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Optimization of Nonlinear Transport-Production Task of Medical Waste

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Abstract

The paper reflects on optimization of transportation - production tasks for the processing of medical waste. For the existing network of collection points and processing plants, according to its algorithm, the optimal allocation of tasks to the cost of transport to the respective plants has to be determined. It was assumed that the functions determining the processing costs are polynomials of the second degree. To solve the problem, a program written in MatLab environment equalization algorithm based on a marginal cost JCC was used.

1. Introduction

The fundamental definitions of logistics have evolved considerably in recent years. From the point of view of the tasks of logistics it is worthwhile to defer to the definitions contained in The Council Supply Chain Management Professionals (CSCMP) Glossary of Terms, which slightly differ from some European definitions (e.g. ELA). The following description of the objects of logistics and of logistics management demonstrates this quite clearly. By CSCMP: *objects of logistics* are physical goods such as raw materials, preliminary products, unfinished and finished goods, packages, parcels, and containers or waste and discarded goods. *Logistics management* is the part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and

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related information between the point of origin and the point of consumption in order to meet customers' requirements.

According to the European Logistics Association- ELA (2005): *Logistics* – it is the management of processes of goods and/or persons transfer together with activities supporting these processes in systems in which they occur. Systems, in which these processes (of goods and/or persons transfer) appear to be both economic systems – whose activity is profit oriented (industrial enterprises or commercial companies together with the delivery/supply chains) – as well as the non-profit systems (the public medical service, the public education, municipal systems, environment or surrounding systems).

Logistics is an area of business which aims at the optimization of processing of goods, information and capital flows in the logistics chain (from raw materials to the final product and its use). The whole logistics chain can be broken into separate, elementary links, which are codependent with close environment [10] and stay in "peculiar" relations with the superior system [9, 10]. Recently, a lot of business decisions and industrial processes have been influenced by sustainable development principles. This is partly related to an enhancement in environmental protection, which includes a more cautious approach towards non-renewable raw materials. Humankind has been shaping the environment to maximize its own profits for a long time. Actions undertaken by humans have often had destructive, irreversible consequences on the ecosystem. Fortunately, people have become more aware of the fact that the environment cannot exercise a limitless stabilizing function to their actions and therefore they have created a series of ecological norms and strategies. Nowadays, the principle behind business decisions is to achieve harmonious economical development without having a destructive influence on the ecosystem [7].

Legal regulations constitute frameworks for all business operations. Companies, on all levels of their development, have to obey the rules of the local market in which they are established. An ecological policy program should be embedded in a company's strategy. Constant development that takes into consideration ecological aims is not a burden to economical growth on a micro or macro scale. Recognizing the importance of the problem of industrial and consumer waste's destructive impact, a number of countries created a series of legal acts which are designed to lead to a reduction of the negative influence of human actions on the ecosystem. The ordinances and acts on environmental protection and waste management are considered to be one of the most voluminous and complicated legal segments of international, European and internal laws of many countries. The most important European Union legal regulations on environmental protections are [17]:

General regulations on waste

– Council Directive of 15 July 1975 on waste (75/442/EEC) which defines waste as any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of the national law in force. This act excludes some kinds of waste such as: radioactive waste, waste waters or agricultural waste.

Some of the regulations of the 75/442/EEC Directive have been changed by the following acts: 91/156/EEC of 18 March 1991; 91/692/EEC of 23 December 1991; 96/350/EC of 24 May 1996 and 96/59/EC of 16 September 1996,
– Council Directive of 12 December 1991 (91/689/EEC) on hazardous waste.

Directives on utilization, disposal and transportation of waste
– Directive 2000/76/EC of 4 December 2000 on the incineration of waste,
– Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste,
– Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control,
– Council Directive 75/439/EEC on the disposal of waste oils,
– Council Directive 78/176/EEC on waste from the titanium dioxide industry,
– Council Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture,
– Council Directive 91/157/EEC on batteries and accumulators containing certain dangerous substances,
– Council Directive 96/59/EC on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT),
– Directive 2000/53/EC on end-of life vehicles,
– Directive 2000/59/EC on port reception facilities for ship-generated waste and cargo residues,
– Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment,
– European Parliament and Council Directive 94/62/EC on packaging and packaging waste,
– Council Regulation (EEC) No 259/93 on the supervision and control of shipments of waste within, into and out of the European Community.

