Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 48 ISSUE 2 October 2011

Ecological optimisation of materials technological processes

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Received 05.08.2011; published in revised form 01.10.2011

Cleaner production and biotechnology

ABSTRACT

Purpose: In this paper the necessity of ecological optimisation of materials technological processes was presented. The Procedure of the Optimum Materials Technological Process (POMPT) with Poli-Opt version 1.0 program to optimisation of materials technological processes was discussed.
Design/methodology/approach: In this article the essence of multicriterial optimisation was presented. The method of the polyoptimisation - genetic algorithms (GA) for the technological processes optimisation has been showed. Application of the POMPT procedure by general analysis and estimation for 4 zinc plating technological processes has been tested and illustrated.
Findings: The characteristic of GA method, stages of the POMPT procedure with usage of the computer program to optimisation of the technological processes were discussed.
Research limitations/implications: The presented POMPT procedure is not the closed solution but it is the object which should be subject to further testing and improvements in the range of the optimisation methodology usage and information technique.
Practical implications: The proposed POMPT procedure of technically, ecologically and economically optimum materials technological process is the effective and relatively simple tool making possible the analysis and estimation of the technological processes and the optimisation of a group of the materials technological processes in the direction of improvement of the negative environmental influences.
Originality/value: With regard to increasing quantity of possible technical solutions, the optimisation methods and the POMPT procedure should have more and more meaning in the materials engineering.
Keywords: Industrial application; Cleaner production methods; Multiobjective optimisation; Genetic algorithms; Optimum materials technological process

Reference to this paper should be given in the following way:
R. Nowosielski, A. Kania, Ecological optimisation of materials technological processes, Journal of Achievements in Materials and Manufacturing Engineering 48/2 (2011) 192-199.

1. Introduction

Decided majority of the representatives of various options of the sustainable development (SD) affirm that the politics and practical workings towards SD have to have the “local” character. Taking into consideration this aspect one can affirm that the technological process is the smallest, convenient “local” area. The search of the best process (optimum process) among the given collection has the special meaning. During the designing (ecodesigning) and even earlier, during the formation of conception of a product and technological process one should consider many factors and criteria which can be classified in criteria: technical, economic and environmental [1,2]. Obviously, considering the problem in detail, one can distinguish different criteria e.g. market, qualitative, etc. [3-5]. The environmental criteria take into account reduction or minimisation of the negative influence of a product and process on the natural environment, but more and more often they complying with principles and postulates of the sustainable development conception. All processes of a product designing and connected with its producing the technological process contain the elements of selection of quantity and the kinds of materials, from that the product will be made, but also the materials (ecomaterials) which are indispensable for functioning of the technological process (tools, devices, installations, etc.) [6]. The complex analysis, in this range, requires the usage of procedures: life cycle assessment of a product, engineering of the life cycle assessment of a product and designing of the life cycle assessment of a product [7,8]. This exhibits the special part of materials and materials engineering in the ecodesigning process with usage of ecomaterials [9]. The presented way of approach to the optimisation of technological processes is universal and can be applied in reference to any group of technological processes, and also materials processes.

2. Optimisation (ecological optimisation) - definition and approach

In the literature there are many definitions of optimisation but it is difficult to find a notion of ecological optimisation (ecooptimisation). In the colloquial language the optimisation means the choice of the best, so the optimum possibility [10]. In many professional articles we can find the following definition of the optimisation: "marking using the mathematical methods of the best (the most profitable) solution of the given problem with regard to the chosen criteria" [11]. So the ecooptimisation we can define as: "the search with using the mathematical methods of the best solution of the given problem with regard to the environmental criteria, taking into consideration especially the waste reduction".

According to the above mentioned the optimum process (from the environmental point of view) is the process which characterizes following parameters [11]: low cost of used, small expenditure and accessible investment costs, energy-saving, materials-saving, small waste, using small renewable resources (lack of unrenewable resources exploitation), accessibility and kind of materials, applying materials about high quality, susceptibility to recycling, safety, lesser quantity of operations, easiness of repairs and modernisation, product to needs of market adaptation, agreement with requirements of BREF, etc.

