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# Optimal Products Portfolio Design of a Sustainable Supply Chain Using Different Recipes for Dairy Products Production

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This study proposes a deterministic optimization approach for products portfolio design of a Sustainable Supply Chain (SSC) comprising suppliers, plants and markets for production of dairy products using different recipes. It includes three interconnected models of the recipes used for the production of the dairy products, the SC design and the SC environmental impact. The latter is assessed in terms of wastewater and $CO_2$ emissions associated with the dairy production and the transportation. The models are included in an optimization working frame along environmental and economic criteria. The proposed approach has been implemented on a case study from Bulgaria – for production of two types of curd at two recipes using two types of milk. Optimization problems have been formulated in terms of MINLP. They are solved at different imposed environmental pollution taxes on the dairies regarding both wastewater and $CO_2$ emissions. The optimal SC products portfolio for the production of the planned products is obtained satisfying the best trade-off between environmental and economic criteria.

## 1. Introduction

The dairy industry produces large amounts of pollutions in terms not only of $CO_2$ emissions but also of wastewater. Over the last decade, approaches have been developed for the reduction of the environmental impact of wastewater through utilization of the by-products to obtaining value-added products (Tanzi et al., 2017). The most effective pathway for environmental impact assessment of the dairy production systems is implementation of Life Cycle Analysis approach (Vagnoni et al., 2017). It is included in the strategy for optimal design of SSC. Most of developed SSC approaches result in the formulation of multi-objective MINLP optimization problems with environmental and ecological criteria included. Most often as economic criteria maximization of the total profit (Bottani et al., 2019) and minimization of the total costs (Mohebalizadehgashti et al., 2020) are used. As environmental ones – the reduction of the $CO_2$ emissions from the transport and energy consumed in the production of the products are used. The latter shows a trend for looking for opportunities for moving from fossil fuel sources towards renewable energy sources (Tarighaleslami et al., 2019). Implementation of these approaches results in obtaining a set of Pareto-optimal solutions which satisfy some level of trade-off between both criteria. Kirilova and Vaklieva-Bancheva (2017) have also developed a multi-objective MINLP optimization approach for product portfolio design of dairy SSC. However, the authors for the first time define a broader environmental working frame which includes not only assessment of the $CO_2$ emission generated from the transport and energy consumed in the production of the products but also the assessment of the wastewater generated during the production of products and theses ones associated with used raw materials.
This approach is reduced to single-objective whereby both environmental and economic criteria are defined in terms of money (costs) to obtain the best trade-off between both objectives.
The present study proposes an extended version of the approach of Kirilova and Vaklieva-Bancheva (2017) with the inclusion of an additional model of production recipe for the production of the products. It has been implemented at different environmental pollution taxes. It is shown how the obtained solution influences the sustainability of the SC operation and can be used in the decision-making process.

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## 2. Optimization approach description

The study proposes an approach for optimal design of production portfolios of dairy SC including milk suppliers $S$, dairies $I$ in which a group of products $P$ are produced in certain quantities to satisfy given consumer demands (short-term) and markets $M$ in which the products are sold. The products $P$ are produced in different recipes $R$ using different raw materials for a time horizon $H$ (h). Three interconnected deterministic models are proposed for: (i) production of the products using different recipes; (ii) SC design; and (iii) SC environmental impact. The latter is assessed in terms of two areas:1) Wastewater generated at each processing task of the production recipes, including those related to the raw materials used; 2). $CO_2$ emissions related to the energy consumption from the dairies and $CO_2$ emissions produced during transportation. Biochemical Oxygen Demand during 5 days ($BOD_5$) is used for main indicator for the wastewater assessment. Part of $BOD_5$ load is related to the raw materials and depends on their amounts and composition. The rest is related to the losses of raw materials, intermediates, by-products and products resulting from spills or sticking on the walls of the apparatus which can be regulated to certain levels. Environmental pollution taxes on dairies have been imposed to keep wastewater and $CO_2$ emissions below acceptable levels. The milk fat content is selected as a key variable in the models because both the yield of target products and $BOD_5$ depend on it. The models are included in an optimization framework along with environmental and economic criteria. Several optimization problems are formulated at different environmental pollution taxes concerning both wastewater and $CO_2$ emissions in terms of MINLP. They are solved using GAMS software.

