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MULTICRITERIA OPTIMIZATION MODEL FOR END-OF-LIFE VEHICLES' RECYCLING NETWORK

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ABSTRACT

A growing ecological awareness in modern societies, legal regulations aiming at a reduction of waste storage and economic benefits that we can have from recycling of used products led to a situation that the creation of recycling networks has become an important issue, particularly in developed countries. The paper presents issues related to the design of recycling network whose purpose is to collect from the last owner, dismantle, and properly recover end-of-life vehicles.

Creating recycling network has become an indispensable element that accompanies the development of the automotive industry. Its functioning is within the realm of interest of a variety of government agendas, companies participating in the network, vehicle manufacturers, and vehicle end-users. The interests of these groups need to be considered when deciding about the network organization. Very often, these interests are divergent and it is extremely difficult to take into account the preferences of all the interested parties. In such a case, making right decisions is aided by multicriteria decision support tools. The proposed decision support tools consist in formulating a research problem in the mathematical language in the form of an optimization task related to the determining of a recycling network entity location. The selection of the optimum locations of the individual recycling network entities will depend on the preferences of the decision-maker and the resources at the decision-maker's disposal as well as the conditions that the network must meet.

The paper presents a bi-criteria model of network entity location that takes into account the preferences of the vehicle owners and network participants. A mathematical formulation of the optimization task has been presented, including the objective functions and limitations that the solutions have to comply with. Then, the model was used for the network optimization in Poland.

Keywords: decision support system, end-of-life vehicles, location modeling, optimization, recycling network.

1 INTRODUCTION

The automotive industry has long been a key sector of the world economy. Vehicles have become indispensable in everyday life and are a symbol of modern times. A dynamic advancement of automotive industry also results in negative consequences for humans and their natural environment. One of these consequences is the waste generated by the vehicle in the phase of production, operation, and disposal. A way to reduce this negative effect is recycling, that is, economic use of waste except energy recovery.

The introduction of the principle of sustainable development in the developed countries, including European Union, has led to the adoption of legal regulations that force the EU member states to guarantee the recycling of end-of-life vehicles (ELV).

A condition for the realization of an ELVs recycling is creating a network for collection and treatment of vehicles otherwise known as ELVs recycling network. Initially, the actions related to the formation of a recycling network did not result from the ecological needs. The reason for the first recycling networks was the economical benefits that could be derived from vehicle waste recovery. The characteristic feature of recycling networks formed for economical reasons was a spontaneous and uneven development. As time passed, together with social development, more attention was paid to the negative impact of the ELVs on the environment – accumulation of waste on the disposal sites, leakage of hazardous substances leading to ground water contamination, and wastage of natural resources that could otherwise be recovered.

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The current reasons for the creation or modification of recycling networks are a result of the following: needs related to the disposal of ELVs, including, in particular the size of the flows of the waste material and materials coming from the vehicles, applicable legal regulations in waste management (particularly those related to ELVs) and the economic analysis of the entities participating in the network.

2 LITERATURE SURVEY

The optimization of the location of a network entity in traditional logistics has received a lot of attention for many years and the reverse logistics has been a subject of investigations for a relatively short period of time. Because it is gaining in popularity, many papers have been written treating on the entities participating in the reverse logistics. The range of the investigations covers the area of municipal waste, hazardous waste, packaging, electrical and electronic equipment, and waste paper or general end-of-life products. It is relatively seldom, judging from the scale of the problem, that the issue of optimization of location of ELV recycling network is treated in the literature. In relevant literature, we can find only a few examples of research studies devoted to the design of vehicle-recycling network. The main assumptions of these works have been presented below.

Mansour and Zarei [1] have set a goal to identify the sources of costs related to the obligation imposed by the EU regulations and developed a model that included the optimization of the ELV reverse logistics showing the number, location and throughput of the return stations, dismantlers, and the flow statistics among the entities. What makes this model different is that the modeling of the process and the recovery is done for more than one period, while most of the models described in the literature assume a single stage end-of-life product processing. The use of the multi-period model allowed incorporating the differences in the ELVs supply between the periods and included the storage costs. As a criterion of optimization, the authors adopted the minimization of costs of logistics for the vehicle manufacturers and the minimization of the material flow among the entities.