We can optimise the whole technological process, but during the optimisation optimality criterion of function received has to be equal for all subsystems. The optimisation usually encloses the most essential (neuralgic) technological operations that in the direct way influence on the course of technological process.

Generally, optimisation can be divided on [11-13]: single-criterial (when achievement of the optimum state is required in view of one criterion of this state estimation), multicriterial - polyoptimisation (when achievement of the optimum state is required in view of many criteria of this state estimation).

The multicriterial optimisation is the helpful tool in the choice of the technological process about the smallest harmfulness for the environment [12]. The polyoptimisation can be apply when the choice among at least two technological processes is possible, when we expect, that the total influences on the environment are different in relation to intensity [11].

We have to deal with the polyoptimisation in case of the various criteria of the estimation. To evaluation of the environmental influences of technological processes the role of these criteria can fulfill: minimum total added materials consumption, minimum total energy consumption, minimum total quantity of waste, minimum cost of the process applying.

In the multicriterial optimisation the decision task should take into consideration several objective functions. Polyoptimisation depends on the optimum solution finding which is acceptable for every criterion.

Every optimisation task can be characterized by means [10]: decision variables, objective function, restrictive conditions, wharfage conditions.

In the literature there are many multiobjective methods. Among them we can favour [11]:

- Weighted Objectives Method - operation of multicriterial optimisation to single-criterial is the essence of this method.
- Hierarchical Optimisation Method - operation of multicriterial optimisation to optimisation in relation to all criteria is also the essence of this method.
- Trade-Off Method, ε-constraint Method - in this method value levels which can accept individual criteria are established. This leads to the limitation of the admissible solutions space.
- Global Criterion Method - this method searches for the approximate solutions $F(X^*)$. It can be solution making extremum for separately considered individual criteria.
- Distance Function Method and Minimum-Maximum - in these methods, similarly as in Global Criterion Method, in the beginning they search for approximate or optimum solution. In the second phase of the process minimum of the function is counted in a form:

$$\sum_{i=1}^{M}\left[\left(\frac{f_i(X^*)-f_i(X)}{f_i(X^*)}\right)^P\right]^{\frac{1}{P}} \rightarrow MIN \tag{1}$$

where:
$f_i(X^*)$ - optimum solution, $f_i(X)$ - real solution, P - value of superscript (often it is 2).

- Goal Programming Method - in this approach criteria as aims are treated. They are also treated as the liminal values which criteria values cannot cross. On the value of criteria can be put the conditions: larger or equal, smaller or equal, equal.
- Utility Function Method - method which is known form for economic sciences.
- Evolutionary Algorithms.

The last one this is a group of methods which to the techniques of artificial intelligence is classified. They are useful when potential number of solutions can reach the large number (millions or more level). In such case, when search of the optimum solution from the global collection of solutions is necessary, traditional methods characterize too small effectiveness in comparison with evolutionary algorithms [13].

Evolutionary algorithms consist of three main classes: genetic algorithms (GA), evolutionary strategies (ES) and evolutionary programming (EP).

Genetic algorithms are based on biological evolution mechanisms: natural selection and inheritance.

To the basic genetic operators one can classify (Fig. 1) [11]:

- mutation (random change of single individual genotype),
- crossing (generation of one or many descendant individuals whose chromosomes on the basis of parents chromosomes formed).

