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A MINLP Model to Optimal Design of a Sustainable Dairy Supply Chain Taking into Account Preferences of the Network Actors

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The increase of pollutants generated in the production of dairy products, the increase of the production costs and emerging social problems requires the development of approaches for resilience improvement of the considered product productions. An effective way to achieve this is by optimising all activities across the supply chain: from milk suppliers through the production itself to end-users meeting environmental, economic and social criteria. The other important aspect of solving this type of problems is taking into account the preferences of all actors in the network. The present study proposes a mixed-integer non-linear programming (MINLP) model for the optimal design of a sustainable dairy supply chain (SC) for the production of different dairy products satisfying the preferences of all actors of the network - milk suppliers, dairies and markets. The approach includes models for the production of dairy products along with the economic, environmental and social impact of the considered SC. Three optimization problems are defined and solved at different optimisation criteria representing the preferences of all actors in the SC. The first solution results in the supply of 162,022 kg of two types of milk for the production of 61,758 kg of low and high-fat content products. The latter exceeds the market demands. This is the solution with the largest economic and social costs and lowest production profit of 118,008 BGN. The second solution is related to the production of 60,023 kg of both products. This is the solution with the lowest economic costs and largest production profit of 143,809 BGN. In solution 3, full satisfaction of market requirements was achieved. It is related to the supply of 132,146 kg of both types of milk for the production of 60,057 kg of both products.

1. Introduction

Among the food industries, dairy production is one of the most inefficient due to the fact that it requires large quantities of raw materials for the production of small quantities of products. The latter is related to the generation of a large amount of waste across the supply chain as a result of by-products obtained or lossees of target ones. Recently, various methods and techniques have been developed to increase the environmental and economic sustainability of this type of production. However, they mainly focus on either the initial or final stages of the dairy supply chain. Tavana et al. (2017) have provided a selection method that can be implemented to identify a network of suppliers satisfying customer requirements related to reasonable price and quality of products. Falcone et al. (2017) have studied the shelf life of dairy products in order to reduce the waste and food losses. Meneses et al. (2020) have assessed the potential of different milk by-products for their further use as ingredients in the development of other products. Perimal et al. (2017) have maximized the profitability of the value-added products through obtaining the optimal processing routes of dairy industry sludge. The most effective way to achieve full sustainability of dairy production is the optimisation of all activities across the supply while meeting both environmental (Palmieri et al., 2017) and economic (Chen et al., 2014) or economic, environmental and social objectives. Social performance is usually associated with increasing levels of consumer health (Sazvar et al., 2018), providing jobs to service all supply chain activities

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(Kirilova et al., 2020) or locating facilities in less developed regions (Mota et al., 2015). On the other hand, the developed approaches are based on the application of multi-objective decision-making optimisation methods such as an augmented ε-constraint (Sazvar et al., 2018) or those using weighting coefficients (Tavana et al. 2017). They aim to meet customer requirements related to network of suppliers (Tavana et al., 2017) or producers in order to maximize production profits (Potrč et al., 2020). There are no approaches for the optimal design of sustainable dairy supply chains, which, in addition to the requirements of the producers, also satisfy the posed preferences of the remainder actors included in the supply chain.

This study proposes an extended version of the approach of Kirilova et al. (2021) to design a sustainable dairy supply chain in which the preferences of all actors in the network are met. The approach includes four models for the production of dairy products; the SC design, the SC environmental impact and the SC social impact. The SC environmental impact is assessed in terms of wastewater and CO_2 emissions associated with dairy production and transportation. The SC social impact is related to the employees hired by suppliers, dairies and markets. The optimisation criterion includes all aspects of sustainability - environmental, economic and social defined in terms of costs and the preferences regarding the quantities of raw materials needed for production and market demands.

2. Description of the optimisation approach

2.1 Needed data

In order to develop the mathematical models, three groups of data should be known: 1). Raw material and products data - the composition of used raw material and dairy products; 2). SC data – data for the production system - data about processing times and types, and volumes of the equipment units used for implementations of production tasks. They are pasteurisers, curd vats, drainers. There are also given the fractions of the processed raw materials and raw products and target products; markets' demands; capacities of the milk suppliers; selling prices of milk and products; production costs, distances between milk suppliers, dairies and markets; transportation costs; vehicles' types and capacities; 3) environmental impact data - related to the environmental impact of pollutants obtained from the implementation of the SC activities in relation to two areas of impact - air and water. For the assessment as indicators, BOD_5 for the wastewater and CO_2 for the air emissions of pollutants are used; 4). Social impact data – social costs related to the employees (job positions) hired by suppliers, dairies and markets. There are costs for salaries, social benefits as food, working clothes, medical care and insurance and the average quantities of raw materials/products processed by employees in suppliers, dairies and markets.