The model of optimization of the location of the entities of ELV recycling network in Mexico has been presented in the work by Cruz-Rivera and Ertel [2]. In this model, it has been assumed that the return stations are also dismantlers, that is, the structure of the network has been simplified. Yet, the scenarios of return station locations were shown for the return of 75%, 90%, and 100% of the ELVs on a given area. The basic feature that distinguishes this model is that the locations of the regional distribution centers are not selected from among the initially set potential locations but are indicated by the model.

A monocriterion model for the modification of a recycling network in a selected area has been described in work by Merkisz-Guranowska [3]. In this model, a criterion function has been used based on the minimization of overall costs of the network functioning that cover the costs of entity operation and the costs of ELV transport and the transport of the waste that comes from these vehicles. The characteristic feature of the presented model is that not only the return stations and dismantlers but also the industrial shredders are subjected to the optimization.

The above-presented works are focused on designing of a separate network for the reverse logistics. Because of the differences in the new and end-of-life streams of products, rarely is it proposed to connect the reverse logistics with the new vehicle distribution network. The model designed for locating of the new vehicle distribution network entities joined with the ELV recycling network has been presented in the work of Zarei et al. [4]. In this case, the optimization is based on simultaneous minimization of costs of forward logistics and reverse logistics and both of the logistic systems are a unity. The objective function minimizes the costs of developing joint distribution and return entities, the costs of developing the dismantlers and the costs of transport of ELVs and materials.

The proposed model assumes that an ELV recycling network organization that meets the assumptions of the ELV directive, that is, takes the specificity of the European member states into account.

Also Schultmann et al. [5] in network optimization, set a goal to integrate reverse logistic with a traditional logistics network. The main stress in the design of the network was put on the possibility of including the flows from the reverse logistics network to the original production and distribution network. The effect was presenting of the model of location/allocation covering at the same time the selection of the entities location and the material flows based on the German ELV recycling network.

3 NETWORK STRUCTURE

The recycling network is composed of the following entities:

- Return stations where vehicles brought in by the owners are collected. The task of a return station is to deliver an ELV to the next entity, that is, to the dismantler.
- Dismantlers whose task is to collect the ELV from the return stations or directly from the vehicle owners, dismantle them and forward the parts and other elements to the material recycling facilities as well as the dismantled vehicle hulk to the industrial shredders.
- Industrial shredders, where, in the shredding process, metal fractions are recovered.
- Material recycling facilities responsible for waste recovery and its resale on the market.

Figure 1 presents a general model of the network that includes the relations among the recycling network entities in the form of physical flow of goods (ELV and waste).

The ELVs are assigned to the places of their origin, that is, the vehicle owners. Vehicles are taken back at the return stations and then subsequently go to the dismantlers. They may also go directly to the dismantler omitting the return stations. At the dismantlers all the consumables and dangerous elements as well as parts for further use are removed from the vehicle including those for material recycling. The parts that are good for further use go directly to the sales channels, and the other

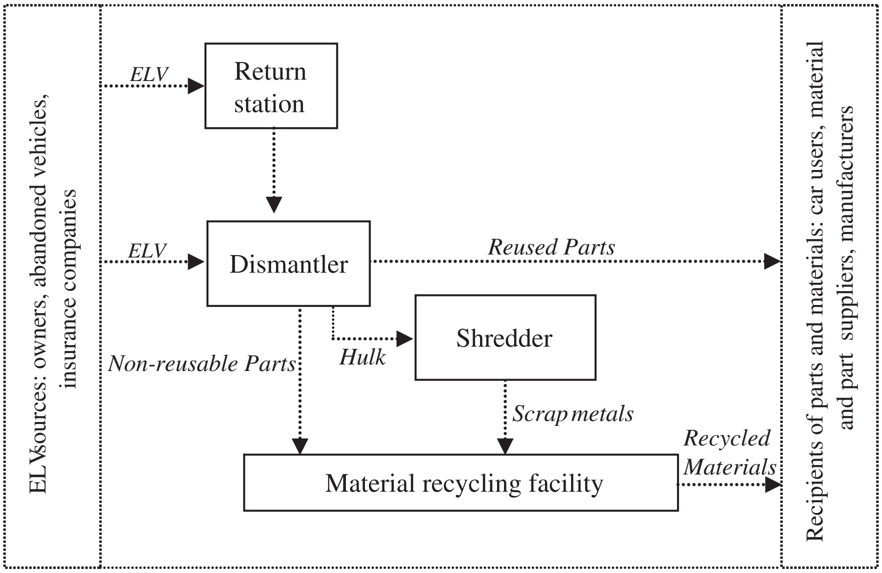

Figure 1: The participants and the flows in the recycling network.

retrieved elements are forwarded to the recycling facilities that carry out the treatment and disposal process. The rest of the body goes to the industrial shredders. There, in the shredding process metal, non-metal fractions, and shredder residue are obtained. Scrap metal is forwarded to material recycling facilities and steelworks as well. Shredder residue is combusted with energy recovery or stored at the disposal sites. In some countries, depending on the existing infrastructure, further processing and segregation of the non-metal fractions are possible, which reduces the amount of waste for storage. Recycling facilities sell the recovered materials in the market.