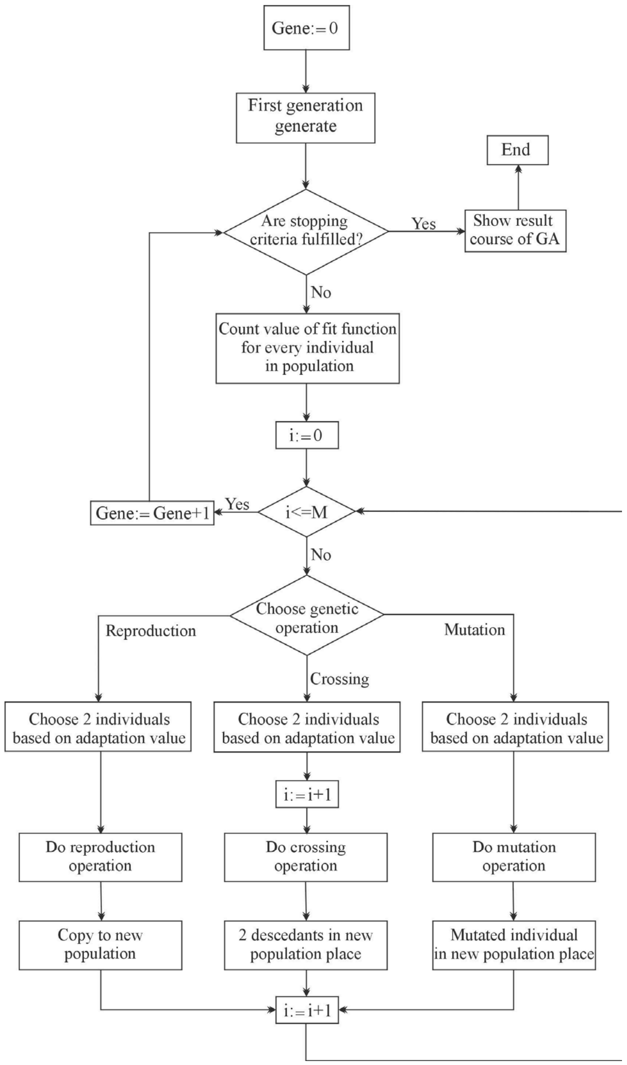

Fig. 1. Schema of the genetic algorithm [14]

In the general frame of usage of the genetic algorithms for real problems solving one can distinguish two main phases [11]:

- initial, depends on specify of problem and adaptation of its nomenclature to GA nomenclature and the preliminary population creation,
- solutions searching, which consists of: individuals estimation, reproduction process and genetic operators.

3. Procedure of the Optimum Materials Technological Process - POMPT

The POMPT procedure defines main conditions that must be realised for the technological processes optimisation effect [11,15]. The main aim of the universal procedure is definition of the objective function. It is very important because from it form depends the correctness of the optimisation carried out. Taking into consideration the criteria of the environmental influences the simplified objective function was defined [15]:

$$f(x)=w_1\cdot\frac{Z_Z}{B_Z}(x)+w_2\cdot\frac{Z_E}{B_E}(x)+w_3\cdot\frac{O}{B_O}(x)+w_4\cdot\frac{K}{B_K}(x) \qquad (2)$$

$$f\rightarrow \min$$

where:
f - objective function,
x - decision variables,
Z_Z - total resources and auxiliary materials consumption in the technological process,
Z_E - total energy consumption in the technological process,
O - total waste quantity in the technological process,
K - total costs of the technological process usage,
B_Z - resources consumption in the process related to BREFs (BAT Reference Documents) requirements,
B_E - energy consumption in the process related to BREFs (BAT Reference Documents) requirements,
B_O - quantity of waste in the process related to BREFs (BAT Reference Documents) requirements,
B_K - costs of the process usage related to BREFs (BAT Reference Documents) requirements,

and w_i - weights such, that:

$$w_i \in [0,1] \qquad \sum_{i=1}^{k} w_i = 1$$

Taking above into consideration the modified POMPT procedure worked out. It consists of 6 stages [15]:

Stage 1- Characteristic of the technological processes subject to the optimisation
Stage 2 - Functional unit definition
Stage 3 - Inventory and database creation
Stage 4 - Reference of data to BREFs requirements
Stage 5 - Optimisation of the materials technological processes
Stage 6 - Verification of the optimum technological process

The main aim of the functional unit in the Stage 2 is the assurance of the solutions comparability. It is very important when different technological processes were subjected to the optimisation.