2. Logistic Problems of Medical Wastes

Medical waste, also known as clinical waste, normally refers to waste products that cannot be considered general waste, produced from healthcare premises, such as hospitals, clinics, doctors offices, veterinary hospitals and labs. In Europe, wastes are defined by the European Waste Catalogue (EWC) Codes. EWC Codes are 6 digits long, with the first two digits defining the over-arching category of waste, the next two defining the sub-category, and the last two defining the precise waste stream. Clinical waste comes under the ”18” codes, for example: ”18 01 01” corresponds to healthcare waste (18), from humans (01), that is sharp and not infectious (01). It has many waste things thrown (01).

Examples of hazardous waste (no. *):
18 01 02* body parts and organs including blood bags,

18 01 03* wastes that contain live pathogens or their toxins,

18 01 10* dental amalgam waste.

According to Pfohl [11], the reverse logistics is a system which allows economically and environmentally effective flow of residues with simultaneous spatial and time transformation, including variations of quantity and quality. The basic economic aim of waste logistics is achieved by reducing logistics cost and improving service levels [8] (mainly by proper collection of residues in generation places, and by proper supply of secondary raw materials to the point of their reuse). The environmental aims involve the protection of natural resources and minimisation of secondary pollution resulting from the disposal processes [15]. The Ordination of the Minister of Environment (2001), on waste catalogue classifies the waste depending on generation source, into 20 groups. Group 18 includes medical and veterinary waste, which is the subject of the method presented herein.

As of the status in 2010, in Poland, 137 million Mg waste was generated altogether, out of which 125 mil. Mg of industrial waste and 12 mil. Mg of municipal waste. It is estimated (the data changes quite dynamically, but it is not the subject of this study) that ca. 86.6% municipal waste in Poland goes to landfills, above 10% is selectively collected and segregated, and only 3.2% biologically and thermally disposed. To compare, in the EU states (2008) for ca. 260 mil. Mg municipal waste, only 48% goes to landfills, and ca. 20% is incinerated. The share of incinerated waste varies significantly. For example, the largest waste amounts are incinerated in Denmark (54%), Sweden (45%), but only 7% in Spain, 9% in Finland, 10% Austria.

Waste disposal by incineration is a technology which raises controversy. Nevertheless, this technology is not given enough attention in Poland, and the only important waste incineration plant in Warsaw has the capacity of some 40 000 Mg per annum, whereas the capacities suggested by experts for large cities range from 150 000 to 250 000 Mg of waste incinerated per annum. In Poland, incineration plants are designed to be built in Łódź (250 000 Mg), Krakow (250 000 Mg), but the example of Krakow shows how long the way from plan to completion is. The problem of incineration plant is very important for waste from group 18, i.e. medical and veterinary waste. Considerable part of it are hazardous waste, yet, since they are low percent of total waste, small, local incinerators suffice for their disposal. According to the information of the Ministry of Environmental Protection, there are about 50 such incinerators in Poland (as of November 2007). The capacities of such incinerators are on average from 0.1 to 0.3 Mg/h. Also alternative methods can be applied for disposal of medical waste. Those are mostly: autoclaving, thermal sterilisation, microwave-assisted sterilisation, steam sterilisation. There have been discussions, for years, in Poland over the profitability of alternative methods (regarded by many as cheaper than incineration), as well as over the legal possibility to approve such methods for use by hospitals or private entities interested in waste disposal business. An important problem related to medical waste disposal is also properly organised transport, which requires, among others, specialised solutions.

According to World Health Organization, Healthcare waste (HCW) is defined as the total waste stream from a healthcare facility (HCF) like by-products of healthcare that includes sharps, non-sharps, blood, body parts, chemicals, pharmaceuticals, medical devices and radioactive materials. Improper management of HCW results in infections, injuries or health hazards for healthcare workers, waste handlers and the community. In United States of America alone, the hospitals generate approximately 6 600 tons of waste in a day. Operating rooms and labor-and-delivery suites make up 70% of total hospital waste. As much as 70-75% of that is non-hazardous solid waste, such as paper, cardboard, food waste, metal, glass, and plastics. An integrated waste reduction and recycling strategy will help to manage the waste stream better [18].