The specificity of the functioning of the network entities and their mutual relations are described in detail in following works [6, 7].

4 RECYCLING NETWORK MODELING

The decisions related to the organization of the recycling network need to take into account a variety of aspects. The most important are

- applicable legal regulations,
- economical conditions for the functioning of the entities of a recycling network,
- vehicle supply, and
- accessibility and location of the industrial shredders and material recycling facilities.

A way to support the decisions that include all of the indicated aspects is a formulation of a research problem in the mathematical language in the form of an optimization task of determining the location of the network entities. The selection of the optimum locations of the individual type of entities will depend on the preferences of the decision-maker (expressed by the objective function) and the resources that the decision-maker has at its disposal (taken into account in the limitations).

In monocriterion optimization tasks for the evaluation of the solutions, a single evaluation function is used that expresses the preference of the decision-maker. In some cases, it is difficult to determine one objective function because of the involvement of many entities representing different points of view, each extremizing their individual benefits.

In such a situation, we need to use multicriteria models that assume minimization or maximization of the objective function composed of many partial criterions. Each of these criterions reflects (very often contrary) the preferences of the parties involved. This is particularly useful when optimizing the complex systems that a recycling network definitely belongs to.

For multicriteria functions, the condition for finding the optimum solution is the existence of a common set of admissible decisions corresponding to the individual partial criterions. This means that the objectives must be related to one another. The partial functions reflect different objectives and preferences of the decision-maker that have to be realized at the same time. The basis for the selection of the solutions is the whole set of objectives considered. Among individual objectives appears competitiveness, which means that the improvement of the realization of one objective results in the deterioration of the realization of at least one of the other objectives. There is no decision whatsoever (solution or action) that is the best at the same time in every aspect. The term optimum in this case has a different meaning from that in the classic theory of optimization. Solving multicriteria tasks leads the determination of the best alternative considering various interactions within the set limitations so that the decision-maker is most satisfied reaching the acceptable level of the set of criterions.

The objective function can thus be presented as a set of measurable evaluating criterions and take the following notation:

$$F = \{f_1, f_2, \ldots, f_k, \ldots f_K\}, \tag{1}$$

where

F – global evaluation function,
f_k – partial evaluation function,
K – number of partial evaluation functions.

To the individual partial functions weights are assigned reflecting the significance of a criterion. The weights are shown as certain numerical values.

In the further part of the paper, the author will present a bi-criteria model of optimization of recycling network locations.

5 BI-CRITERIA MODEL OF THE RECYCLING NETWORK REORGANIZATION

In the bi-criteria model described below, two partial functions of evaluation were used: one assigned to the network participants and the other reflecting the preferences of the vehicle owners who can also be referred to as the network users. For the network participants, maximization of the profitability was assumed as an objective function, and for the vehicle owners the assumed criterion was the minimization of costs related to the forwarding of an ELV for recycling.

The first partial objective function marked f_1, related to the profitability of the entities, is expressed with the difference between the total network revenues and the total network costs, that is, it includes:

- The revenues of the return stations (R^{CP}), dismantlers (R^{CS}), and industrial shredders (R^{CM}).
- The costs of functioning of the entities: that is, return stations (K^{CP}), dismantlers (K^{CS}), and industrial shredders (K^{CM}) that are composed of overheads and variable costs.
- The costs of transport of ELVs and waste between the return stations and the dismantlers (K^{TC}), the return stations and the industrial shredders (K^{TD}), the return stations and selected material recycling facilities (K↑TE, K↑TF) and the industrial shredders and selected material recycling facilities (K↑TG, K↑TH).