### 2.1 Needed data

1). Raw materials and products data - the composition of used raw materials and products. 2). SC data – the production system; markets' demands; capacities of the milk suppliers; selling prices of milk and products; production costs; distances between suppliers, dairies and markets; transportation costs; vehicles' payload capacities. 3). Environmental impact data - the pollutants related to the SC activities.

### 2.2 Decision variables

Following variables are 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; 3). Continuous variables to follow for milk fat content in the used raw materials.

### 2.3 Mathematical models

Production recipes modelling

The productions of two types of curd $p = 1,2,\ p \in P$ in two recipes $r_p = 1,2,\ r_p \in R_p$, each of which uses as a raw material – standardized whole milk (RM1) and skim condensed milk (RM2) with fat content $\mathrm{x}(r_p)$ (%) are considered. The production recipes comprise different production tasks $\forall l,\ l \in L(r_p)$ performed in units of different types. The first recipe includes three production tasks: milk pasteurization; acidification to produce curd-raw product; draining to produce curd-target product. The second production recipe includes one more production task - milk dilution which precede the implementation of the other three production tasks. Description of the production tasks for the second production recipe is presented in Table 1. In it: $y(\mathrm{x}(r_p))$ (kg) is the water used for dilution of condensed milk; $YP(\mathrm{x}(r_p))$ (kg) is yield of curd – raw product containing residual whey.

The mathematical model of production recipes includes dependencies for:

1). Determination of the protein, casein and lactose concentrations in raw materials:

Production recipe 1: Skimming of whole standardized milk.

$$MP(\mathrm{x}(r_p)) = \mathrm{MP}\left[1 + \frac{\mathrm{MF} - \mathrm{x}(r_p)}{\mathrm{CF} - \mathrm{MF}}\right],\ MC(\mathrm{x}(r_p)) = \mathrm{MC}\left[1 + \frac{\mathrm{MF} - \mathrm{x}(r_p)}{\mathrm{CF} - \mathrm{MF}}\right],\ ML(\mathrm{x}(r_p)) = \mathrm{ML}\left[1 + \frac{\mathrm{MF} - \mathrm{x}(r_p)}{\mathrm{CF} - \mathrm{MF}}\right],\quad r_p = 1, \forall p,\ p \in P. \tag{1}$$

Production recipe 2: Dilution of skimmed condensed milk.

$$MP(\mathrm{x}(r_p)) = \mathrm{MP}\frac{\mathrm{x}(r_p)}{\mathrm{MF}},\ MC(\mathrm{x}(r_p)) = \mathrm{MC}\frac{\mathrm{x}(r_p)}{\mathrm{MF}},\ ML(\mathrm{x}(r_p)) = \mathrm{ML}\frac{\mathrm{x}(r_p)}{\mathrm{MF}},\qquad r_p = 2, \forall p,\ p \in P. \tag{2}$$

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 skim milk.

2). Determination of curd yield $Y(\mathrm{x}(r_p))$ (kg) (Johnson, 2000):

$$Y(\mathrm{x}(r_p)) = \frac{\left[RF(\mathrm{x}(r_p)).\mathrm{x}(r_p) + RC_p.MC(\mathrm{x}(r_p))\right]RS_p}{PS_p}\ ,\ r_p = 1, 2; r_p \in R_p, \forall p, p \in P \tag{3}$$