Effective and efficient healthcare waste management is required to reduce the amount of hazardous and infectious wastes produced in the hospitals. Effective healthcare waste management not only helps the community and people, but also helps the hospitals and can bring in financial benefits along with health and environmental benefits. Some of the benefits are mentioned below:

- effective segregation keeps ordinary glass, plastic and paper away from infectious materials, allowing them to be recycled,
- by separating municipal and genuinely infectious waste, hospitals minimize the amount of waste that requires the most expensive forms of treatment,
- most of the infectious waste is incinerated and this pollutes the environment. Hence the segregation of wastes reduces the hospital's environmental footprint.

The various steps involved in the healthcare waste management are:

- generation of hazardous or infectious waste,
- segregation,
- temporary storage,
- transport,
- treatment,
- reuse/recycling,
- recovery,
- final disposal.

To solve the issues taking into consideration complex structure of the transport system and disposal of transported material in specific points, various methods used in logistics systems are used [16, 4], together with methods known from operational tests [2, 14, 3].

One of the best known is called TPT the task of transportation – production of non-linear (eg. quadratic) cost function.

3. Model of a Transport and Production Task (TPT)

Quite often the relationships existing within analyzed economic processes (manufacturing and processing) are non-linear. A decision task may be defined as non-linear, if a target function or at least one of limiting conditions is a non-linear function (i.e. square, exponential or logarithmic). Ecological factor is dominating within the waste processing techniques, however, both technical and economic aspects are equally more and more often important (processing taken as cost, transportation taken as cost, waste collection logistics).

Therefore, a decision task presented below:

$$f(x) \to \max, \tag{1}$$

$$f(x) \to \min, \tag{1'}$$

$$g_i(x) \geq 0 \quad (i = 1, ..., m), \tag{2}$$

or

$$g_i(x) \geq 0 \quad (i = 1, ..., m), \tag{2'}$$

$$g_i(x) = 0 \quad (i = m + 1, ..., r), \tag{3}$$

$$g_i(x) = 0 \quad (i = m + 1, ..., r), \tag{3'}$$

is defined as a non-linear programming (NP) task, if the target function $f(x)$ or at least one of the limiting conditions $g_i(x)$ is a non-linear function, while $x = (x_1, \ldots, x_n)$ denotes n-dimensional vector of decision variables.

Two types of functions are of fundamental importance in non-linear programming: convex function and concave function [1], [5]. Two basic types of non-linear programming task can be distinguished:

1. convex programming tasks (CP),
2. non-convex programming tasks (NCP).

The convex programming task is defined as a non-linear programming task, where:

– target convex function is minimized or target concave function is maximized,
– set of acceptable solutions is convex.

Among convex programming tasks, square programming tasks are of a particular importance. Square programming task is defined as CP task, where:

– target function is a square function,
– all $g_i(x)$ functions are linear.

A general case of non-linear task is described below:

– a company processes homogenous raw material (waste); and has m purchasing (collection) facilities of raw material as well as n plants processing this raw material (waste),
– unit transportation cost is known from each of the collection facilities to various processing plants,
– quantity of raw materials (waste) collected at each purchasing point (collection site) is known.

The function describing waste processing cost at each plant depending on processing yield has to be determined. It was assumed that the functions determining processing costs are the second degree polynomials. They take into consideration only variable costs, dependent on production volume. It was also assumed that the total volume of purchased raw material (wastes) will be transported to plants and processed by those plants. Further on, it was also assumed that these manufacturing plants are capable of processing all delivered material (due to two or three shift operation system).

In the operational tests, so called transport and production task TPT refers to optimisation of total transport and processing cost of homogeneous raw materials supplied to factories which process them into finished products [1, 13].

In the TPT task the values of x_{ij} andx_j, variables are sought, in order to:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} + \sum_{j=1}^{n} f_j(x_j) \longrightarrow \min, \tag{4}$$

for limiting conditions:

$$\sum_{j=1}^{n} x_{ij} = a_i, (i = 1, \ldots, m,) \tag{5}$$

$$\sum_{i=1}^{m} x_{ij} = x_j, (j = 1, \ldots, n), \tag{6}$$

$$x_{ij}, x_j \geq 0, (i = 1, \ldots, m; j = 1, \ldots, n). \tag{7}$$

The function of purpose (4) minimises the total waste transport and processing cost. Condition (5) means that every supplier delivers the entire waste resource they have. Meeting the condition (6) means that a j^{th} plant will process all waste delivered.

