for the robust design of a first-mile logistics system for the storage and cooling of milk as a perishable product taking into account decisions related to open facilities and the flow of products, including sustainability indices. The authors defined milk production and milk price as uncertain parameters. The proposed model is solved using the Epsilon constraints method, and the sustainability is calculated considering an extension of the FePIA methodology for a bi-objective function: maximization of profit and minimization of CO_2 emissions. Hemmati *et al.* [16] proposed a robust bi-level mathematical model for economic and environmental optimization of a multi-echelon perishable dairy supply chain under uncertain products demands, transportation costs and the lifetime of perishable dairy products. Zarei-Kordshouli *et al.* [9] applied a fuzzy goal programming method to solve the supply chain design problem to minimize the total costs, maximize the suppliers' sustainability and resiliency, and maximize the distribution centers' resiliency.

The use of weights in front of the objective functions in the considered problems for the optimal design of DSCs under uncertain conditions has a significant impact on the obtained solutions. Breen *et al.* [12] developed a weighted multi-objective optimization method based on a genetic algorithm for obtaining the optimal dairy farm equipment, management practices and electricity tariffs. Changing the weights for the economic and environmental costs in the weighted objective function leads to different solutions for the optimal combination of equipment.

Touil *et al.* [8] applied the credibility-based fuzzy mathematical programming model and the crisp equivalent model to solve the problems of integrating production and distribution in the SC planning of the dairy industry in Morocco. They used a weighted Hurwicz criterion for a single objective function to maximize the total profit including the total costs for a three-echelon multi-product milk supply chain. Production cost, inventory holding and transport costs, products demands, production capacity, and safety stock level are considered as uncertain (fuzzy numbers). Gholizadeh *et al.* [5] used heuristic robust optimization and an extended ε-constraint approach for optimal design of a multi-period multi-product closed loop DSC under uncertain total costs, capacities of facilities, return rate of products, and products demands. A weighted objective function for maximizing total profit and minimizing environmental impact is considered. Several scenarios were created and a sensitivity analysis of the profitability of the closed-looped supply chain with respect to the product lifetimes was applied. Shafiee *et al.* [6] applied a multi-objective mathematical model to design a multi-period and multi-product DSC composed of suppliers, producers, and retailers to minimize the total costs and the environmental impacts and maximize the social impacts. The authors applied a robust optimization approach to deal with uncertainty associated with demand, transportation costs, production costs, holding costs, and facilities' capacity. A hybrid method based on a heuristic algorithm, and an augmented ε-constraint method are developed to solve the proposed model.

Wastes reduction in DSCs operating under uncertain conditions

Wastes and losses of raw materials and dairy products along the supply chain are a growing problem due to environmental, social and economic impacts. The presence of uncertainties regarding various DSC parameters further affects these losses. Recently, more attention has been paid to this issue, looking for opportunities to reduce waste by proposing solutions to improve the sustainability of dairy supply chains. Ebrahimi *et al.* [17] developed a stochastic DSC valorization optimization model under uncertain raw material price and products demands. The model takes into account the multipurpose and batch characteristics of dairies and the time resource distribution over the processing nodes and products. As a result of its implementation, food waste and supply chain costs have been reduced and the profit function and the overall structure of the chain have been obtained. For model analysis, three different scenarios were designed under different conditions with and without accounting for by-products. Kazancoglu *et al.* [18] applied the Grey prediction method to predict the potential milk losses over a long period, according to triple bottom line (TBL) and considering the uncertainty of data for raw milk losses in the supply chain in Turkey.

In summary, the main focuses of the reviewed past researches are listed below:

- Most previous studies focused on minimizing the costs and environmental impact of the considered DSCs and did not consider social costs in their model.
- All studies provided environmental impact assessments only in terms of greenhouse gas emissions related with transport or raw material and products and consumed energy by dairy production. There is a lack of approaches to assess the environmental impact of dairy industry in terms of wastewater from the production of dairy products and those related to the processing of the used raw materials – different types of milk.
- The uncertainties taken into account most often relate to product demands, transport and production costs, facility capacity, transport traffic, etc.

Recently, Kirilova *et al.* [19] proposed a deterministic approach for optimal design of sustainable DSC for the production of different types of dairy products according to different technologies while meeting economic, environmental and social criteria defined from a cost perspective. The environmental criterion includes assessments of pollutant emissions in relation to two areas of impact - air and water. The model [19] was extended with a Robust Counterpart (RC) for uncertain product demands [20] using the approach [21]. It was solved by considering economic and environmental criteria for a case study, consisting of two suppliers, two dairies and two markets. Based on previous studies, the present study represents an implementation of Kirilova *et al.* [20] approach to an illustrative case study from Bulgaria of DSC consisting of three suppliers, two dairies and three markets. The three dimensions of the sustainability are considered. Products demands, raw materials prices, products prices and social costs are considered as uncertain parameters.