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). Determination of Fat in Dry Matter - $FDM_p$ (%) (Johnson, 2000) used as an indicator of curd quality:

$$FDM_p = \frac{PF_p}{PS_p}\ \forall p, p \in I \tag{4}$$

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

*Table 1: Description of production tasks in the second production recipe*

| Production task | Processing time, (h) | In/Out materials | Fractions | Unit type |
|---|---|---|---|---|
| Dilution | 0.5 | In: condensed skim milk<br>In: water<br>Out: diluted condensed milk | 1<br>$y(\mathrm{x}(r_p))$<br>$1+y(\mathrm{x}(r_p))$ | milk containers |
| Pasteurization | 0.5 | In: diluted condensed milk<br>Out: pasteurized milk | 1<br>1 | pasteurizers |
| Acidification | 4 | In: pasteurized milk<br>In: yeast<br>Out: curd – raw product<br>Out: whey | 0.88<br>0.12<br>$YP(\mathrm{x}(r_p))$<br>$1-YP(\mathrm{x}(r_p))$ | curd vats |
| Draining | 0.5 | In: curd – raw product<br>Out: curd – target product<br>Out: whey | 1<br>0.9<br>0.1 | drainers |

All dependencies are referred to 1 kg raw material and 1 kg target product. The models of the production recipes provide connection between the production tasks by calculating the size factors representing the “volumes” of materials that have to be processed in production tasks so as to produce 1 kg from target products.

**Supply Chain modelling**

1). Mass balance equations for the subsystem’s 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 to structure the SC between suppliers and dairies and dairies and markets.

$$QM(r_p)_i = \sum_{s=1}^{S} YY(r_p)_{i,s} \cdot \gamma_{i,s},\ QP(r_p)_i = \sum_{m=1}^{M} XX(r_p)_{i,m} \cdot \chi_{i,m},\ \forall i, i \in I; \forall r_p, r_p \in R_p; \forall p, p \in P. \tag{5}$$

**Supply Chain environmental impact modelling**

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

$$BOD_M(\mathrm{x}(r_p)) = \left[0.89.\mathrm{x}(r_p) + 1.031.MP(\mathrm{x}(r_p)) + 0.69.ML(\mathrm{x}(r_p))\right]10^{-2},\text{(kg } O_2 \text{ /kg milk)},\ \forall r_p, r_p \in R_p, \forall p, p \in P. \tag{6}$$

$$BOD_{Cu}(\mathrm{x}(r_p)) = \frac{BOD_M(\mathrm{x}(r_p))}{YP(\mathrm{x}(r_p))}, \text{(kg O}_2\text{ /kg curd)}, \forall r_p, r_p \in R_p, \forall p, p \in P. \tag{7}$$

$BOD_5$ load related to the wastes, production tasks and eligible levels of losses $LS$ are listed in Table 2.

The environmental impact assessment $PBOD_p$ for production of 1 kg of each type of curd is:

$$PBOD(\mathbf{x}(r_p)) = \sum_{w=1}^{W} BOD_w \sum_{l=1}^{L(r_p)} m(\mathrm{x}(r_p))_{w,l}, \text{(kg O}_2\text{)}, \forall p, p \in P. \tag{8}$$

where $m(\mathrm{x}(r_p))_{w,l}$ ( $\forall w, w \in W$ ; $\forall l, l \in L(r_p)$ ; $\forall r_p, r_p \in R_p$ ; $\forall p, p \in P$ ) 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.

*Table 2: Sources producing $BOD_5$, 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 skim milk | $BOD_M(\mathrm{x}(r_p))$ | 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 | |
| Curd losses | $BOD_{Cu}(\mathrm{x}(r_p))$ | Task 2, $LS2_{Cu}$=0.3<br>Task 3, $LS3_{Cu}$=0.5 | | Task 3, $LS3_{Cu}$=0.3<br>Task 4, $LS4_{Cu}$=0.5 | |
| RM1 | 0.1% | | Task 1, $LS_{WM}$ =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 the energy consumed in the pasteurization process for heating $EH$ and cooling $EC$ of the milk in (kWh/kg milk) referred to 1 kg milk:

$$EIMCO2(\mathbf{x}(r_p)) = \frac{(EH + EC) \cdot ECO_2}{\left(\dfrac{CF - MF}{CF - \mathbf{x}(r_p)}\right)}, \text{(kg CO}_2\text{ /kg curd)}, \forall r_p, r_p \in R_p, \forall p, p \in P. \tag{9}$$

where $ECO_2$ is the mass of $CO_2$ emissions associated with the energy (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 curd)

$$TMCO2 = 2 \cdot \frac{TCO_2}{VCm}, \text{(kg CO}_2\text{ /km·kg milk)} \qquad TPCO2 = 2\frac{TCO2}{VCp}, \text{(kg CO}_2\text{ /km·kg curd)} \tag{10}$$

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.

## 2.4 Constraints

Following constraints are introduced for: 1). Realization of the production portfolio in the time horizon; 2). Capacity of the suppliers of raw materials; 3). Capacity of the markets for realization of the planned quantities of products; 4). Environmental constraints regarding environmental pollution taxes.

## 2.5 Optimization criterion

A single objective optimization function is used. It represents the difference between the production profit and the production costs; the costs for purchasing the required quantities of raw materials; the costs for the transportation; the $BOD_5$ costs paid for treatment of the wastewater generated; the $CO_2$ emissions costs associated with the energy consumed; the $CO_2$ costs associated with transportation.

## 3. Case study

The approach is implemented on a real case study comprising the production of two types of curd - P1 with fat content of 1 % and P2 with fat content 3 %. The products are produced using two types of raw materials - RM1 and RM2 in two production recipes - PR1 and PR2 over time horizon of one month (720 h). The technological boundaries in which RM1 is skimmed and RM2 is diluted with water for the production of the products are $1.4\% \leq x(r_p) \leq 0.05\%$ . The planned quantities of the products that should be produced are 30,000 kg per product.

SC includes two suppliers - S1 and S2, two dairies - D1 and D2 for the production of the products and two markets - M1 and M2 for the realization of the produced products. The composition of RM2 is: water - 70 %; total solids – 30 %; fat content - 1.813 %; lactose – 9.37 %; proteins – 6.1 %; casein – 5.35 %. The composition of RM1 and the target products and the recovery factors for casein and of all solids of the milk are given in (Kirilova and Vaklieva-Bancheva, 2017). For the purpose of modelling, the equipment units used for performing the production tasks belonging to a given type are combined together, presenting a common equipment unit of given type with volume determined as the sum of the volumes of the respective units. The equipment units and theirs summarized volumes are listed in Table 3.

*Table 3: Equipment units with summarized volumes*

| | Milk tanks, ($m^3$) | Pasteurizers, ($m^3$) | Curd vats, ($m^3$) | Drainers, ($m^3$) |
|---|---|---|---|---|
| D1 | 1,450 | 800 | 950 | 300 |
| D2 | 1,450 | 950 | 1,050 | 340 |

Capacities of suppliers and the prices of RM1 and RM2 and market demands and selling prices of products are given in Table 4. Production costs related to: D1 are 0.9 BGN/kg for P1 and 1.1 BGN/kg for P2; D2 are 1.2 BGN/kg for P1 and 1.3 BGN/kg – for P2.