2.2 Decision variables

To describe the optimisation problem, the following groups of decision variables should be introduced: 1). Binary variables to structure the SC between suppliers, dairies and markets; 2). Continuous variables to follow the transfer of raw materials and products flows between suppliers and dairies and dairies and markets. They are introduced to account for the quantities of raw materials bought by dairies from the suppliers and the quantities of products produced in dairies and sold at markets; 3). Continuous variables to follow for milk fat content in the used raw materials; 4). Integer variables for the number of employees (job positions) depending on the processed quantities of raw materials/products in suppliers, dairies and markets.

2.3 Mathematical models

The approach includes four models: 1). Models of production recipes. The production of two types of curd - low-fat content and high-fat content in two different recipes, each of which uses as a raw material – standardised whole milk and skim condensed milk are considered. The production recipes comprise different production tasks performed in units of different types. The first recipe includes three production tasks: milk pasteurisation, acidification to produce a raw dairy product, draining to produce target dairy product, while the second one includes four production tasks: milk dilution, milk pasteurisation, acidification and draining. The mathematical description of the production recipes includes: dependencies for the composition of the raw materials; target products yield equations describing the compositions as functions of the fat content in the used raw materials; equations for the quality of target products. 2). Supply chain model. The mathematical description of the three-echelon supply chain includes: mass balance equations for the subsystem's suppliers-dairies and dairies-markets to prevent the accumulation of raw materials in the suppliers and products in the dairies; equations for determination of the quantities of raw materials required from each dairy to produce the planned quantities of products. 3). Model of supply chain environmental impact. The environmental impact model includes equations about the environmental impact of the pollutants related to the wastewater and CO_2 emissions related to energy consumption and transport. 4). Model of supply chain social impact. Equations for the number of employees (job positions) who should be hired by suppliers, dairies and markets. They depend on the processed quantities of raw materials/products.

2.4 Constraints

To estimate the feasibility of the obtained sustainable dairy supply chain, the following constraints are introduced for i). The production of products in the time horizon; ii). The capacity of the suppliers of raw materials; iii). The capacity of the markets for taking of the planned quantities of products; iv). Environmental impact costs to be paid for the treatment of the pollutants. These are the costs for BOD_5 removal in the WWTPs and the CO_2 costs related to the production of the dairy products and transportation of raw material and products.

2.5 Optimisation criteria

Three different optimisation criteria are defined:

- The profit of the considered dairy production F_1 which is subjected to maximisation. It is determined as the difference between the revenue from the sale of the products at the markets and the economic, environmental and social costs, as follows:

$$F_1 = F_R - (F_{P_{costs}} + F_{M_{costs}} + F_{T_{costs}} + F_{BOD5_{costs}} + F_{CO2E_{costs}} + F_{CO2T_{costs}} + F_{SS_{costs}} + F_{SD_{costs}} + F_{SM_{costs}})$$
$$MAX\ (F_1) \quad (1)$$

Where F_R (BGN) is the revenue from the sale of the products at the markets; $F_{P_{costs}}$ (BGN) is the total production cost for the dairies; $F_{M_{costs}}$ (BGN) is the total cost incurred by the dairies for purchasing the required quantities of milk from suppliers for the production of the dairy products; $F_{T_{costs}}$ (BGN) is the total cost for the transportation of the milk and products between suppliers, dairies and markets; $F_{BOD5_{costs}}$ (BGN) is the total BOD_5 cost paid for treatment of the wastewater generated during the production of the products; $F_{CO2E_{costs}}$ (BGN) is the total cost associated with CO_2 emissions from the production; $F_{CO2T_{costs}}$ (BGN) is the total CO_2 cost associated with emissions of pollutants generated during milk and dairy products transportation; $F_{SS_{costs}}$, $F_{SD_{costs}}$, $F_{SM_{costs}}$ (BGN) are costs related to the number of employees (job positions) who should be hired by the suppliers, dairies and markets. BGN is the Bulgarian currency (Bulgarian Leva).