Inventory and database creation stage contains quantitative and qualitative description of inputs and outputs in the technological process. It is necessary to do the balance of added materials, energy, waste and costs, in this place. The aggregated data - measured directly in the productive places or estimated one should classify in the following categories: added and auxiliary materials input, energy input, process outputs (emissions to air, water, soil), cost of the process usage.

The data collecting process is very labour-consuming. It requires of a good knowledge of every operation in the analysed technological process. During the data collecting it is important to continuous control of data reliability and correctness.

In Stage 4 one should relate the data from analysed technological processes to the BREFs limits for the specific production technology. Because of that the BREFs limits do not take into account the costs of technological processes usage, these costs were accepted conventionally (the average costs of materials, energy, etc. were used in this aim) [15].

To the optimisation of the materials technological processes the Poli-Opt version 1.0 program was used.

3.1. Poli-Opt program

For the materials technological processes optimisation with regard to the accepted environmental criteria (minimum added materials consumption, minimum energy consumption, minimum waste, minimum costs) the Poli-Opt version 1.0 program can be used. This computer program is based on the genetic algorithms (GA) and it is written in C++. It is the basis of the Procedure of the Optimum Materials Technological Process (POMPT procedure).

The first step before starting of the work in the program is the database in Excel (or Access) preparation (in the separate sheets for every optimisation criterion - what is required for correct working of the optimisation program with GA using). It is necessary to save all the data from the analysed processes (resulting from the estimation criteria).

After creation of the computer database and transfer of the ”BazaDanych.xls” file to the Poli-Opt program, the weights of individual estimation criteria were defined.

Weight values for accepted estimation criteria can suitably be modified. The necessary condition for the correct program working is the proper settlement of the weights of the estimation criteria, so that theirs sum was equal 1. This approach is generally accepted in the professional literature. The optimisation with regard to the one established criterion is also possible.

For the optimisation of the technological processes the same weight values were established.

In case of GA the following parameters of the genetic operators were defined: mutation probability - 0.35, crossing - 0.01, generations number - 100, individuals number - 100. For established parameters of the genetic operators the Poli-Opt program finds the optimum solution of the problem the most quickly. These values can be modified, too.

After load the data one can run the genetic algorithm and start the optimisation process. The Poli-Opt software counted modified objective function (f) (3-6) [15].

After calculations end the programme shows window about favourable or unfavourable end of the optimisation process.

In case of the favourable end of the optimisation process the Poli-Opt program displays the optimum solution (optimum technological process) with the data input and the number of generation in which the optimum solution was find.

The Poli-Opt program makes possible the reference of the data input (relating to usage of different added materials, energy, quantity and kinds of waste and costs of usage of particular operations of the optimum technological process) to meeting them the standard requirements. This effect makes possible the isolation of all areas that are subject to modernisation and they are not satisfy the standards - quotient of data from the optimum technological process to meeting them standard data > 1.

The presented computer program to the optimisation of the materials technological processes has an iterative character. During the estimation one should the data proof carry out. This is effective, quick and simple with usage of such Poli-Opt program.

4. Testing of the POMPT procedure

The proposed POMPT procedure is a universal and a simply tool. It can be applied for the estimation and the optimisation of every materials technological process.

For testing of the POMPT procedure 4 realistic zinc plating technological processes were chosen. These processes are very similar (similar average productions, zinc coated details surface, working time, etc.). They consist of the following operations (Fig. 2):

- defatting,
- rinsing,
- pickling,
- fluxing (dry and wet),
- zinc plating.