ROBUST MULTI-OBJECTIVE OPTIMIZATION APPROACH

General formulation of the optimization problem

A robust optimization model was developed to design a sustainable three-echelon DSC for the production of different products according to different technologies (recipes) while meeting economic, environmental and social criteria. Products demands, raw materials prices, products prices and social costs are considered as uncertain parameters. It includes models for: (i) the production of the products according to the recipes; (ii) the design of DSC; (iii) environmental and (iv) social performance of the DSC. The environmental impact of DSC is assessed in terms of two areas: wastewater generated in each processing task of the production recipes, including those related to the used raw materials; CO_2 emissions related to the energy consumed by the dairies and CO_2 emissions generated due to transportation of raw materials and products. Biochemical Oxygen Demand during 5 days (BOD_5) is used to evaluate wastewater generated from dairy production. Pollution taxes are imposed on dairies to keep the wastewater and CO_2 emissions below set acceptable levels. The social impact of the DSC is related to the employees hired by the three echelons of the considered DSC. The optimization problems are completed with constraints on the realization of the production portfolio over time horizon, the planned amounts of products and the environmental impact costs that must be paid to treat pollutants. The optimization criterion represents a revenue from the total profit after deducting production costs, raw materials costs, transportation costs, environmental costs and social costs.

Needed data

In order to develop the mathematical models, three sets of data must be known: 1). Data on raw materials and products - composition of used raw materials and target products; 2). DSC data – data for production system; markets demands; capacities of the milk suppliers; prices of milk and products; production costs, distances between suppliers, dairies and markets; transportation costs; vehicles' types capacities; 3). Environmental data - related to pollutants generated in DSC; 4). Social data – related to employees (job positions) hired by suppliers, dairies and markets. These are the costs for salaries, benefits, working clothing, medical care and insurance and the average amounts of raw materials/products processed by employees.

Decision variables

The following decision variables are defined:

1) Binary variables to define a DSC; 2) Continuous variables defining the raw materials and products flows between different DSC sites; 3) Continuous variables determining the milk fat content of the raw materials used; 4) Integer variables determining the number of employees (job positions) depending on processed quantities of raw materials/products.

Mathematical models

➢ *Models of production recipes.* The production of two types of cottage cheese - low-fat content and high-fat content takes place according to two production recipes (PR1 and PR2) as each of them uses different raw material for production of both products - standardized whole milk (raw material 1 – RM1) and skimmed condensed milk (raw material 2 – RM2). The PRs include different production tasks conducted in different equipment units. PR1 includes three production tasks: milk pasteurization (Task 1); acidification to produce a raw dairy product (Task 2); draining to produce target dairy product (Task 3). PR2 involves one more production task: milk dilution (Task 1); milk pasteurization (Task 2); acidification (Task 3) and draining (Task 4).

The mathematical description of the production recipes includes:

1) Dependencies for determination of the protein, casein and lactose concentrations in raw materials:

Production recipe 1: Skimming of whole standardized milk.

$$MP(\mathrm{x}(r_p)) = \mathrm{MP}\left[1 + \frac{\mathrm{MF} - \mathrm{x}(r_p)}{\mathrm{CF} - \mathrm{MF}}\right], (\%),$$

$$MC(\mathrm{x}(r_p)) = \mathrm{MC}\left[1 + \frac{\mathrm{MF} - \mathrm{x}(r_p)}{\mathrm{CF} - \mathrm{MF}}\right], (\%),$$

$$ML(\mathrm{x}(r_p)) = \mathrm{ML}\left[1 + \frac{\mathrm{MF} - \mathrm{x}(r_p)}{\mathrm{CF} - \mathrm{MF}}\right], (\%),$$

$$r_p = 1, \forall p, p \in P. \quad (1)$$

Production recipe 2: Dilution of skimmed condensed milk.

$$MP(\mathrm{x}(r_p)) = \mathrm{MP}\frac{\mathrm{x}(r_p)}{\mathrm{MF}}, (\%),$$

$$MC(\mathrm{x}(r_p)) = \mathrm{MC}\frac{\mathrm{x}(r_p)}{\mathrm{MF}}, (\%),$$

$$ML(\mathrm{x}(r_p)) = \mathrm{ML}\frac{\mathrm{x}(r_p)}{\mathrm{MF}}, (\%),$$

$$r_p = 2, \forall p, p \in P. \quad (2)$$

where MF (%), MP (%), MC(%) and ML (%) are the concentrations of milk fat content, proteins, casein and lactose in the used raw materials. CF(%) is cream fat content. $MP(\mathrm{x}(r_p))$ (%), $MC(\mathrm{x}(r_p))$ (%) and $ML(\mathrm{x}(r_p))$ (%) are the concentrations of proteins, casein and lactose in the skimmed milk. r_p is the recipe used for the production of the dairy product *p*.

