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Multi-objective Optimization of Curds Manufacture

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Abstract

In this paper, an important profit/environmental impact trade-off problem in dairy is presented as a multi-objective optimization problem. A Genetic Algorithm (GA) is used to find the conditions leading to the best compromise between both objectives. Two cases, at different weighting coefficients are considered to illustrate an enhanced effect of the environmental impact on the multi-objective function.

Keywords: Multi-objective optimization, Genetic algorithms, Dairy, Profit, Environmental impact.

1. Introduction

A number of business and environment programs, initiated for Central and Eastern Europe, aim to assist the environmental performance of companies. Many of them, involving small and medium-size enterprises, promoted the use of innovative policies and instruments to deal with local and global environmental issues.

The problem discussed in this work focuses in the necessary trade-off between plant profit and environmental impact in dairy products manufacturing. The aim is to find the best compromise between plant income for a given demand of two types of curds and the *BOD* load generated in their manufacture. The effect of the amount and composition of processed milk, processing unit's assignment and number of processed batches is taken into account in both objectives. Additionally, the *BOD* load is formulated so as to account for the inherent losses, which are considerable in dairy plants. Both targets are in a conflict and the search for a best trade-off between them entails formulating the multi-objective optimization problem and the application of an appropriated solution technique.

2. Process Description

Curds are milk products containing about 80% water and 20% solids (casein, fat, minerals, microelements and other milk components). They are produced by acidification of the skimmed standardized whole milk with lactic acid bacteria or acidifiers.

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A description of the main production tasks ($l \in L, L = 3$) (Baltadzhieva, 1993) and related information (Stefanis et al.1997) are presented in Table 1.

Table 1. Processing tasks description, where CY1(x) is a yield of curds by-product with* x *- milk fat content in the skim milk.*

Processing tasks	Task Duration	Input/Output	Fractions
Task 1	30 min.	In. Skim milk	1
Pasteurization		Out. Pasteurized Skim milk	1
Task 2	240 min.	In. Skim milk	0.88
Acidification		In. Culture	0.12
		Out. Curds by-product	*CY1(x)**
		Out. Whey	1-*CY1(x)*
Task 3	30 min.	In. Curds by-product	1
Draining - target		Out. Curds target product	0.9
products processing		Out. Drained Whey	0.1

The particular case study under investigation involves the manufacturing of two types ($i \in I,\ I = 2$) of curds: low fat-P1 (0.3%) and high fat-P2 (1%). The products composition and values of recovery factors are presented in Table 2.

Table 2. Products composition and values of the recovery factors.

Pro-ducts	Composition of target products			Recovery factors values	
	Moisture %	Fat %	Solids %	*RS* - solids recovery factor	*RC* - casein recovery factor
P1	80	0.3	20	1.724	0.96
P2	81.58	1.009	18.42	1.386	0.96

Both products manufacture cyclically in a single campaign ($TC_i = 4$ hours). The dairy comprises the equipment units listed in Table 3.

Table 3. Plant data.

Type	Pasteurizers				Vat reactors			Drainers			
No	1	2	3	4	5	6	7	8	9	10	11
V [m^3]	300	250	150	100	300	400	250	80	60	60	100

The production demand for each product is 7000 kg and must be manufactured into the horizon H of 400 hours. The cost of input milk CM is 0.25 BG Lv per kg, whereas the target products are sold at $CC1$ =1.10 and $CC2$=1.42 BG Lv per kg.

Short Time High Temperature pasteurization by steam takes place in task 1 followed by cooling with chilly water. The heating energy required per kg of skimmed milk EH is 300 kJ/kg, while that required for cooling EC is 228 kJ/kg (Baltadzhieva, 1993). The costs per kJ of steam and chilly water are respectively CS=6, 32.10^{-6} and CW=1, 55.10^{-5} BG Lv. The plant has two operators at a labor cost of LC=1, 08 BG Lv per hour.