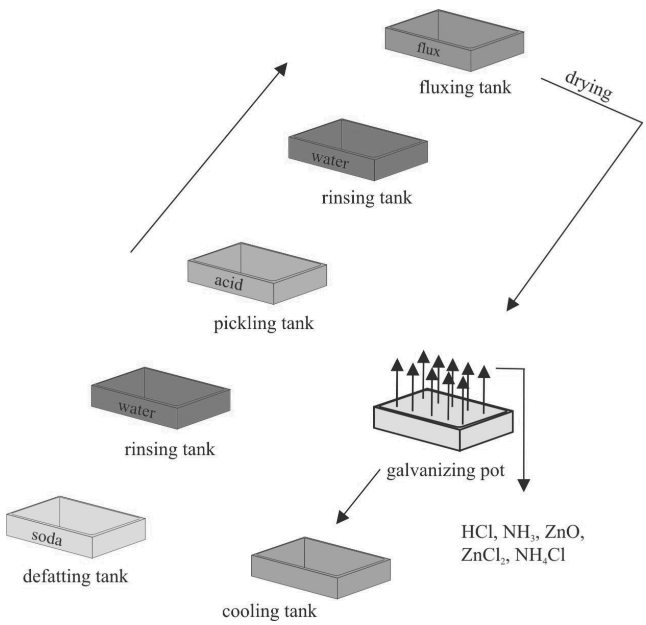

Fig. 2. Schema of the zinc plating technological process [16]

$$w_1^* = \frac{f^*{}_{max}}{f_{1\,max} - f_{1\,min}} \qquad w_2^* = \frac{f^*{}_{max}}{f_{2\,max} - f_{2\,min}} \qquad w_3^* = \frac{f^*{}_{max}}{f_{3\,max} - f_{3\,min}} \qquad w_4^* = \frac{f^*{}_{max}}{f_{4\,max} - f_{4\,min}} \tag{3}$$

$$f^*{}_{max} = \max\left[f_{1\,max} - f_{1\,min}, f_{2\,max} - f_{2\,min}, f_{3\,max} - f_{3\,min}, f_{4\,max} - f_{4\,min}\right] \tag{4}$$

$$f^*(x) = w_1 \cdot w_1^* \cdot [f_{1\,max} - f_1(x)] + w_2 \cdot w_2^* \cdot [f_{2\,max} - f_2(x)] + w_3 \cdot w_3^* \cdot [f_{3\,max} - f_3(x)] + w_4 \cdot w_4^* \cdot [f_{4\,max} - f_4(x)] \tag{5}$$

In case, when: $w_i^* = 0$ $\qquad f_{i\,max} - f_{i\,min} = 0$ (6)

where:
$f^*(x)$ - modified objective function,
x - following technological process,
$f_1(x)$, $f_2(x)$, $f_3(x)$, $f_4(x)$ - objective functions concerning of adequate criteria,
w_1, w_2, w_3, w_4 - weights value reference to the technological processes criteria,
w_1^*, w_2^*, w_3^*, w_4^* - weights value reference to the scaling objective function with regard to accepted criteria.