For the partial objective function expressing the profitability of the network, maximum value of the function will be the sought, that is

$$f_1 = \max\{R^{CP} + R^{CS} + R^{CM} - K^{CP} - K^{CS} - K^{CM} - K^{TC} - K^{TD} - K^{TE} - K^{TF} - K^{TG} - K^{TH}\} \qquad (2)$$

The second partial objective function was expressed as a sum of costs borne by the vehicle owners resulting from the returning of a vehicle to the network. The evaluation function at the same time aims at ensuring the network accessibility. The more return stations/dismantlers in a given area, the lower the costs for the vehicle owners; thus, the minimization of the costs of ELV returning to the network is equal to the maximization of accessibility.

The objective function related to the minimization of costs of ELVs returning to the recycling network comprises the minimization of

- the costs of transport of ELVs between the sources and the return stations (K^{TA}).
- the costs of transport of ELVs between the sources and the dismantlers (K^{TB}).

Obviously we are seeking the minimum value of this function, that is

$$f_2 = \min\{K^{TA} + K^{TB}\}. \qquad (3)$$

The data necessary for the mathematical formulation of the bi-criteria optimization tasks for recycling network reorganization are as follows:

- Overheads of the return stations (k_P^{SP}), dismantlers (k_S^{SS}), industrial shredders (k_m^{SM}).
- Unit variable costs of the dismantlers (k_S^{JZS}) and industrial shredders $(k_{\downarrow}m^{\uparrow}JZM)$.
- Unit transport overheads between the sources and the return stations $\left(k_{i,p}^{TSA}\right)$, the sources and the dismantlers $\left(k_{i,s}^{TSB}\right)$, the return stations and the dismantlers $\left(k_{p,s}^{TSC}\right)$, the dismantlers and the industrial shredders $\left(k_{s,m}^{TSD}\right)$, the dismantlers and the plastic recycling facilities $\left(k_{s,t}^{TSE}\left(\mu_s^{SD}\right)\right)$, the dismantlers and the non-ferrous metals recycling facilities $\left(k_{s,n}^{TSF}\left(\mu_s^{SD}\right)\right)$, the industrial shredders and the ferrous metals recycling facilities $\left(k_{m,n}^{TSG}\left(\mu_m^{MP}\right)\right)$ and the industrial shredders and the non-ferrous metals recycling facilities $\left(k_{m,z}^{TSH}\left(\mu_m^{MP}\right)\right)$.
- Unit variable transport costs between the sources and the return stations $\left(k_{i,p}^{TZA}\right)$ the sources and the dismantlers $\left(k_{i,s}^{TZB}\right)$, the return stations and the dismantlers $\left(k_{p,s}^{TZC}\right)$, the dismantlers and the industrial shredders $\left(k_{s,m}^{TZD}\right)$, the dismantlers and the plastic recycling facilities $\left(k_{s,t}^{TZE}\left(\mu_s^{SD}\right)\right)$, the dismantlers and the non-ferrous metals recycling facilities $\left(k_{s,n}^{TZF}\left(\mu_s^{SD}\right)\right)$, the industrial shredders and the ferrous metals recycling facilities $\left(k_{m,n}^{TZG}\left(\mu_m^{MP}\right)\right)$ and the industrial shredders and the non-ferrous metals recycling facilities $\left(k_{m,z}^{TZH}\left(\mu_m^{MP}\right)\right)$.
- The matrix of distance between: the sources and the return stations $\left(d_{i,p}^{A}\right)$, the sources and the dismantlers $\left(d_{i,s}^{B}\right)$, the return stations and the dismantlers $\left(d_{p,s}^{C}\right)$, the dismantlers and the industrial shredders $\left(d_{s,m}^{D}\right)$, the plastic $\left(d_{s,t}^{E}\right)$ and non-ferrous metals $\left(d_{s,n}^{F}\right)$ recycling facilities and the industrial shredders and the non-ferrous metals $\left(d_{m,n}^{G}\right)$ and ferrous metals $\left(d_{m,z}^{H}\right)$ recycling facilities.
- The number of ELVs in each municipality $(q_{\downarrow}i^{\uparrow}I)$.
- The throughput potential of the existing dismantlers $\left(\mu_s^{SD}\right)$, industrial shredders $\left(\mu_m^{MP}\right)$ and the plastic recycling facilities $\left(\mu_t^{ZRT}\right)$, non-ferrous metals recycling facilities $\left(\mu_n^{ZRN}\right)$ and the ferrous metals recycling facilities $\left(\mu_z^{ZRZ}\right)$.
- The conversion ratio of the ELV processed into a hulk (χ^D), into plastics (χ^E), non-ferrous metals (χ^F) and the conversion ratio of the hulk processed into non-ferrous metals (χ^G) and ferrous metals (χ^H).
- The maximum distance between the source and the closest return station or dismantler (d^{max1}).
- Unit revenues of the return station $\left(r_p^{JP}\right)$, the dismantler $\left(r_s^{JS}\right)$ and the industrial shredder $\left(r_m^{JM}\right)$.