Figure 1 shows a diagram of the waste logistics structure of the TPT task being considered in relation to medical waste.

Symbols assumed in the model:

- i – number of the waste collection point (supplier id);
- j – number of the processing plant e.g. incinerator (receiver id);
- x_{ij} – waste quantity delivered from an i^{th} supplier to a j^{th} receiver;
- x_j – quantity of waste processed by the j^{th} receiver;
- a_i – quantity of waste accumulated by the i^{th} supplier;
- c_{ij} – unit cost of waste transport from the i^{th} supplier to the j^{th} receiver;
- c_j – minimum unit cost of waste processing in a j^{th} plant;
- e_j – speed (rate) of unit increase of waste processing cost;
- $f_j(x_j)$ – cost of x_j waste processing in the j^{th} plant;

It was assumed that that the $f_j(x_j)$ waste processing cost function is described with a polynomial of the second degree in a form:

$$f_j(x_j) = c_j x_j + e_j x_j 2, \text{ where } c_j, e_j > 0 \tag{8}$$

The first derivative of that function determines the marginal cost of processing:

$$f_j`(x_j) = c_j + 2\ e_j x_j, \tag{9}$$

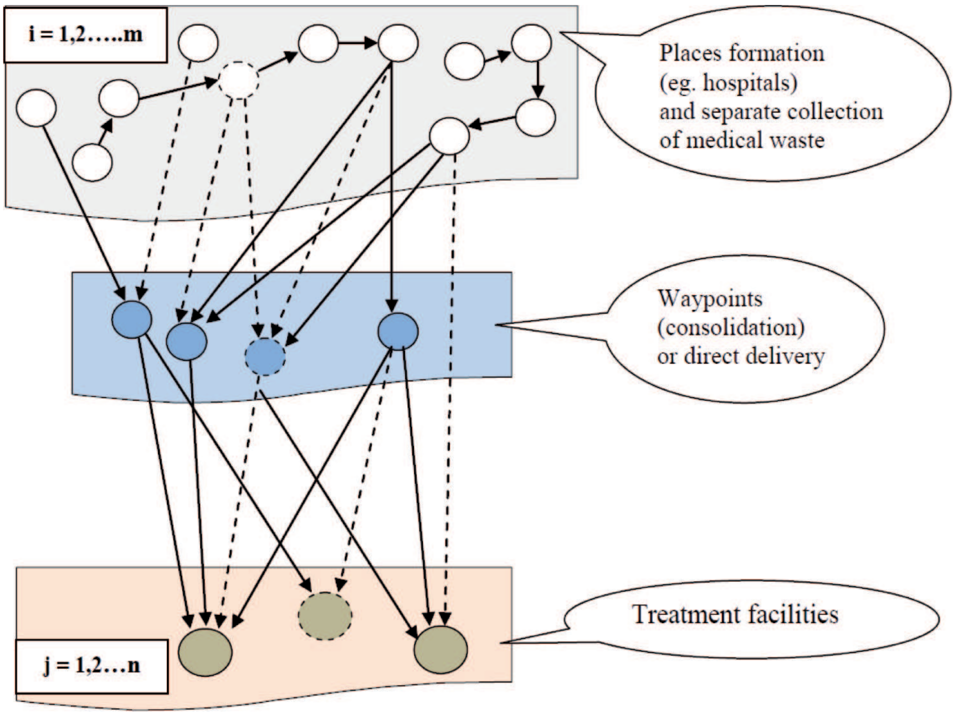

Fig. 1. TPT system structure diagram

whereas the second derivative determines the rate of marginal cost increase:

$$f_j''(x_j) = 2\, e_j \tag{10}$$

Average cost of processing in the j^{th} plant is determined with the correlation:

$$K_j^p(x_j) = c_j + e_j x_j, \tag{11}$$

The TPT task (4) – (6) is a square programming task of special "transport-related" structure. It can be solved by using the algorithm for equalising marginal cost.

Marginal cost is the cost incurred to the producer due to increasing the production amount by one unit. In the case studied, it is the cost of processing an additional unit of waste. According to the economy theory, the marginal cost may not be negative. This means that increasing the production may not induce the reduction of total cost.