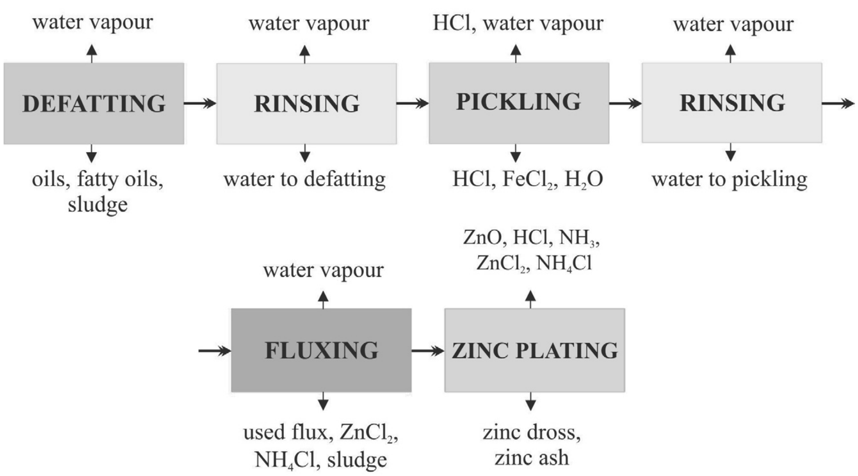

Fig. 3. Schema of the process flow of the zinc plating technological process

The qualification of the functional unit is a very important stage of the procedure. It makes the added materials, energy and waste balance carrying out easy. In this aim the best available techniques (BAT) usage (the concept of BAT was introduced as a key principle in the IPPC Directive - Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control. The best available techniques indicate the way in which the installation is operated. This ensures a high level of the environmental protection as a whole. The BAT take into account the balance between the costs and the environmental benefits. So, they are the basis of cleaner production - CP and ISO 14001 standard. The European IPPC Bureau has prepared reference documents called BREF outline “best available techniques” applicable to the individual industrial sectors) [17].

Considering this, that the limits appointed the BAT usage are referred to the average: raw materials consumption, energy consumption, waste quantities in the count over again for 1 Mg treatment details, we accepted the agreed surface of zinc coated details (the platform grid) equal 4.5 m^2 applying to 1 Mg.

For the estimation formulated the optimum functional unit: „Raw and added materials consumption, energy consumption to the technological process realisation and total raw materials costs, energy costs, quantities of waste in the counted over again on the zinc coated surface equal 64.5 m^2”.

For the facilitation of the collecting data added materials balance, energy balance, waste balance and costs balance of the technological process used, separately for every analysed zinc plating technological process operation carried out (Table 1-4).

The zinc plating technological process is a low waste process. Nevertheless one should pay attention for the areas that large quantity of waste produce (Fig. 3).

In the defatting, pickling and fluxing operations waste are used operation tanks subject to regeneration, neutralization and disposal. In case of zinc plating operation waste in the form of zinc dross and zinc ash are directed to zinc metallurgy in the aim of further processing.

An interesting element of the materials technological processes optimisation carried out is the database in Excel creation.

According to the POMPT procedure, the inventory table for every criterion separately created. In every line compared the data concerning: added materials consumption (Table 1), waste quantities (Table 2), energy consumption (Table 3) and costs (Table 4) for the following operations of 4 analysed zinc plating technological processes.

The last, fifth line of the computer database concerns of limits: raw materials consumption, energy consumption, waste quantities for every zinc plating technological processes operations which are defined for the zinc plating in BAT Reference Documents (unity zinc plating). For the best optimisation effects obtaining the reference to the average limits values proposed by BREFs are recommended.

These tables created (in agreement with the Poli-Opt program requirements) in the Excel under the name "DataBase.xls".

After the computer database creation the optimisation process with the Poli-Opt version 1.0 usage started.

For the same weights values (raw materials used: 0.25, waste: 0.25, energy: 0.25, costs: 0.25) of the environmental criteria, default parameters of the genetic operators (mutation probability - 0.35, crossing - 0.01, generations number - 100, individuals number - 100) the optimum solution was the zinc plating technological process 4.

Table 1.
Raw and added materials used [g/Mg]

No. of the process	water - defatting	water - rinsing I	water - pickling	water - rinsing II	water - fluxing	defatting medium	HCl acid	inhibitor	flux	zinc	zinc ash
1	35800	0	34200	38250	22400	830	4130	60	33480	32630	7252
2	48010	36740	14830	36740	8600	2982	2570	64	5850	32630	0
3	31630	0	30250	40150	19970	571	4440	53	31356	32630	7252
4	21994	22410	12790	22410	960	1076	2095	28	24254	32630	7252
5	12000	15000	17500	15000	10000	2000	9200	100	2500	73400	7500

Table 2.
Waste quantity [g/Mg]

No. of the process	defatting - sewage and sludge	defatting - oiled sludge	washings I	pickling - sewage and sludge	washings II	fluxing - sewage and sludge
1	10130	1000	0	23900	34500	39780
2	28880	1000	28900	9600	28900	14400
3	9240	1000	0	20810	31200	35980
4	7500	1000	15000	7501	15000	52590
5	2700	160	15000	25000	15000	10000