The objective is to ascertain the decision variables that determine:

- Locations of the return stations $\left(x_p^{PZ}\right)$, dismantlers $\left(x_s^{SD}\right)$ and industrial shredders $\left(x_m^{MP}\right)$.
- The flow quantities: between the sources and the return stations $\left(q_{i,p}^{A}\right)$, the sources and the dismantlers $\left(q_{i,s}^{B}\right)$ and at the input to the return stations $\left(q_p^{PZ}\right)$, the dismantlers $\left(q_s^{SD}\right)$, the industrial shredders $\left(q_m^{MP}\right)$, the plastic recycling facilities $\left(q_t^{ZRT}\right)$, the non-ferrous metals recycling facilities $\left(q_n^{ZRN}\right)$ and ferrous metals recycling facilities $\left(q_z^{ZRZ}\right)$.
- The assigning of each of the entities to the entity that is the next link in the technological chain for a given set of relations, that is: return stations to the dismantlers $\left(y_{p,s}^{C}\right)$, the dismantlers to the industrial shredders $\left(y_{s,m}^{D}\right)$, plastic recycling facilities $\left(y_{s,t}^{E}\right)$ and non-ferrous metals recycling facilities $\left(y_{s,n}^{F}\right)$ and the industrial shredders to the non-ferrous metals recycling facilities $\left(y_{m,n}^{G}\right)$ and ferrous metals recycling facilities $\left(y_{m,z}^{H}\right)$.

A full notation of partial objective function f_1 assuming the maximum value takes the following form:

$$f_1 = \sum_{p\in P} r_p^{JP} q_p^{PZ} + \sum_{s\in S} r_s^{JS} q_s^{SD} + \sum_{m\in M} r_m^{JM} q_m^{MP} - \sum_{p\in P} k_p^{SP} x_p^{PZ}$$

$$\begin{aligned}
&-\sum_{s\in S}(x_s^{SD}k_s^{SS}+k_s^{JZS}q_s^{SD})-\sum_{m\in M}(x_m^{MP}k_m^{SM}+k_m^{JZM}q_m^{MP})\\
&-\sum_{p\in P}\sum_{s\in S}q_p^{PZ}\left(d_{p,s}^{C}k_{p,s}^{TZC}+k_{p,s}^{TSC}\right)-\sum_{s\in S}\sum_{m\in M}\chi^{D}q_s^{SD}(d_{s,m}^{D}k_{s,m}^{TZD}+k_{s,m}^{TSD})\\
&-\sum_{s\in S}\sum_{t\in T}\chi^{E}q_s^{SD}[d_{s,t}^{E}k_{s,t}^{TZE}(\mu_s^{SD})+k_{s,t}^{TSE}(\mu_s^{SD})]\\
&-\sum_{s\in S}\sum_{n\in N}\chi^{F}q_s^{SD}[d_{s,n}^{F}k_{s,n}^{TZF}(\mu_s^{SD})+k_{s,n}^{TSF}(\mu_s^{SD})]\\
&-\sum_{m\in M}\sum_{n\in N}\chi^{G}q_m^{MP}[d_{m,n}^{G}k_{m,n}^{TZG}(\mu_m^{MP})+k_{m,n}^{TSG}(\mu_m^{MP})]\\
&-\sum_{m\in M}\sum_{z\in Z}\chi^{H}q_m^{MP}[d_{m,z}^{H}k_{m,z}^{TZH}(\mu_m^{MP})+k_{m,z}^{TSH}(\mu_m^{MP})],
\end{aligned}\tag{4}$$

where

p – current number of the return station,
P – the set of return stations,
s – current number of the dismantler,
S – the set of dismantlers,
m – current number of the industrial shredder,
M – the set of industrial shredders,
t – current number of the plastic recycling facility,
T – the set of plastic recycling facilities,
n – current number of the non-ferrous metals recycling facility,
N – the set of non-ferrous metals recycling facilities,
z – current number of the ferrous metals recycling facility,
Z – the set of ferrous metals recycling facilities,

and the partial objective function f_2 assuming the minimum value takes the form:

$$f_2=\sum_{i\in I}\sum_{p\in P}q_{i,p}^{A}\left(d_{i,p}^{A}k_{i,p}^{TSA}+k_{i,p}^{TZA}\right)+\sum_{i\in I}\sum_{s\in S}q_{i,s}^{B}\left(d_{i,s}^{B}k_{i,s}^{TZB}+k_{i,s}^{TSB}\right)\tag{5}$$

where

i – current number of the ELV source,
I – the set of ELV sources.