2) Equations for target products yield $YP(\mathrm{x}(r_p))$ (kg) describing the compositions as functions of the fat content in used raw materials [22]:

$$YP(\mathrm{x}(r_p)) = \frac{\begin{bmatrix} RF(\mathrm{x}(r_p)).\mathrm{x}(r_p) + \\ + RC_p.MC(\mathrm{x}(r_p)) \end{bmatrix} .RS_p}{PS_p}, (\mathrm{kg}),$$

$$r_p = 1, 2; r_p \in R_p, \forall p, p \in P \quad (3)$$

where PS_p (%) is the solids' content in products and RC_p (%) and RS_p (%) are the recovery factors for casein and all solids. $RF(\mathrm{x}(r_p))$ (%) is the milk fat recovery factor.

3) Equations for quality of target products - Determination of Fat in Dry Matter - FDM_p (%) [22] used as an indicator for curd quality:

$$FDM_p = \frac{PF_p}{PS_p}, (\%), \forall p, p \in I \quad (4)$$

where PF_p is fat content of the product, (%).

Production times and equipment used to perform the production tasks, as well as the fractions of the processed raw materials, raw products and target products, referred to 1 kg milk and 1 kg cottage cheese - target product in PR2, are given in [19].

The equations (1-4) presented above refer to 1 kg milk and 1 kg target product. Production recipe models provide a relationship between the production tasks by calculating size factors representing the "volumes" of materials that must be processed in production tasks to produce 1 kg of target products. The size factors together with the quantities of produced products related to the products portfolio and production tasks are used to determine the constraints for realization of the production portfolio over the time horizon. They are described in details in [23].

➢ *Model of DSC*

The mathematical description of the DSC includes:

1) Mass balance equations for the subsystems suppliers-dairies and dairies-markets to prevent from the accumulation of raw materials $QM(r_p)_i$ (kg) in the suppliers and products $QP(r_p)_i$ (kg) in the dairies. $YY(r_p)_{i,s}$ (kg) are the quantities of raw materials bought by dairies *i* from the suppliers *s*, $XX(r_p)_{i,m}$ (kg) are the quantities of products *p* produced in dairies *i* and sold at markets *m*, $\gamma_{i,s}$ and $\chi_{i,m}$ are binary variables for defining links between suppliers and dairies and dairies and markets in the DSC.

$$QM(r_p)_i = \sum_{s=1}^{S} YY(r_p)_{i,s} \cdot \gamma_{i,s}, \text{ (kg)},$$

$$QP(r_p)_i = \sum_{m=1}^{M} XX(r_p)_{i,m} \cdot \chi_{i,m}, \text{(kg)},$$

$$\forall i, i \in I; \forall r_p, r_p \in R_p; \forall p, p \in P. \quad (5)$$

➢ *Model of supply chain environmental impact*

The environmental impact model includes equations for:

1) BOD_5 associated with the wastes generated during conducting of all production tasks in both recipes and introduced from outside related to the pre-processing of used raw materials.

$$BOD_M(\text{x}(r_p)) = \begin{bmatrix} 0.89.\text{x}(r_p) + \\ +1.031.MP(\text{x}(r_p)) + \\ +0.69.ML(\text{x}(r_p)) \end{bmatrix} .10^{-2}$$

(kg O_2 /kg milk), $\forall r_p, r_p \in R_p, \forall p, p \in P.$ (6)

$$BOD_{Cu}(\text{x}(r_p)) = \frac{BOD_M(\text{x}(r_p))}{YP(\text{x}(r_p))}, \quad (7)$$

(kg O_2 /kg product), $\forall r_p, r_p \in R_p, \forall p, p \in P.$

where $BOD_M(\text{x}(r_p))$ is the BOD load related to spills of skim milk during implementation of Task 1 in PR1 and Task 2 in PR2 as a function of milk fat content $\text{x}(r_p)$. $BOD_{Cu}(x(r_p))$ is the BOD load related to losses of cottage cheese during implementation of Task 3 in PR1 and Task 4 in PR2 as a function of milk fat content $\text{x}(r_p)$. $YP(\text{x}(r_p))$ is the yield of cottage cheese produced according to production recipes as a function of milk fat content $\text{x}(r_p)$ in used milk.

The total environmental impact assessment $PBOD_p$ for production of 1 kg of each type of cottage cheese is:

$$PBOD(\mathbf{x}(r_p)) = \sum_{w=1}^{W} BOD_w \sum_{l=1}^{L(r_p)} m(\text{x}(r_p))_{w,l}, \quad (8)$$

(kg O_2), $\forall p, p \in P$.

where $m(\text{x}(r_p))_{w,l}$ ($\forall w, w \in W$; $\forall l, l \in L(r_p)$; $\forall r_p, r_p \in R_p$; $\forall p, p \in P$) are environmental impact indices determining the mass of each type of waste w generated in any production task l related to 1 kg target product. For their determination In/Out fractions, target products yield (Eq. 3) and the eligible levels of losses listed in Table 1 are used [23].