3. Waste Analysis

Wastewater generated after process cleaning has a considerable *BOD*. The *BOD* load depends on both, the composition and amount of processed milk, and spillage and losses of raw material, by-product and product as follows (Carawan at al., 1979, Overview of Dairy Processing, 2000):

I) the *BOD* load of 1 kg skimmed standardized whole milk is determined as follows:

$$BOD_M(x) = 0.89.x + 1.031.MP\%(x) + 0.69.ML\%(x)\,, \tag{1}$$

where: - x is a milk fat in %, and $MP\%(x)$ and $ML\%(x)$ are protein and lactose presented as functions of the milk fat in a skimmed standardized whole milk,

II) The *BOD* load of associated to the processing tasks inherent losses are:

Task 1. The waste is due to glued coagulated milk on the pasteurizer's walls. The *BOD* depends on the mass of processed milk: The *BOD* load of 1 kg of pasteurized milk is:

$$BOD_P = 1.5.10^{-3} \quad [\text{kgO}_2\text{/kg pasteurized milk}]. \tag{2}$$

Task 2. The pollution results completely from a spilled whey. The inherent leaks are *WL%*=1.6% of the processed whey mass. The *BOD* load of 1 kg of acid whey is:

$$BOD_W = 32.10^{-3} \quad [\text{kg O}_2\text{/kg acid whey}]. \tag{3}$$

Task 3. The polluting is due to both:

i) Discharge drained from the curds whey. The *BOD* load of 1 kg of acid whey is the same as in *Task 2*;

ii) Inherent losses of the target products gluing on the drainer's wall. They depend on the curds fat content *FC%* (Table 2)- $CL\% = 0.0017.FC\%$. The *BOD* load of 1 kg of curds is:

$$BOD_C(x) = CY(x).BOD_M(x)\frac{kg\ O_2}{kg\ cheese}. \tag{4}$$

4. Formulation of the Multi-objective Optimization Problem

4.1. Variables

Continuous variables $x_i, i \in I,\ I = 2$, are introduced to account for the fat skimming of the used standardized whole milk. A set of binary variables $\zeta_{p,i}$ is used to structure production routes for each product i, as follows: $\zeta_{p,i} = 1$ if unit $p \in P, P = 11$, is used for product i and $\zeta_{p,i} = 0$ otherwise. Integer variables $n_i\ i \in I,\ I = 2$ are introduced to account for the number of produced batches.

4.2. Mathematical model of curds processing

The mathematical model that describes target products manufacturing comprises:

a) The *FDM* (Fat in Dry Matter) equation. It keeps for the quality of target product (Johnson, 2000). The *FDM* value is determined using the product composition data listed in Table 2 and fat recovery factors RF_i calculates accordingly:

$$FDM_i = \frac{RF_i x_i}{(RF_i x_i + RC_i MC\%_i)RS_i}, \quad \forall i \in I \tag{5}$$

where: $MC\%_i$, is the casein content presented as a function of the milk fat content in skimmed standardized milk.

b) The Van Slyke balance equation. It is used to target product yield calculation as functions of fat content in the used milk:

$$CY_i = \frac{\left[RF_i.x_i + RC_i.MC\%_i\right].RS_i}{SC\%_i}, \ \forall i \in I \tag{6}$$

c) Constraint keeping positive and less or equal to 1 value of the respective fat recovery factor:

$$0 < RF_i \le 1, \ \ \forall i \in I \ . \tag{7}$$

d) Constraint determining technological boundaries for milk skimming for the product:

$$0.05 \le x_i \le 1.4, \qquad \forall i \in I \ . \tag{8}$$

4.3. Additional constraints

A) <u>Structural constraints.</u> They support structuring the feasible (at least one suitable units to be assigned to each task) and compatible production routes. The identification of appropriate units-*p* for tasks-*l* is carried out using the following array of binaries:

$$ID(i) = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}' \ \forall i \ . \tag{9}$$

Production routes' feasibility is kept by the following constraints:

$$\prod_{l=1}^{L_i} \left(\sum_{p=1}^{P} ID(i)_{l,p} \zeta_{p,i} \right) \ge 1 \qquad \forall i, \ \ i \in I \ . \tag{10}$$

while their compatibility requires:

$$\sum_{i=1}^{I} \zeta_{p,i} \le 1 \quad \ \forall p, \ \ p \in P \ . \tag{11}$$

B) <u>Production constraints</u>. They aim to ensure manufacturing the planed amounts within the time horizon H .

The products batch size is given by:

$$Batch_i = \min \left\{ \frac{\sum_p V_p .ID(i)_{lp} .\zeta_{p,i}}{s(i)_l} \right\}, \ \forall l, \ \ l \in L_i, \ \ \forall i, \ \ i \in I \ , \tag{12}$$

where the size factors - $s(i)_l$ depend on the milk fat.