The method of marginal cost equalisation MCE is used to solve square programming tasks of the following structure:

$$F(X) = \sum_{i=1}^{m}\sum_{j=1}^{n} d_{ij}x_{ij} + \sum_{j=1}^{n} e_j\left(\sum_{i=1}^{m} x_{ij}\right)^2 \longrightarrow \min, \tag{12}$$

The TPT task can be brought to that task, with a square cost function assuming that:

$$d_{ij} = c_{ij} + c_j. \tag{13}$$

Partial derivatives of the function F(X) ($X=[x_{ij}]$) of the TPT task determine the marginal cost for individual routes. If the marginal transport and processing cost of waste from the i^{th} supplier, and processed in x_j quantity in the j^{th} plant, is marked as $k_{ij}(x_j)$, then:

$$k_{ij}(x_j) = F'(x_{ij}) = d_{ij} + 2e_j \sum_{i=1}^{m} x_{ij} = c_{ij} + c_j + 2e_j x_j. \tag{14}$$

Consequently, the cost $k_{ij}(x_j)$ is marginal for the route <*i, j*>.

The marginal cost equalisation method consists in:

- determining the best possible, allowable starting solution,
- improving the following solutions X^1, X^2, ..., by shifts equalising the marginal cost.

A sequence of the following solutions X^1, X^2, ..., X^r, ..., achieved in the MCE method needs to be finite. It is however important that the final solution does not differ too much (in a sense of the value of the function of purpose) from the optimum solution, meaning that X^r is the exact ε solution.

4. Exemplification

Supplies of medical waste and its incineration (group 18) was the subject of examination in Podkarpackie Province (ca. 2 000 Mg/year). The basic source of waste is 60 hospital (large, small) and many surgeries (not included in the calculations). In Podkarpackie region, there are 2 medical and veterinary waste (group 18) incinerators:

ECO-TOP Rzeszów – capacity: 0.29 Mg/h,
RAF- Ekologia Jedlicze – capacity: 1.13 Mg/h,
and 3 small medical waste disposal plants.

The calculations include properly grouped hospitals (depending on the location as per the diagram Fig. 1):

Rzeszów (D1 – 5 hospitals),
Dębica (D2 – 1 hospital),
Jasło (D3 – 2 hospitals),
Krosno (D4 – 5 hospitals),
Sanok (D5 – 1 hospital),
Przemyśl (D6 – 3 hospitals)
– total: 6 suppliers and 17 hospitals.

The task was formulated as follows:

6 suppliers:
D1, D2, D3, . . . , D6 supplies medical waste to 2 incinerators:
S1, S2, with the limitations:
S1 (Rzeszów): may accept and process 700 Mg or 1 000 Mg of waste,
S2 (Jedlicze): may accept and process 1 500 Mg of waste.

The data is compiled in Table 1 and includes:
– unit cost of transport (PLN per Mgkm),
– delivered quantities per year A_i (Mg),
– incineration demand per year B_j (Mg).

Table 1

Unit cost of transportation, supply and demand

Suppliers	**Supply A_i** [Mg]	**Incinerators** variant v1 **S1 (RZ)**	variant v1 **S2 (JE)**	variant v2 **S1 (RZ)**	variant v2 **S2 (JE)**
D1 (Rzeszów)	**500**	5	60	5	60
D2 (Dębica)	**80**	40	60	40	60
D3 (Jasło)	**200**	70	15	70	15
D4 (Krosno)	**400**	70	5	70	5
D5 (Sanok)	**120**	100	50	100	50
D6 (Przemyśl)	**300**	80	100	80	100
Demand B_j [Mg]	**1 600**	**700**	**1 500**	**1 000**	**1 500**

The task is solved with a PC program developed with MatLab software, for MCE, with a GUI graphic interface [6, 12]. After all required data is introduced, the user is notified of correct task solution (Fig. 2). The y-axis gives accurate solutions (in %), and the x-axis the number of iterations (max = 5). As the number of iteration increases, the solution approaches to an optimal solution. The best solution was obtained for iteration No. 5, where the solution is different from an optimal solution by only 1% (e = 0.01).