It can be seen from Table 1 that BOD_{Pa} is the BOD load related to deposits on the pasteurizer walls during pasteurization of the skim milk (Task 1 in PR1 1 and Task 2 in PR2), BOD_{Wh} is the BOD load related to spills of whey produced as by-product during discharging of the cottage cheese vats (Tasks 2, 3 in PR1 and Tasks 3, 4 in PR2). LS_{SM} represents losses of skim milk in milk pasteurization (Task 1 in PR1 and Task 2 in PR2). LS_{Wh} represents losses of whey in acidification and draining of the produced cottage cheese (Tasks 2, 3 in PR1 and Tasks 3, 4 in PR2), while $LS2_{Cu}$ and $LS3_{Cu}$ represent losses of cottage cheese (Tasks 2, 3 in PR1 and Tasks 3, 4 in PR2).

Table 1. BOD_5 load related to wastes, production tasks and eligible levels of losses.

Type of wastes	BOD_5 load, (kg O_2 /kg milk(product)	Recipe 1		Recipe 2	
		generated waste, (%)	"introd." waste, (%)	generated waste, (%)	"introd." waste, (%)
Spills of skimmed milk	$BOD_M(\text{x}(r_p))$	Task 1; LS_{SM}=1.2		Task 2; LS_{SM}=1.2	
Deposits on units walls	$BOD_{Pa} = 1.5.10^{-3}$	Task 1		Task 2	
Spills whey	$BOD_{Wh} = 32.10^{-3}$	Task 2, 3; LS_{Wh}=1.6		Task 3, 4; LS_{Wh}=1.6	
Cottage cheese losses	$BOD_{Cu}(\text{x}(r_p))$	Task 2, $LS2_{Cu}$=0.3 Task 3, $LS3_{Cu}$=0.5		Task 3, $LS3_{Cu}$=0.3 Task 4, $LS4_{Cu}$=0.5	
RM1	0.1%		Task 1, LS_{SM} =1		
RM2	0.146%			Task 1, LS_{SM} =1	Task 1, LS_{SM} =1

2) Equations for the impact of CO_2 emissions associated with heating and cooling of milk referred to 1 kg milk as follows:

$$EIMCO2(\mathbf{x}(r_p)) = \frac{(EH + EC)\cdot ECO_2}{\left(\dfrac{CF - MF}{CF - \mathbf{x}(r_p)}\right)}, \quad (9)$$

(kg CO_2 /kg cottage cheese), $\forall r_p, r_p \in R_p, \forall p, p \in P.$

where EH and EC is needed energy by the heating and cooling processes during pasteurization task in (kWh/kg milk), ECO_2 is the mass of CO_2 emissions associated with the energy consumption (kg CO_2/kWh).

3) Equations for the impact of CO_2 emissions associated with the transport of raw materials and products, referred to 1 kg from both:(kg CO_2 /km·kg cottage cheese):

$$TMCO2 = 2\cdot\frac{TCO_2}{VCm}, \text{ (kg } CO_2 \text{ /km·kg milk)},$$

$$TPCO2 = 2\frac{TCO2}{VCp}, \text{ (kg } CO_2 \text{ /km·kg product)} \quad (10)$$

where TCO_2 is the quantity of CO_2 emissions produced by fuel combustion (kg CO_2/ km) and VCm (kg) and VCp (kg) are the payload capacities of used vehicles for transportation of raw materials and products.

- *Model of supply chain social impact.*

The supply chain social impact model includes equations for the numbers of employee that will be hired by the suppliers Eq. (11), dairies Eq. (12) and markets Eq. (13). They depend on the average quantities of raw materials/products processed by employees in suppliers, dairies and markets.

$$NE\_S = \sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{r=1}^{R}\frac{YY_{i,s,r}\cdot\gamma_{i,s,r}}{AQ_s\cdot NWD}, \quad (11)$$

$\forall i \in I, s \in S, \forall r, r \in R.$

$$NE\_P = \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{r=1}^{R}\frac{XX_{i,p,m,r}\cdot\gamma_{i,p,m,r}}{AQ_p\cdot NWD}, \quad (12)$$

$\forall i \in I, p \in P, \forall m, m \in M, \forall r, r \in R.$

$$NE\_M = \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{r=1}^{R}\frac{XX_{i,p,m,r}\cdot\gamma_{i,p,m,r}}{AQ_m\cdot NWD}. \quad (13)$$

$\forall i \in I, p \in P, \forall m, m \in M, \forall r, r \in R.$

where NE_S, NE_P, NE_M are the numbers of employees (job positions) that will be hired by suppliers s, dairies i and markets m. AQ_s, AQ_p, AQ_m (kg) are the average quantities of raw materials/products that employees can process per day in the different echelons of the DSC. NWD is the number of working days per month, $XX_{i,p,m,r}$ (kg) are the quantities of product p produced according to recipe r in dairy i and sold at market m, $\gamma_{i,p,m,r}$ is binary variable used to structure the supply chain between the dairies and markets.

Constraints

To estimate the feasibility of the obtained sustainable product portfolios, the following constraints are introduced for: 1). Realization of the production portfolio in the time horizon; 2). Capacity of the suppliers; 3). Capacity of the markets; 4). Environmental impact costs that must be paid for treatment of the pollutants released in air and water. These are the costs for BOD removal in the wastewater treatment plants (WWTPs) and the CO_2 costs associated with the production of the products in the dairies and the transportation of raw materials and products.