- Index of customers' demand satisfaction, F_2. It is evaluated by the ratio between products demands and products on markets. It is subject to maximisation:

$$MAX\ F_2 = \sum_{m=1}^{M} \sum_{p=1}^{P} \frac{\sum_{i=1}^{I} X_{i,p.m}}{MDem_{p.m}} \quad (2)$$

- Index of milk vendors' satisfaction, F_3. It is evaluated by the ratio between the capacities of milk suppliers and available quantities of milk. It is subject to maximisation too:

$$MAX\ F_3 = \sum_{s=1}^{S} \sum_{p=1}^{P} \frac{\sum_{i=1}^{I} Y_{i,p.s}}{MSup_{s.p}} \quad (3)$$

The formulated optimisation problem belongs to the MINLP. It contains both binary and continuous variables, sets of modelling equations, inequality constraints and optimisation criteria. The optimisation problem is solved by maximising each of the defined optimisation criteria.

3. Case study

The approach is implemented on a real case study from Bulgaria comprising the production of two types of curd with a low and high-fat content (P1 and P2) using two production recipes (PR1 and PR2) with two types of raw materials (RM1 and RM2). The products are produced in two dairies (D1 and D2) supplied with RM1 and RM2 by two suppliers (S1 and S2). The products are sold in two markets (M1 and M2). The planned quantities of the products that should be produced are 30,000 kg per product. Production takes place over a time horizon of one month (720 h). The equipment units for performing the production tasks and their summarised volumes are listed in Table 1. To formulate the portfolio feasibility constraints, the processing times should also be known. Capacities of suppliers (kg), prices of RM1 and RM2 (BGN/kg), market demands (kg) and prices of products (BGN/kg) are presented in Table 2.

Table 1: Equipment units with summarised volumes

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

Table 2: Data about the capacity of suppliers and milk prices and products demands and products prices

	Capacity		Milk price			Product demand		Product price	
	RM1	RM2	RM1	RM2		M1	M2	M1	M2
S1	80,000	70,000	0.6	1	P1	20,000	10,000	5.8	5.9
S2	140,000	70,000	0.45	1.3	P2	15,000	15,000	6.2	6.6

In Table 3, distances (km) between suppliers, dairies and markets are presented. It also includes data about the type of the used vehicles (V) - milk tanker truck with petrol engine – V1 and refrigerator truck with diesel engine – V2 such as: payload capacity – PC (L); the energy of fuel – EF (kWh/L); CO_2 (kg CO_2/kWh) generated from fuel combustion; fuel consumption – FC (L/100km) and fuel price - FP(BGN/L).

Table 3: Distance between suppliers, dairies and markets

	Distance				V	PC	EF	CO_2	FC	FP
	S1	S2	M1	M2						
D1	41	36	31	40	V1	2,500	8.056	0.249	32	2.22
D2	31	61	35	44	V2	4,000	9.583	0.267	23	2.27

The latter is used for the calculation of the CO_2 emissions associated with transportation and transportation costs. The energy consumed in both recipes and CO_2 emissions related to the dairy processes and the prices of BOD_5 paid to wastewater treatment plants and CO_2 paid by dairies is also known.

Table 4: Social impact data

Employees	CS	CWCl	CSB	CMI	AQ of RMs/Ps
Suppliers	1,300	200	100	90	1,000
Dairies	2,300	300	200	90	300
Markets	1,200	100	60	90	80

In Table 4 the average costs (BGN) related to the number of employees (job positions) who should be hired by the suppliers, dairies and markets are given. They include costs for salaries - CS, working clothes - CWCl, social benefits – CSB and medical insurance - CMI. The same table also shows the average quantities (kg) – AQ of raw materials or products that employees can process per day in the different echelons of the SC.

4. Results and discussions

Three MINLP optimisation models were defined and solved using GAMS software. The first optimisation problem is solved at the maximum ratio of material flows of raw materials regarding the capacities of the milk supply centres. The second optimisation problem is solved at maximum profit from the production of dairy products. The third optimisation problem is solved at the maximum ratio between material flows of dairy products to products demands.

Table 5 presents the obtained optimal values of revenues, economic, environmental and social costs, as well as the production profits for the solutions. In addition, the values of all three criteria: F_1, F_2, F_3, Eqs(1-3), are represented for the solutions. The three solutions meet the market demands for the supply of 30,000 kg of each of the two products or a total of 60 t. The first two solutions were obtained at the same values of the environmental constraints imposed in terms of fees that should be paid for BOD removal in the WWTPs, CO_2 emissions due to transport of raw materials and products and consumed energy by the dairy production process, with a total value of 4,190 BGN. Solution 3 was obtained at smaller values for the environmental constraints of 3,870 BGN. The differences in the values of economic costs are due to the different quantities of raw materials used for the production of the products according to recipes PR1 and PR2. The solution 1 shows that milk suppliers deliver a total of 162,022 kg of both types of milk for the production of 61,758 kg of both products. 22,317 kg of P1 and 24,441 kg of P2 are delivered to M1. The obtained optimal products portfolios for solution 1, Solution 2, and solution 3 are represented in Figures 1-3.