Solving an optimization task requires compliance with a variety of limitations resulting from the specificity of the functioning of a recycling network, legal regulations and other requirements of a recycling network.

The eqn (6) refers to the collection of all ELVs from the sources. The other limitations eqns (7)–(12) are limitations that determine the flows of ELVs and waste materials transferred between the entities in a subsequent stage of the technological cycle.

$$\sum_{p=1}^{P}q_{ip}^{A}+\sum_{s=1}^{S}q_{is}^{B}=q_i^{I};\quad \forall i=1\ldots I\tag{6}$$

$$\sum_{i=1}^{I} q_{ip}^{A} = q_{p}^{P}; \quad \forall p = 1 \ldots P \tag{7}$$

$$\sum_{i=1}^{I} q_{is}^{B} + \sum_{p \in P^{S}(s)} q_{p}^{P} = q_{s}^{S}; \quad \forall s = 1 \ldots S \tag{8}$$

$$\chi^{D} \sum_{s \in S^{M}(m)} q_{s}^{S} = q_{m}^{M}; \quad \forall m = 1 \ldots M \tag{9}$$

$$\chi^{E} \sum_{s \in S^{T}(t)} q_{s}^{S} = q_{t}^{T}; \quad \forall t = 1 \ldots T \tag{10}$$

$$\chi^{F} \sum_{s \in S^{N}(n)} q_{s}^{S} + \chi^{G} \sum_{m \in M^{N}(n)} q_{m}^{M} = q_{n}^{N}; \quad \forall n = 1 \ldots N \tag{11}$$

$$\chi^{H} \sum_{m \in M^{Z}(z)} q_{m}^{M} = q_{z}^{Z}; \quad \forall z = 1 \ldots Z. \tag{12}$$

Then, limitations were introduced related to the throughput potential eqns (13)–(17). The flows to the dismantlers, industrial shredders and material recycling facilities cannot exceed the maximum capacity of these entities. The exception is the return stations that can collect any number of ELVs. For them, the only limitation is the capacity of the dismantlers they collaborate with.

$$q_{s}^{S} \le \mu_{s}^{S}; \quad \forall s = 1 \ldots S \tag{13}$$

$$q_{m}^{M} \le \mu_{m}^{M}; \quad \forall m = 1 \ldots M \tag{14}$$

$$q_{t}^{T} \le \mu_{t}^{T}; \quad \forall t = 1 \ldots T \tag{15}$$

$$q_{n}^{N} \le \mu_{n}^{N}; \quad \forall n = 1 \ldots N \tag{16}$$

$$q_{z}^{Z} \le \mu_{z}^{Z}; \quad \forall z = 1 \ldots Z \tag{17}$$

Another limitation eqn (18) that was introduced is related to the accessibility of the return stations and/or dismantlers from the point of view of the ELV owner. It has been assumed that the owner must have access to the station or dismantler within a certain distance that cannot be exceeded ($d^{\max 1}$).

$$\underset{p}{\exists} : \left(x_{p}^{P} = 1 \wedge d_{ip}^{A} \le d^{\max 1} \right) \vee \underset{s}{\exists} : \left(x_{s}^{S} = 1 \wedge d_{is}^{B} \le d^{\max 1} \right); \quad \forall i = 1 \ldots I \tag{18}$$

Moreover limitation eqns (19) and (20) were introduced to guarantee that the owner should not travel more than a certain distance ($d^{\max 2}$) to return an ELV to the recycling network.

$$d_{ip}^{A} \le d^{\max 2}; \quad \forall i = 1 \ldots I, p = 1 ... P, q_{ip}^{A} \ne 0 \tag{19}$$

$$d_{is}^{B} \le d^{\max 2}; \quad \forall i = 1 \ldots I, s = 1 ... S, q_{is}^{B} \ne 0 \tag{20}$$

Limitations eqns (21)–(23) assume that that if a location of a given entity is not selected, no ELVs or waste will be directed to that entity.

$$x_{p}^{PZ} = 0 \Rightarrow q_{p}^{PZ} = 0; \quad \forall p = 1 \ldots P \tag{21}$$

$$x_s^{SD} = 0 \Rightarrow q_s^{SD} = 0; \quad \forall s = 1 \ldots S \tag{22}$$

$$x_m^{MP} = 0 \Rightarrow q_m^{MP} = 0; \quad \forall m = 1 \ldots M \tag{23}$$

Additionally we need to include in the limitations the condition that the variables determining the flow size are positive real numbers and the values of the flows between sources, return stations and dismantlers must be integers as they denote the number of ELVs. Besides, the location variables are binary numbers.