Optimization criterion

A single objective optimization function is used F_{profit}, (BGN) as an optimization criterion. It represents the difference between the production profit and the economic, environmental and social costs, as follows:

$$\begin{aligned} F_{Profit} &= F_R - (F_{P\_Costs} + F_{M\_Costs} + F_{T\_Costs} + \\ &F_{BOD\_Costs} + F_{CO2\_E\_Costs} + F_{CO2\_T\_Costs} + \\ &F_{Social\_Costs\_Suppliers} + F_{Social\_Costs\_Dairies} + F_{Social\_Costs\_Markets}) \end{aligned} \quad (14)$$

where F_R (BGN) is the income from the sale of products in the markets; F_{P_Costs} (BGN) are the total production costs for the dairies; F_{M_Costs} (BGN) are the total costs of the dairies for purchasing the required quantities of both types of milk from suppliers for the production of the products; F_{T_Costs} (BGN) are the total costs for the transportation of the milk and products between suppliers, dairies and markets; F_{BOD_Costs} (BGN) are the total costs for BOD_5 paid for treatment of wastewater generated during the production of the products; $F_{CO\_2\_E\_Costs}$ (BGN) are the total costs for CO_2 emissions associated with the energy consumed by pasteurization process; $F_{CO\_2\_T\_Costs}$ (BGN) are the total costs associated with CO_2 emissions of pollutants generated during milk and products transportation; $F_{Social\_Costs\_Suppliers}$, $F_{Social\_Costs\_Dairies}$ and $F_{Social\_Costs\_Markets}$ are costs related to the number of employees (job positions) that will be hired by the suppliers, dairies and markets.

The latter terms of the optimization criterion (14) are the following:

$$F_{Social\_Costs\_Suppliers} = NE\_S \cdot (CS_{suppliers} + CWCl_{suppliers} + CSB + CMI), \text{ (BGN)}, \quad (15)$$

$$F_{Social\_Costs\_Dairies} = NE\_S \cdot (CS_{dairies} + CWCl_{dairies} + CSB + CMI), \text{ (BGN)}, \quad (16)$$

$$F_{Social\_Costs\_Markets} = NE\_S \cdot (CS_{markets} + CWCl_{markets} + CSB + CMI) \text{ (BGN)}, \quad (17)$$

Here, CS, $CWCl$, CSB, CMI are costs for salaries, working clothing, benefits and medical insurance related to employees (job positions) that will be hired by the suppliers, dairies and markets.
The objective function (14) is subject to maximization:

$$MAX\ (F_{Profit}) \quad (18)$$

The formulated optimization problem belongs to the MINLP. It contains both binary and continuous variables, sets of modeling equations and inequality constraints. A detailed description of the optimization approach presented above with models for i) the production of the products; ii) planning of activities in SCs; iii) describing the environmental impact of SCs is given in [23].

Robust optimization model

The deterministic model presented above is extended with Robust Counterpart to cope with uncertain products demands, raw material prices, product prices and social costs. For this purpose, the robust optimization approach of Ben-Tal *et al.* [21] was applied. The general formulation of a compact robust optimization problem is as follows:

$$\begin{aligned} &max \quad ax + by \quad (19)\\ &s.t. \quad bx \le c\\ &\qquad bx = dy\\ &\qquad a, c, d \in U \end{aligned}$$

where a, c and d are the model parameters that vary under a given uncertainty set U. A vector x is a robust feasible solution to problem if it satisfies all realizations of the constraints from the uncertainty set U.

Each uncertain parameter is assumed to vary in a specified closed bounded box as follows:

$$u_{Box} = \left\{\theta \in R^n : \left|\theta_t - \overline{\theta}_t\right| \le \rho G_t\right\},\ t = 1,...,n \quad (20)$$

where $\overline{\theta}_t$ is the nominal value of θ_t as t-th parameter of vector θ. G_t and ρ are positive numbers representing the so called "uncertainty scale" and "uncertainty level". According to that, the RC model can be stated as follows:

$$\begin{aligned} &max \quad z \quad (21)\\ &s.t. \quad ax + by \le z \quad \forall a \in u^a_{Box}\\ &\qquad bx \le c \quad \forall c \in u^c_{Box}\\ &\qquad bx = dy \quad \forall d \in u^d_{Box}\\ &\qquad y \in \{0,1\} \quad X \in R^+ \end{aligned}$$

The RC model (21) can be converted to a tractable equivalent model where U_{Box} is replaced by a finite set U_{Extr} consisting of the extreme points of U_{Box} as follows:

$$ax \le z - by,\quad \forall a \in u^a_{Box} / u^a_{Box} = \left\{a \in R^{na} : \left|a_t - \overline{a}_t\right| \le \rho_a G^a_t\right\},\ t = 1,...,n_a \quad (22)$$

The left-side of inequality (22) contains the vector of uncertain parameters, while all parameters of the right-hand side are certain. Thus, the tractable form of the above semi-infinite inequality can be written as follows:

$$\begin{aligned} &\sum_t \left(\overline{a}_t x_t + y_t\right) \le z - by, \quad (23)\\ &\rho_a G^a_t x_t \le y_t \quad \forall t \in \{1,...,n_a\}\\ &\rho_a G^a_t x_t \le -y_t \quad \forall t \in \{1,...,n_a\} \end{aligned}$$

Similarly, the equality and inequality constraints in Eq. (21) can be converted to their tractable equivalent equations through extending the use of the extreme points of U_{Box}.