Table 5: Data related with obtained optimal solutions

Solutions	Solution 1, (BGN) $MAX\ F_3 = 0.450,$ $F_1 = 118{,}008$ BGN, $F_2 = 1.029$	Solution 2, (BGN) $MAX\ F_1 = 143{,}809$ BGN, $F_3 = 0.430,$ $F_2 = 1.000$	Solution 3, (BGN) $MAX\ F_2 = 1.001,$ $F_1 = 118{,}681$ BGN, $F_3 = 0.367$
Revenue	379,971	372,822	367,331
Economic costs	167,840	137,683	157,640
Environmental costs:	4,083	4,190	3,870
- BOD_5;	2,193	2,300	2,300
- CO_2 from transport;	444	445	380
- CO_2 associated with energy consumed	1,446	1,445	1,190
Social costs	7/9/36 90,040	7/9/34 87,140	7/9/34 87,140
Optimal production profit	118,008	143,809	118,681

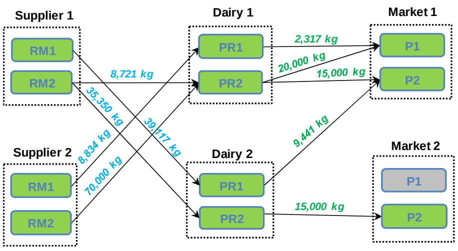

Figure 1: Optimal products portfolio of dairy SC for solution 1 where satisfaction the requirements of the suppliers is met

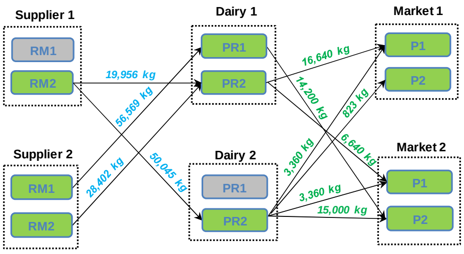

Figure 2: Optimal products portfolio of dairy SC for solution 2 where satisfaction the requirements of the dairies is met

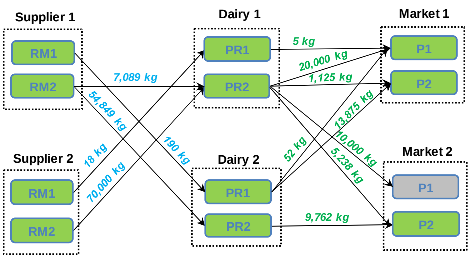

Figure 3: Optimal products portfolio of dairy SC for solution 1 where satisfaction the requirements of the markets is met

These quantities are much higher than the required market demands. Only 15,000 kg of P2 are delivered to M2 and no amount of P1. Figure 2 shows solution 2 using 154,972 kg of both types of milk for the production of 60,023 kg of both products. In this solution, S1 supplies only RM2 to D1 and D2. D2 uses only RM2 for the production of both products. For the same solution, 20,000 kg of P1 and only 835 kg from P2 are delivered to M1. 10,000 kg of P1 and 29,201 kg of P2 are delivered on M2. In this solution, P2 is delivered to M2 in a much larger amount than required and to M1 in a much smaller amount than required by market demands. In solution 3, full satisfaction of market demands was achieved. 132,146 kg of both types of milk were used for the production of 60,057 kg of both products. The three solutions can be used in the decision-making process in terms of seeking a compromise between the satisfaction of the requirements of suppliers, dairies and markets.

5. Conclusions

The present study proposes an approach for designing an optimal sustainable supply chain for the production of different types of dairy products, which simultaneously satisfies environmental, economic and social criteria. It was implemented using different objective functions representing the preferences of suppliers, dairies and markets. The first solution, which results in satisfying the requirements of the milk suppliers is related to the largest economic costs of 167,840 BGN and social costs of 90,040 BGN and the lowest production profit of 118,008 BGN. The second solution leads to satisfaction of the preferences of the dairies for the production of 60,023 kg of both products. This is the solution with the lowest economic costs of 137,683 BGN and the largest production profit of 143,809 BGN. In solution 3, full satisfaction of market requirements was achieved. This solution results in the lowest environmental costs of 3,870 BGN. In the future, a multi-objective optimization problem will be defined and solved to simultaneously satisfying the preferences of all actors in the network.

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