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Bicriteria Models of Vehicles Recycling Network Facility Location

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Abstract

The paper presents the issues related to modeling of a vehicle recycling network. The functioning of the recycling network 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. The paper presents bicriteria models of network entity location that take into account the preferences of the vehicle owners and network participants related to the network construction and reorganization. A mathematical formulation of the optimization tasks has been presented including the objective functions and limitations that the solutions have to comply with. Then, the models were used for the network optimization in Poland.

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 i.e. economic use of waste except energy recovery.

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A condition for vehicle recycling is a creation of a network for end-of-life vehicle (ELV) collection and processing. This network, otherwise known as 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 i.e. to the dismantler.
- Dismantlers whose task is to collect the ELV from the return stations or directly from the vehicle owners, then remove the vehicle consumables, parts that are good for further resale as used spare parts and other parts and elements for material.
- Recycling and finally forward them 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.

The specificity of the functioning of the network entities and their mutual relations have been described in [4,6].

2. Literature Survey

Construction of the structure of a recycling network may take place in two cases. The first one is a situation when the network on a given area has to be built as a greenfield project and the second is a reorganization to an already existing network. The network is built as a greenfield project if on a given area there has not been any infrastructure related to the vehicle recycling before. Reorganization of an existing network consists in closing some of the entities and/or opening others.

The reasons behind the construction and reorganization of the network mainly result from the following: requirements in end-of-life vehicle management including, in particular the flow of waste and materials from the vehicles, currently applicable waste management legislation, particularly that related to the ELV waste management and economic analysis of the entities participating in the network.

The designing of recycling network may take place in the following situations:

- Organization of the network on a selected area by an organization, institution or any other entity responsible for the construction of the network,
- Creation of a new entity (a new dismantler or return station belonging to an already existing entity) and a selection of its location in relation to other entities of the network,
- Network reorganization, if it is insufficiently expanded and if there is a necessity of complementing it with new entities,
- Network reorganization if there are too many entities and some of them must be closed down in order to ensure economic efficiency of the system.

A way to support decision-making that includes all the indicated situations is a formulation of a research problem in a mathematical language in the form of an optimization task related to determining of the location of the network entities. The selection of the optimum locations of entities depends on the preferences of a decision maker (expressed as an objective function) and the resources that the decision maker has at their disposal (included in the limitations).

The problem of single criteria models of determining the location of the recycling network entities has been discussed in works by Cruz-Rivera and Ertel [1], Zarei et al. [13], Mansour and Zarei [3], Schultmann et al. [11]. A common feature of these models is that the objective function is the minimization of the costs of transport and the costs of the initial investment except the work by Schultmann et al. where the only minimized costs is the cost of transport. In all the mentioned works the research problem was related to the selection of the location of the dismantlers and in the work by Mansour and Zarei also the return stations. Models described in the paper by Zarei et al. comprised both reverse logistics and forward logistics of new vehicles and the dismantlers and the dealership retail points (at the same time functioning as the return stations) were optimized at the same time. A more detailed description of single criteria models used in modeling of vehicle recycling networks we can find in [5].

In single criteria optimization tasks for the evaluation of solutions a single objective function is used being the reflection of the preferences of the decision maker. In some cases it is difficult to determine a single objective function because of the involvement of many stakeholders representing different points of view while each of them attempts to extremize their individual benefit.

In such a situation we need to use the multi criteria models that assume the minimization/maximization of the objective function composed of many partial criteria. Each of these criteria reflects often contradictory preferences of the stakeholders. This is particularly useful in the optimization of complex systems to which vehicle recycling network belongs.

Among the individual objectives a phenomenon of competitiveness occurs, which means that the improvement in the realization of one objective results in a deterioration of the realization of at least one of the other objectives [2]. In general there is no decision (solution or action) that is best from all possible points of view. The term “optimum” in this case has a different meaning that in the conventional theory of optimization. Solving multicriterial tasks leads to determining of the best alternative taking into account various interactions within the set limitations so that the decision maker is most satisfied reaching the acceptable level of the set of criteria [7].

In the further part of the paper bicriteria models of the optimization of location of the entities of a recycling network have been presented for reorganization of an existing network and construction of a new recycling network.

3. Mathematical Formulation of the Problem

3.1. The mapping of data

For the purpose of solving of an optimization task the author assumed that the optimized entities would be the return stations, dismantlers and industrial shredders. As collaborating recycling facilities ferrous metal, non-ferrous metal and plastic recycling works have been selected. In the optimization the author did not include recycling facilities processing the waste whose collection does not generate costs for the optimized enterprises (batteries, used lubricants).