Table 3.
Energy consumption [kWh/Mg]

No. of the process	defatting	pickling	fluxing	zinc plating
1	11.860	2.980	17.680	330.450
2	9.136	0	0	221.460
3	10.139	2.763	15.580	315.605
4	7.240	0	0	154.340
5	22.300	12.500	0	180.000

Table 4.
Costs [PLN/Mg]

No. of the process	defatting	rinsing I	pickling	rinsing II	fluxing	zinc plating
1	6.60	0	14.25	1.53	141.35	244.55
2	19.70	1.40	6.38	1.40	24.74	219.08
3	5.35	0	13.32	1.49	139.21	240.45
4	4.79	0.74	4.42	0.74	98.96	184.00
5	18.60	0.66	11.07	0.66	15.00	390.56

The optimum zinc plating technological process did not realise all requirements of BREFs for zinc plating. Because of that several areas separated that should be subject to the modernisation. The minimisation should be subject: water consumption in defatting operation, water consumption in the rinsing I operation (after defatting operation), water consumption in the rinsing II operation (after the pickling operation), flux used, sewage and sludge quantity in the defatting operation, sewage and sludge quantity in the fluxing operation, costs of the rinsing I and II operations, costs of the fluxing operation.

After consideration of all the areas above, several modernisations of the optimum technological process proposed. For every selected area at least 2 modernisations were proposed (in the modernisations were not considered: costs of devices purchase and costs of exploitation considering their ecological and economic advantages in application).

From a large group of possible solutions chosen these, which characterized simplicity and low realisation costs.

In the aim of the optimum zinc plating technological process improvement were finally proposed:

- defatting using micro- and ultrafiltration along side with a tank cover,
- cascade rinsing (with ionic exchange) for the rinsing I and II operations,
- rinsing optimisation and the deiron washings cleaning for the fluxing operation.

The proposed improvements made possible a decrease, to the expected level, the quantity of waste in the defatting and fluxing operations and decrease of water consumption in the rinsing I and II operations and reduction of the flux consumption, also (Fig. 4).

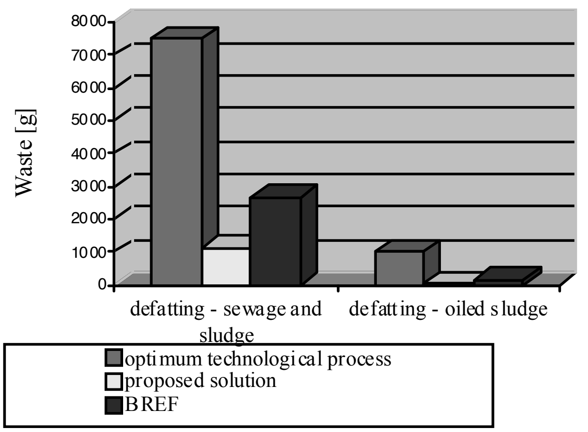

Fig. 4. Statement of waste in the defatting operation

5. Conclusions

The problem of decision making (management) in the companies usually relates to the technological processes (materials technological processes).

For increasing quantity of possible technical solutions, the optimisation methods should have more and more meaning in the materials engineering.

However, practically there is no possibility of determination of absolutely the best technology or technological process. One can only design the better process in comparison with another because of received criteria. So the proposal of the multicriterial optimisation and usage of the genetic algorithms. The GA have a particular use accomplishing the select of the best technological process in respect of the environmental criteria (e.g. raw and added materials used, waste quantity and also costs of technological process, etc.).

The proposed POMPT procedure of technically, ecologically and economically optimum materials technological process is the effective and relatively simple tool making possible analysis and estimation of the technological processes. It is mainly useful for the optimisation of a group of technological processes in the direction of improvement of the negative environmental influences.

This procedure is not the closed solution but it is the object which should be subject to further testing and improvements in the range of usage of the optimisation methodology and information technique [18].

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