Finally, the tractable form of the robust compact model can be presented as follows:

$$\begin{aligned} &max \quad z\\ &s.t. \quad \sum_t \left(\overline{a}_t x_t + y_t\right) \le z - by\\ &\rho_a G^a_t x_t \le \gamma_t, \quad \forall t \in \{1,...,n_a\}\\ &\rho_a G^a_t x_t \le -\gamma_t, \quad \forall t \in \{1,...,n_a\}\\ &b_k x \le \overline{c}_k + \rho_c G^c_k \quad \forall k \in \{1,...,n_c\}\\ &b_j x \le \overline{d}_j y + \rho_d G^d_j \quad \forall j \in \{1,...,n_d\}\\ &y \in \{0,1\} \quad X, \gamma \in R^+ \end{aligned}$$

It can be used for modeling the uncertain products demands, raw material prices, product prices and social costs in the considered dairy DSC.

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 (P1 and P2) according two production technologies using standardized whole milk and skimmed condensed milk as raw materials (RM1 and RM2). The production of both types of products is conducted in two dairies (D1 and D2). Three suppliers provide the raw materials for the dairies (S1, S2 and S3). The produced products are supplied to three markets (M1, M2 and M3). The products production is realized in a time horizon of one month. The production units used and their summarized volumes are listed in Table 2, [24].

Table 2. Equipment units with summarized volumes, (m^3).

	Milk tanks	Pasteurizers	Cottage cheese vats	Drainers
D1	1,450	800	950	300
D2	1,450	950	1,050	340

Capacities of the three suppliers (kg) are presented in Table 3 [25]. Distances (km) between suppliers, dairies and markets are listed in Table 4.

Table 3. Capacities of suppliers (kg).

	Capacity (kg)	
	RM 1	RM 2
S1	97,000	57,000
S2	100,540	54,500
S3	113,000	78,000

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

	S1	S2	S3	M1	M2	M3
D1	10	15	20	98	136	46
D2	20	10	15	22	23	75

Table 5 presents the data on the 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 (kg).

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 [26]. The CO_2 emissions associated with both processes is 0.46 kg CO_2/kWh [27]. The costs of CO_2 are 0.00998 BGN/kg CO_2. The price of BOD_5 paid to WWTPs 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 with an energy price of 0.14072 BGN/kWh. The average quantities (kg) of raw materials or products that employees can process per day in suppliers, dairies and markets are 500 kg milk, 150 kg products and 40 kg products/day. The average costs (BGN) according to Eqs. (15-17), related to the number of employees (job positions) to be hired by the suppliers, dairies and markets are taken from [28]. They include costs for salaries (BGN) [29], work clothes (BGN), social benefits (BGN) and medical insurance (BGN).

RESULTS AND DISCUSSION

The proposed robust optimization approach is implemented in a real case study from Bulgaria. DSC includes three suppliers, two dairies and three markets. Uncertain products demands, raw material prices, product prices and social costs are considered as uncertain parameters. Several robust optimization problems were formulated and solved under nominal data and two different uncertainty levels (UL) (ρ = 0.5 and 1). At each uncertainty level, ten random realizations were uniformly generated within the following uncertainty set: [$nominal\ value \pm \rho*$SD], where SD is the standard deviation of the obtained results. The optimization models were solved using GAMS® optimization software-BARON solver as all calculations were 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 were used to evaluate the models: mean and standard deviation of the obtained results.

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 optimization problems are formulated and solved with fixed values for the environmental cost constraints, as follows: cost for treatment of wastewater generated in both dairies - 4,500 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 - 13,000 BGN. The optimization problems were formulated and solved at given boundaries of varying of the products demands as follows: Product 1, Market 1 – 25,000 ÷ 35,000 kg; Product 1, Market 2 – 15,000 ÷ 25,000 kg; Product 1, Market 3 – 20,000 ÷ 30,000 kg; Product 2, Market 1 – 5,000 ÷ 15,000 kg Product 2, Market 2 – 35,000 ÷ 45,000 kg; Product 2, Market 3 – 20,000 ÷ 30,000 kg. On the other hand, the raw materials prices vary in the following boundaries: Supplier 1, Recipe 1 - 1.40 ÷ 2.40 BGN; Supplier 2, Recipe 1 - 1.30 ÷ 2.30 BGN; Supplier 3, Recipe 1 - 1.50 ÷ 2.50 BGN; Supplier 1, Recipe 2 - 2.30 ÷ 3.30 BGN; Supplier 2, Recipe 2 - 2.40 ÷ 3.40 BGN; Supplier 3, Recipe 2 - 2.50 ÷ 3.50 BGN. Products prices vary in the following boundaries: Product 1, Market 1 - 10.80 ÷ 20.80 BGN; Product 1, Market 2 – 12.30 ÷ 22.30 BGN; Product 1, Market 3 – 12.70 ÷ 22.70 BGN; Product 2, Market 1 – 12.10 ÷ 22.10 BGN; Product 2, Market 2 – 11.40 ÷ 21.40 BGN; Product 2, Market 3 – 12.50 ÷ 22.50 BGN. The social costs vary in the following boundaries: Suppliers - 1350 ÷ 2150 BGN; Dairies - 2150 ÷ 3150 BGN and Markets - 1850 ÷ 2650 BGN.