*Table 4: Capacity of suppliers and milk prices and demands and selling prices of products at markets*

| | Capacity (kg) | | Milk price (BGN/kg) | | | Products demands (kg) | | Products prices (BGN/kg) | |
|---|---|---|---|---|---|---|---|---|---|
| | RM1 | RM2 | RM1 | RM2 | | M1 | M2 | M1 | M2 |
| S1 | 80,000 | 70,000 | 0.6 | 1 | P1 | 20,000 | 10,000 | 3.8 | 3.9 |
| S2 | 140,000 | 70,000 | 0.45 | 1.3 | P2 | 15,000 | 45,000 | 4.2 | 4.6 |

Data about the distances between suppliers, dairies and markets and data about the vehicles used for transportation are listed in Table 5. They are used for calculation of the $CO_2$ emissions associated with transportation and transportation costs. The latter in BGN/kg.km is 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 5: Distances between suppliers, dairies and markets in SC and data about the vehicles used*

| | Distance, (km) | | | | Type of vehicle | Type of fuel | Payload capacity (L) | Energy of fuel (kWh/L) | $CO_2$ from fuel combustion (kg $CO_2$/kWh) | Fuel consumption (L/100 km) | Fuel price, (BGN/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | M1 | M2 | | | | | | | |
| D1 | 41 | 36 | 31 | 40 | Milk tanker truck | Petrol | 2,500 | 8.056 | 0.249 | 32.2 | 2.22 |
| D2 | 31 | 61 | 35 | 44 | Refrigerator truck | Diesel | 4,000 | 9.5833 | 0.267 | 23 | 2.27 |

The environmental costs associated with transportation are obtained using data given in Table 5 and the $CO_2$ costs which is 1 BGN/kg $CO_2$. The energy consumed in both recipes for heating of 1 kg milk is $8.333\times10^{-3}$ kWh/kg milk, and for cooling is $6.333\times10^{-2}$ kWh/kg milk. The $CO_2$ emissions associated with both processes is 0.46 kg $CO_2$/kWh. The price of $CO_2$ paid by dairies are $9.98\times10^{-4}$ BGN/kg $CO_2$. The price of $BOD_5$ paid to wastewater treatment plants from D1 is 2.9 BGN/kg, while from D2 it is 3.5 BGN/kg.

## 4. Results and discussions

Optimization problems have been formulated and solved at different boundaries of varying of the environmental pollution taxes concerning both wastewater and $CO_2$ emissions. The optimal SC products portfolio satisfying the best trade-off between environmental and economic criteria was found, Figure 1. It corresponds to values for wastewater treatment taxes for both dairies from 1,000 BGN and 1,244.897 BGN and 14,400 BGN for air pollution tax concerning $CO_2$ emissions.

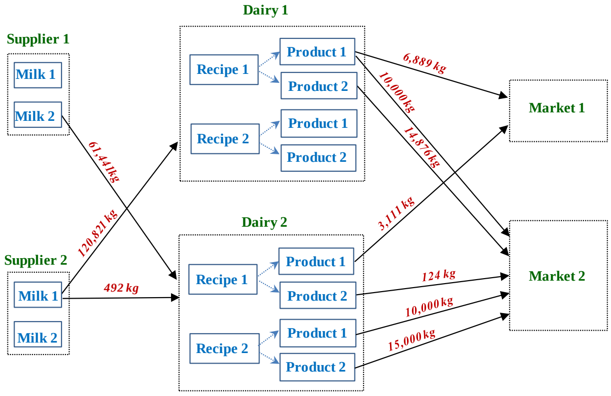


*Figure 1: Optimal products portfolio of the supply chain for dairy products production*

The profit is 49,962.867 BGN. One can see that S2 supplies both dairies with RM1 for the production of the products using PR1, while S2 only supplies D2 for the production of the products using PR2. In D1 are produced P1 and P2 only using PR1, while in D2 are produced both products using both recipes. All products produced are sold on both markets.

## 5. Conclusions

The present study proposes an extended version of the developed by Kirilova and Vaklieva-Bancheva, (2017) approach for optimal product portfolio design of sustainable dairy SC with the inclusion of an additional production recipe for the production of two types of curd. The SC involves two suppliers, two dairies and two markets. Optimization problems are formulated and solved at different environmental constraints concerning both wastewater and $CO_2$ emissions. The optimal SC products portfolio has been found with values for environmental costs from 16,644.897 BGN and a profit of 49,962.867 BGN.

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