6 APLICATION OF THE MODEL TO OPTIMIZATION OF THE POLISH RECYCLING NETWORK

Due to the scale of the problem and the number of variables for the solution of the optimization tasks, the evolutionary algorithms were used with the help of Java software. The evolutionary algorithm combining genetic algorithms with local search enables the achievement of good quality solutions in a reasonable run time.

The model tests were performed on the Polish recycling network. In Poland, in December of 2010, there were 117 return stations, 689 dismantlers and 7 industrial shredders. Dismantlers and industrial shredders collaborate with 26 non-ferrous metal recycling facilities, 18 plastic recycling facilities, and 16 ferrous metal recycling facilities. Because it has been assumed that all ELVs go to the recycling network, it was necessary to place additional locations of the industrial shredders so that all the waste from all the vehicles is processed. In the task, 20 additional potential locations of the industrial shredders have been indicated.

Besides, for the purpose of model validation and recycling network optimization, the following assumptions have been adopted:

- The number of ELVs is 824,733 per annum, that is, 5% of the vehicle fleet in the country. The ELVs are assigned to municipalities that are treated as ELV sources. There are in total 2,478 municipalities in the country.
- In line with the applicable regulations, the maximum distance between the ELV source and the closest return station or dismantler is 50 km.
- The dismantlers and the industrial shredders have a given throughput. Return stations do not have a throughput – they can collect as many ELVs as the dismantler they collaborate with.
- For the industrial shredders and material recycling facilities it has been assumed that a third of their throughput potential is used for the needs of vehicle recycling.
- The average mass of an ELV returned to the network is 1,010 kg.
- The conversion ratios are as follows: the conversion ratio of the ELV to hulk is 0,5713 of the initial ELV mass, the conversion ratio of the ELV to plastic waste is 0,064 of the initial ELV mass, the conversion ratio of the ELV to non-ferrous metals is 0,038 of the initial ELV mass, the conversion ratio of the hulk to ferrous metals is 0,85 of the hulk mass and the conversion ratio of the hulk to non-ferrous metals is 0,05 of the hulk mass.

For the optimization task solved in the multicriteria model in which the improvement of the realization of one partial objective function inhibits the realization of another partial objective function, a single best solution that would extremize the value of all partial functions cannot be found.

To find solutions of the objective function for the presented bi-criteria model, the global function has been reduced to a single objective through a scalarizing function. The selected method consists in assigning weight to each of the partial objective functions and seeking optimum solutions for different combinations of weights. The assigned weight of the partial function denotes the significance of a given element for the solution of the problem. The multicriteria optimization then consists in finding a set of optimum solutions of different compromise levels (relations) between individual criteria. The solution is thus a set of points that fulfill 'optimality' in the Pareto sense. For two functions of one variable, it is a set of solutions that lies between the minimum of these functions that is, the area between the point where one function has an optimum solution and another point where there is an optimum solution for the other objective function. Then, knowing the preferences and the bargain force of the stakeholders whose interests are taken into account in the optimization process, the decision-maker chooses such solutions from the set that best reflect the predetermined preferences.

Analyzing the values of partial functions selected in the multicriteria model, the element decisive about the value of the global objective function is the partial function reflecting the maximization of benefits from the point of view of the network. Optimizing the global objective function without the use of weights would in practice mean a monocriterial optimization for which the best solution would be close to the results of the single criteria model of network reorganization with the objective of profitability maximization. Due to a disproportion of the values of the partial functions for the solution of the optimization tasks, the author assumed that weight u_1 is always equal to 1 so that the values of the objective function for the network participants do not dominate the total value of the global function of utility. Weight u_2 of the partial objective function related to the maximization of the benefits for the owners varies in the range from 1 and 150. For $u_2 = 1$, each Polish Zloty of the minimization of the costs for the owners is worth as much as each Polish Zloty of the maximization of the benefits for the network entities; yet, for $u_2 = 100$, each Polish Zloty of the minimization of the cost for the owners equals 100 Polish Zlotys in the partial objective function for the network participants.