The obtained results for model solutions are shown in Figs. 1 and 2. From Fig. 1 it can be seen that the higher level of uncertainty (ρ=1) is associated with larger economic, environmental, social cost values, and profit. At the higher level of uncertainty, there is an increase in the standard deviation values of the economic costs and the DSC profit by 5.7% and 6.5% and a decrease in the standard deviation values of the environmental and the social costs by 2.8% and 4.7%. One can see that this large variation in the level of uncertainty does not lead to a large difference in the standard deviations of the values mentioned above. The obtained optimal solutions for the number of employees to be hired from the suppliers, dairies and markets in the DSC at the both uncertainty levels are represented in Fig. 2.

It can be seen that the number of the employees to be hired by suppliers, dairies and markets is held constant under the different uncertainty levels, except for the case of the markets.

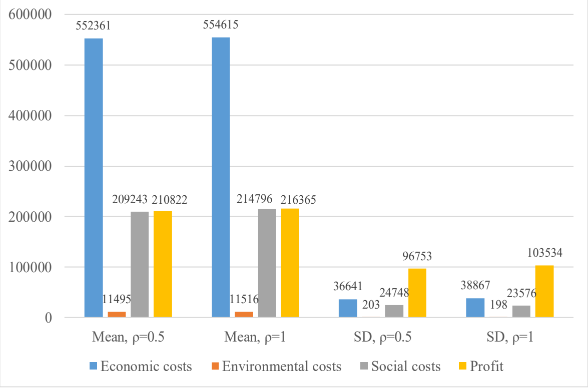

Figure 1. Optimal solutions for the mean and standard deviation values of the economic, environmental, social costs and profit of the DSC at both uncertainty levels – ρ=0.5 and ρ=1.

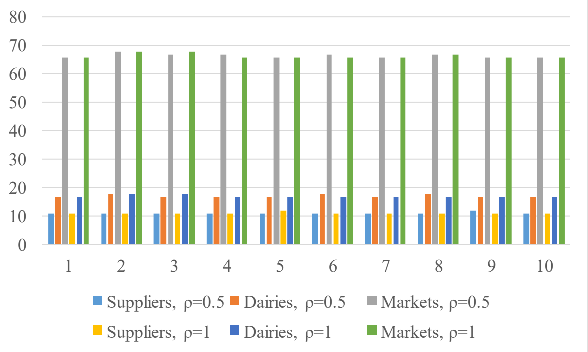

Figure 2. Optimal solutions for the number of employees to be hired from the suppliers, dairies and markets in the DSC at both uncertainty levels – ρ=0.5 and ρ=1.

In the latter, at the higher level of uncertainty, an increase in the values of the standard deviation with 17.7% was observed. Regarding the obtained results for the optimal product portfolios of the two dairies under the different scenarios and levels of uncertainty, the following conclusions can be drawn. The first dairy produces only Product 1 according to the second recipe, which is distributed only to Market 3, and this type of portfolio does not change across scenarios at this level of uncertainty. In the second dairy, with very few exceptions, one type of portfolio is also obtained in the different scenarios, in which both products are produced according to Recipe 2, with Product 1 being distributed to Market 2 and Product 2 to Market 1. Regarding the suppliers of the two types of milk, in the different scenarios with very few exceptions, a solution is obtained, according to which the first dairy is supplied with the second type of raw material only from Supplier 1, while the second dairy is supplied with the second type of milk from all three suppliers. For one of the solutions obtained at the lower level of uncertainty, an optimization problem was formulated and solved using different weights for the three types of costs –

economic, environmental, social. The latter was done to see how the use of weighting factors with the objectives would affect the obtained optimal solutions for the product portfolios of the two dairies and the values of the optimization criterion. Figs. 3 and 4 below show the resulting solutions.