Two variants of the task are presented in the paper:
– v1 variant, in which the task was reduced to 6 suppliers (waste consolidation points) and 2 receivers (incinerators in Rzeszów: process capacity 700 Mg/y and Jedlicze: 1 500 Mg/y),
– v2 variant, with amended the efficiency of the process (incinerators in Rzeszów: process capacity 1 000 Mg/y and Jedlicze: 1 500 Mg/y) and transportation costs.

For the v1 variant, the following demand was assumed from Table 1:
for S1 incinerator – 700 Mg/year, and for S2 incinerator – 1 500 Mg/year (estimated total amount of medical waste in Podkarpackie is between 1 900 and 2 000 Mg/year).

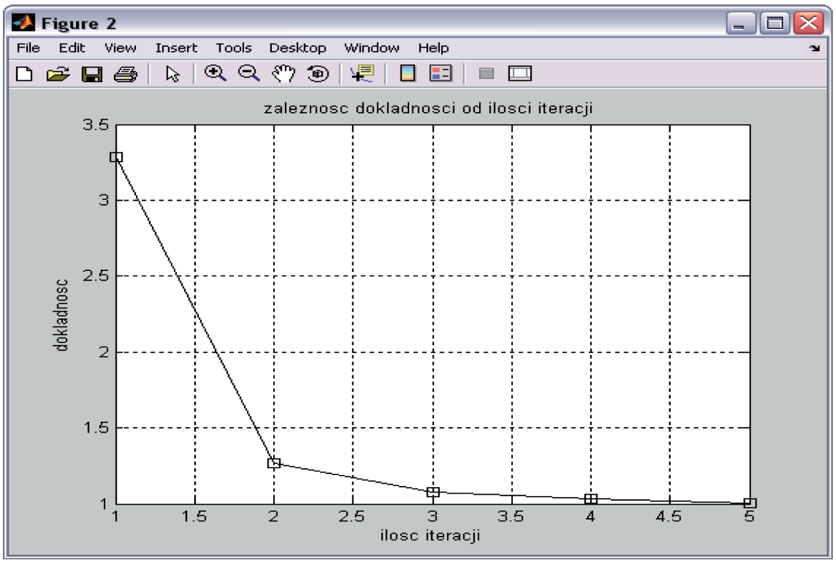

Fig. 2. MCE program – the dependence of accuracy on the number of iterations

Furthermore, based on the studies, it was assumed that the processing functions take the forms:

$$f_1(x_1) = 15\,x_1 + 0.2x_1^2$$

$$f_2(x_2) = 15\,x_2 + 0.1\;x_2^2.$$

Results of calculations for variant 1 is shown in Fig. 3.

For the v2 variant, the demand was assumed as follows:

for S1 incinerator – 1 000 Mg/year, for S2 – 1 500 Mg/year.

The processing functions take the forms:

$$f_1(x_1) = 10\,x_1 + 0.2\;x_1^2$$

$$f_2(x_2) = 10\,x_2 + 0.1\;x_2^2.$$

Results of calculations for the v2 variant are shown in Fig. 4.

If the optimum or ε exact solution is involved, the result is the table showing the following information:

– throughput in individual plants,
– total waste transport and processing cost,
– cost of waste transport,
– cost of waste processing,
– average cost,
– marginal cost,
– waste distribution method.