Depending on the weight of the objective function, the best obtained solution varies (Fig. 2). For the network reorganization model when comparing the best solutions for extreme weights of the partial objective function of the maximization of benefits of the ELV owners ($u_2 = 1$ and $u_2 = 150$), we can see that the reduction of the costs of the owners is 25%, but it is accompanied by a drop in the profitability by 43% (Table 1).

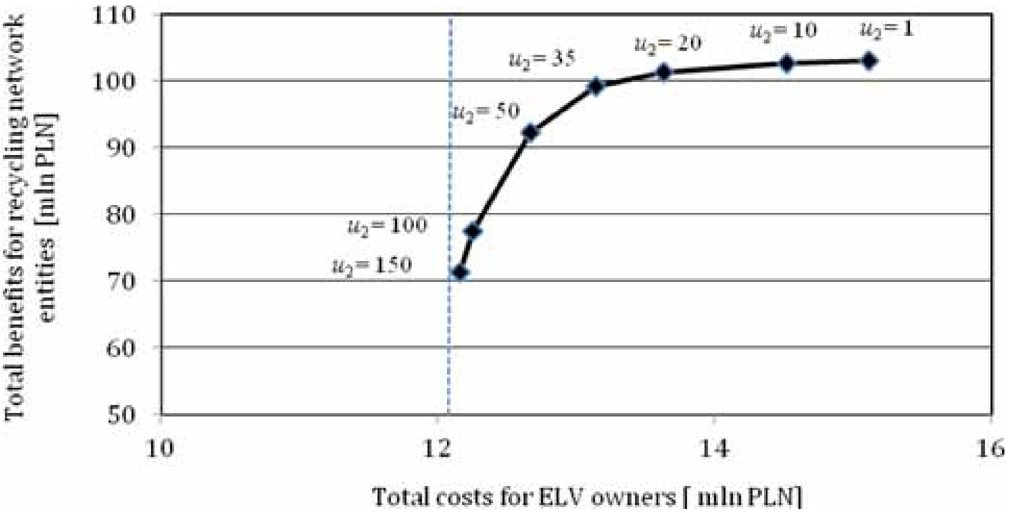

Figure 2: The results of the multicriteria optimization task for a network reorganization depending on the value of u_2.

Table 1: Results of the multicriteria optimization task for a network reorganization depending on the weight of the partial objective function.

Weight u_1	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Weight u_2	**1**	**10**	**20**	**35**	**50**	**100**	**150**
1	2	3	4	5	6	7	8
Total network profit (f_1) [thousand PLN]	102,110	102,690	101,400	99,230	92,230	77,390	71,220
Total owner cost (f_2) [thousand PLN]	15,110	14,520	13,630	13,140	12,670	12,250	12,130
Number of return stations	6	10	11	12	25	31	32
Number of dismantlers	390	388	391	393	406	429	439
Number of industrial shredders	13	13	13	13	13	13	13

Depending on the weight the number of return stations varies from 6 to 32 and the dismantlers from 390 to 439. Hence, the network accessibility changes from 396 locations where the owner can return the ELV (return stations and dismantlers collectively) to 471 locations, that is, it grows by 20%. The number of industrial shredders in all solutions remains 13.

The bottom cost boundary for the vehicle owners is PLN 12.1 million. This is the value of the costs of returning of ELVs to the network for a solution where all the existing return stations and dismantlers are maintained, thus the network accessibility will be extended to 806 ELV collection points. This solution guarantees the accessibility that is 70% better than the solution for the highest analyzed weight for the criterion of cost minimization for the owners but the improvement in the total cost of the returning of the ELV to the network is merely below 1.5%. At the same time, for such a density of the network the loss generated by the whole system amounts to over PLN 65.3 million per annum.

7 CONCLUSIONS

A proper organization of a vehicle recycling network requires a global approach, including all the key entities and flows and relations that occur between them.

Making a decision related to the location of the entities, we should analyze all technical, economic, environmental, and legal aspects. This should ensure that on a given area the network construction or reorganization would render maximum benefits from the point of view of the network participants, ELV owners, government and the economy as a whole.

The paper presents bi-criteria model aiming at the reorganization of a network on a given area that was used for the optimization of the recycling network in Poland. The above-presented sets of effective solutions of the multicriteria tasks cannot be treated as a final solution to the decision-making problem but only be treated as a starting point for the selection of the final solution by the decision-maker.

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