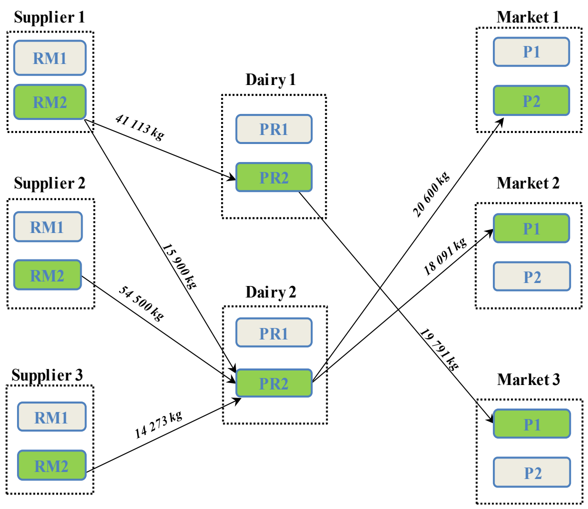

Figure 3. Products portfolio of an obtained optimal solution at an uncertainty level of ρ=0.5.

Figs. 3 and 4 show that the use of weights in front of the objective functions - economic, environmental and social costs leads to different portfolios for the two dairies both in terms of the supply of the two types of raw materials from suppliers of the dairies and in relation to the distribution of the produced output in the markets.

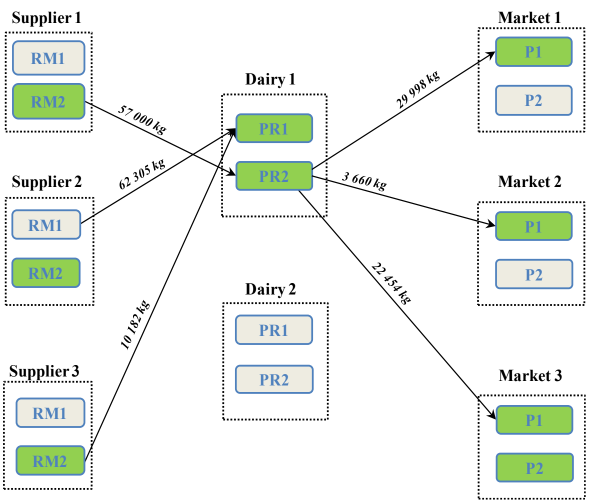

Figure 4. Products portfolio of an obtained optimal solution at an uncertainty level of ρ=0.5 with weights of 0.6, 0.3 and 0.1 for the economic, environmental and social costs.

The portfolio presented in Fig. 3 is related to obtaining a profit from the production of the two products in the amount of BGN 117,394, with values for economic, environmental and social costs of BGN 519,304; BGN 11,410 and BGN 192,627. The number of workers employed by suppliers, dairies and markets for this solution is: 11, 17 and 66, respectively. While the solution presented in Fig. 4, obtained using weights for economic, environmental and social costs of 0.6, 0.3 and 0.1 is associated with a much larger profit of BGN 939,246, as well as larger values for economic, environmental and social costs of BGN 859,819; BGN 14,655 and BGN 313,024. The number of workers employed by suppliers, dairies and markets are: 16, 22 and 83. The latter shows that the use of weights in front of the objectives leads to obtaining completely different solutions. Also, the obtained results enable managers and decision makers in DSC optimization to obtain model predictions when their needs and preferences change in the future. By varying the weights in the objective function under consideration, different scenarios can be played out, preferring each of the three criteria according to the specific case.

CONCLUSIONS

The study represents the implementation of a robust optimization approach for the optimal design of sustainable dairy SC for production of two types of cottage cheese according to two technologies, under uncertain products demands, raw materials prices, products prices and social costs. The considered DSC includes three milk suppliers, two dairies and three markets. The dairy products production is associated with the release of emissions of pollutants into the air and water. Several robust optimization problems were formulated and solved under different random realizations of the uncertain parameters taking into account economic, environmental and social considerations. The nominal data for the products demands, raw materials prices, products prices and social costs were randomly generated under two uncertainty levels using a uniform distribution in a given 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. Moreover, for one of the solutions obtained at the lower level of uncertainty, an optimization problem was formulated and solved with different weights for the three types of costs – economic, environmental, social, such as 0.6, 0.3 and 0.1, respectively. The latter was done with a purpose to show how the use of weights with the objective function would affect the obtained optimal solutions for the product portfolios of the two dairies and the values of the optimization criterion. The obtained results show that the higher level of uncertainty is associated with larger economic, environmental, social cost values, and profit. At the higher level of uncertainty, there was an increase in the standard deviation values of the economic costs and the profit of the DSC by 5.7% and 6.5% and a decrease in the standard deviation values of the environmental and the social costs by 2.8% and 4.7%. 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 17.7% is related with employees to be hired by the markets. The resulting types of product portfolios under the two levels of uncertainty do not differ significantly for the different randomly generated scenarios. On the other hand, the use of weights with the objectives leads to completely different solutions. The use of weights with the objectives has a very large influence on the obtained optimal values for the parameters of a given decision. This enable managers and decision makers in the future to play out different scenarios, favoring each of the three criteria according to the specific case and the needs of the DSC. Generally, it can be concluded that the obtained optimal values of the economic, environmental and social costs show that the optimization approach implementation results in sustainable solutions that do not significantly change with an increase in the uncertainty level of consideration of the uncertain parameters.

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