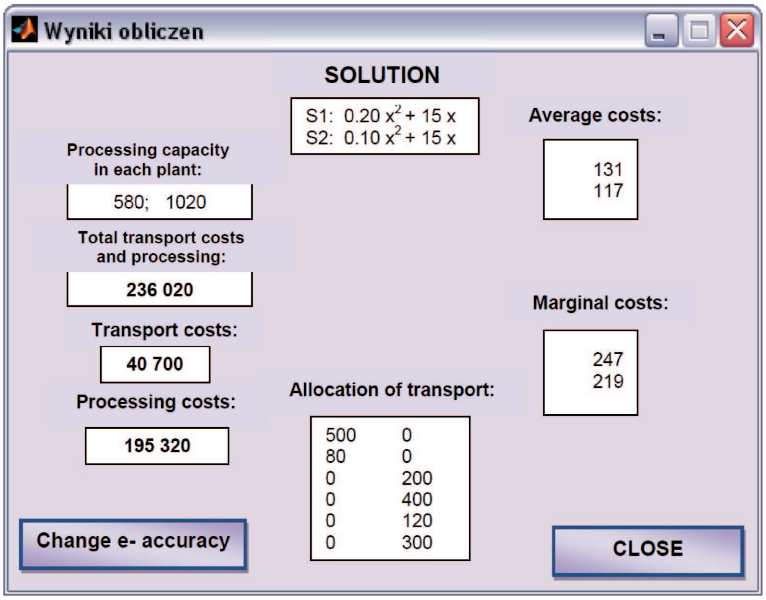

Fig. 3. Results of calculations in the MCE program for the v1 variant

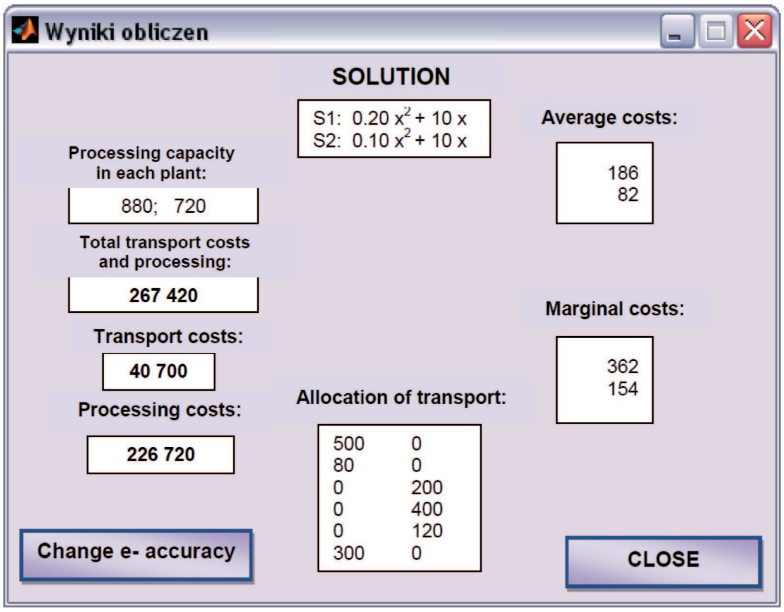

Fig. 4. Results of calculations in the MCE program for the v2 variant

Summary of the results is given in Table 2. It shows sample results of simulations carried out for several variants, in which processing function parameters, transport cost, possibilities of processing in individual plants and consolidation conditions were changed. The summary contains the best results.

According to the summary, the total cost of the task, for the v1 task, is PLN 267 420, and are more than PLN 40 000 greater than the costs of option v2.

The results are also the basis for discussion on the priority as to deliver the waste to the nearest disposal place, as laid down in the provisions of waste laws. Assuming that the system of local incineration plants meets stringent requirements of the EU, it is a proper solution, however, an alternative solution based on a large incineration plant, which performs also other tasks, can be more economically viable.

Table 2

Summary of results for the TPT task

Suppliers	Incinerators				
	variant v1			variant v2	
	S1 (RZ)	**S2 (JE)**	**supply** A_i [Mg]	**S1 (RZ)**	**S2 (JE)**
D1 (Rzeszów)	500	0	**500**	500	0
D2 (Dębica)	80	0	**80**	80	0
D3 (Jasło)	0	200	**200**	0	200
D4 (Krosno)	0	400	**400**	0	400
D5 (Sanok)	0	120	**120**	0	120
D6 (Przemyśl)	0	300	**300**	300	0
demand B_j [Mg]	**700**	**1 500**	**1 600**	**1 000**	**1 500**
prosessing [Mg]	**580**	**1 020**		**880**	**720**
inventory [Mg]	**120**	**480**		**120**	**780**
transport costs [PLN]	**40 700**			**40 700**	
processing costs [PLN]	**226 720**			**195 320**	
total transport costs and processing [PLN]	**267 420**			**236 020**	
average costs [PLN/Mg]	**186**	**82**		**131**	**117**
marginal costs [PLN/Mg]	**362**	**154**		**247**	**219**

According to the studies, it was also found that an efficient use of funds spent on waste management is possible only by systemic logistics solutions (proper collection and storage system), which will be effective in terms of technology and information and, at the same time, optimum in terms of financial spending. The approach proposed in this paper, based on the transport and production task with the square function of cost should enhance decision making in the waste management processes.

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