A number of batches, considering queuing times, must be chosen so as to ensure demand fulfillment into the time horizon:

$$n_i^{\min} \le n_i \le n_i^{\max} \ , \ \ \ \forall i, \ \ i \in I \ , \tag{13}$$

$$n_i .Batch_i \ge Q_i \ , \qquad \forall i, \ \ i \in I \ , \tag{14}$$

$$n_i.TC_i + \sum_l (T_{i,l} - TC_i) \le H ,. \ \ \forall i, \ \ i \in I \ . \tag{15}$$

4.3. Multi-objective function

Because the target is to find the best trade-off between the environmental impact and the profit, the multi-objective optimization criterion must have both into account.

A) The environmental impact. The Global *BOD* "processed" from the plant is used as an environmental impact assessment, Stefanis at al. (1997). It is defined by the *BOD* "generated" in the tasks, due to determined pollutants- $w \in W$, $W = 3$:

$$GBOD = \sum_i n_i Batch_i \sum_w \sum_l m(i)_{w,l} BOD_w \ , \tag{16}$$

where: $m(i)_{wl}$ [kg/kg] are the pollution indices related to pollutants in the tasks, determined on the basis of pollutants mass balance (Hilaly and Sikdar, 1995).

The environmental impact assessment must be subjected to minimization or maximization of its negative value:

$$\Phi 1 = \max_{x,\zeta,n} \left(- \sum_i n_i Batch_i \sum_w \sum_l m(i)_{w,l} BOD_w \right) . \tag{17}$$

B) The income function. It is formulated to present the production profit accounting for the products selling costs, milk cost, energy cost and labor cost. It is subjected to maximization.

$$\Phi 2 = \max_{x,\zeta,n} \sum_i n_i .(-TC_i .2.LC + Batch_i (CC_i - \frac{1}{CY_i} CM - EH.CS - EC.CW)) . \tag{18}$$

The corresponding weighted multi-objective function is:

$$MAX(\alpha 1.\Phi 1 + \alpha 2.\Phi 2) , \tag{19}$$

where: $\alpha 1$ and $\alpha 2$ are weighting coefficients.

The multi-objective optimization problem thus formulated is solved by using Genetic Algorithms developed in IChE-BAS, on the basis of the approach proposed in Handbook of Evolutionary Computation (1997), at the following settings: popsize – 300; generations – 600; selection – linear rank; crossover - uniform and mutation - non-uniform. A dynamic penalization is used to transform the resulting constrained optimization problem to an unconstrained one. Pareto Frontier is generated by applying a methodology proposed by Messac and Ismail-Yahaya (2003).

5. Results

The problem above is solved at two different values of weighting coefficients α. In the first case the values of both coefficients are taken equal to 0,5, which results in the optimal solution of 250,163 at *BOD* load of -242,753 and being the plant income - 743,077 Lv. In the second case the $\Phi 1$ weight is increased to $\alpha 1$=0,7 then $\alpha 2$=0,3. This results in the optimal solution of 53,098 at -233,147 *BOD* load and 721,002 Lv plant income. The values obtained of controlled variables for both cases are listed in Table 4.

For comparison purposes, the problem solution has been run separately for the particular objective functions eq. (15) and eq. (16). Then, the optimal *BOD* load obtained in -183, 6, while profit is 835,61 Bg Lv.

Table 4. Values of controlled variables at the optimal solution.

Product	Batch size [kg]	Milk fat %	Number of batches	Units		
				Task1	Task 2	Task 3
		$\alpha 1$=0,5 $\alpha 2$=0,5; Optimal solution of 250,163				
P1	85,56	0.075	82	1	6	11
P2	111,24	0.233	99	2, 3, 4	5, 7	8, 10
		$\alpha 1$=0,7 $\alpha 2$=0,3; Optimal solution of 53,098				
P1	99,82	0.079	72	2, 4	6	8, 9
P2	103,42	0.237	99	1, 3	5, 7	10, 11

6. Concluding Remarks

This paper deals with a trade-off problem between profit and environmental impact in a dairy plant. A Genetic Algorithm technique is found as an appropriate solution approach. The amount and composition of processed milk and inherent losses are accounted in the Global *BOD* assessment. The conditions at which is attained the best compromise between both objectives are found. The effect of overweighting of the environmental issue on the solution is also shown.

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