The data necessary for the mathematical formulation of the bicriteria optimization tasks for reorganization and creation of a recycling network 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_m^{JZM}).
- Unit transport overheads between the sources and the return stations ($k_{i,p}^{TSA}$), the sources and the dismantlers ($k_{i,s}^{TSB}$), the return stations and the dismantlers ($k_{p,s}^{TSC}$), the dismantlers and the industrial shredders ($k_{s,m}^{TSD}$), the dismantlers and the plastic recycling facilities ($k_{s,t}^{TSE}(\mu_s^{SD})$), the dismantlers and the non-ferrous metals recycling facilities ($k_{s,n}^{TSF}(\mu_s^{SD})$), the industrial shredders and the ferrous metals recycling facilities ($k_{m,n}^{TSG}(\mu_m^{MP})$) and the industrial shredders and the non-ferrous metals recycling facilities ($k_{m,z}^{TSH}(\mu_m^{MP})$).
- Unit variable transport costs between the sources and the return stations ($k_{i,p}^{TZA}$) the sources and the dismantlers ($k_{i,s}^{TZB}$), the return stations and the dismantlers ($k_{p,s}^{TZC}$), the dismantlers and the industrial shredders ($k_{s,m}^{TZD}$), the dismantlers and the plastic recycling facilities ($k_{s,t}^{TZE}(\mu_s^{SD})$), the dismantlers and the non-ferrous metals recycling facilities ($k_{s,n}^{TZF}(\mu_s^{SD})$), the industrial shredders and the ferrous metals recycling facilities ($k_{m,n}^{TZG}(\mu_m^{MP})$) and the industrial shredders and the non-ferrous metals recycling facilities ($k_{m,z}^{TZH}(\mu_m^{MP})$).
- The matrix of distance between: the sources and the return stations ($d_{i,p}^{A}$), the sources and the dismantlers ($d_{i,s}^{B}$), the return stations and the dismantlers ($d_{p,s}^{C}$), the dismantlers and the industrial shredders ($d_{s,m}^{D}$), the plastic ($d_{s,t}^{E}$) and non-ferrous metals ($d_{s,n}^{F}$) recycling facilities and the industrial shredders and the non-ferrous metals ($d_{m,n}^{G}$) and ferrous metals ($d_{m,z}^{H}$) recycling facilities.
- The number of ELVs in each municipality (q_i^{I}).
- The throughput potential of the existing dismantlers (μ_s^{SD}), industrial shredders (μ_m^{MP}) and the plastic recycling facilities (μ_t^{ZRT}), non-ferrous metals recycling facilities (μ_n^{ZRN}) and the ferrous metals recycling facilities (μ_z^{ZRZ}).
- The maximum admissible throughput potential of the created dismantlers (μ_{max}^{SD}) and industrial shredders (μ_{max}^{MP}).

- 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 $\left(\chi^{H}\right)$.
- The maximum distance between the source and the closest return station or dismantler (d^{max1}).
- Unit revenues of the return station (r_p^{JP}), the dismantler (r_s^{JS}) and the industrial shredder (r_m^{JM}).

3.2. Bicriteria model of the recycling network reorganization

In the bicriteria 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 i.e. 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: i.e. 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 i.e.:

$$f_1 = max\{R^{CP}+R^{CS}+R^{CM}-K^{CP}-K^{CS}-K^{CM}-K^{TC}-K^{TD}-K^{TE}-K^{TF}-K^{TG}-K^{TH} \tag{1}$$

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 i.e.:

$$f_2 \quad = \quad \min\{K^{TA} + K^{TB}\} \tag{2}$$

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

$$\begin{aligned}
f_1 = {} & \sum_{p\in P} r_p^{JP} q_p^{PZ} + \sum_{s\in S} r_s^{JS} q_s^{SD} + \sum_{m\in M} r_m^{JM} q_m^{MP} - \sum_{p\in P} k_p^{SP} x_p^{PZ} - \\
& - \sum_{s\in S} (x_s^{SD} k_s^{SS} + k_s^{JZS} q_s^{SD}) - \sum_{m\in M} (x_m^{MP} k_m^{SM} + k_m^{JZM} q_m^{MP}) - \\
& - \sum_{p\in P} \sum_{s\in S} q_p^{PZ} \left(d_{p,s}^{C} k_{p,s}^{TZC} + k_{p,s}^{TSC} \right) - \sum_{s\in S} \sum_{m\in M} \chi^{D} q_s^{SD} (d_{s,m}^{D} k_{s,m}^{TZD} + k_{s,m}^{TSD}) - \\
& - \sum_{s\in S} \sum_{t\in T} \chi^{E} q_s^{SD} [d_{s,t}^{E} k_{s,t}^{TZE} (\mu_s^{SD}) + k_{s,t}^{TSE} (\mu_s^{SD})] - \\
& - \sum_{s\in S} \sum_{n\in N} \chi^{F} q_s^{SD} [d_{s,n}^{F} k_{s,n}^{TZF} (\mu_s^{SD}) + k_{s,n}^{TSF} (\mu_s^{SD})] - \\
& - \sum_{m\in M} \sum_{n\in N} \chi^{G} q_m^{MP} [d_{m,n}^{G} k_{m,n}^{TZG} (\mu_m^{MP}) + k_{m,n}^{TSG} (\mu_m^{MP})] - \\
& - \sum_{m\in M} \sum_{z\in Z} \chi^{H} q_m^{MP} [d_{m,z}^{H} k_{m,z}^{TZH} (\mu_m^{MP}) + k_{m,z}^{TSH} (\mu_m^{MP})]
\end{aligned} \tag{3}$$

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:

$$f_2 = \sum_{i \in I} \sum_{p \in P} q_{i,p}^{A} \left(d_{i,p}^{A} k_{i,p}^{TSA} + k_{i,p}^{TZA} \right) + \sum_{i \in I} \sum_{s \in S} q_{i,s}^{B} \left(d_{i,s}^{B} k_{i,s}^{TZB} + k_{i,s}^{TSB} \right) \tag{4}$$

where:

i – current number of the ELV source,

I – the set of ELV sources.

The objective is to ascertain the decision variables that determine:

- Locations of the return stations (x_p^{PZ}), dismantlers (x_s^{SD}) and industrial shredders (x_m^{MP}).
- The flow quantities: between the sources and the return stations ($q_{i,p}^{A}$), the sources and the dismantlers ($q_{i,s}^{B}$) and at the input to the return stations (q_p^{PZ}), the dismantlers (q_s^{SD}), the industrial shredders (q_m^{MP}), the plastic recycling facilities (q_t^{ZRT}), the non-ferrous metals recycling facilities (q_n^{ZRN}) and ferrous metals recycling facilities (q_z^{ZRZ}).
- 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 i.e.: return stations to the dismantlers ($y_{p,s}^{C}$), the dismantlers to the industrial shredders ($y_{s,m}^{D}$), plastic recycling facilities ($y_{s,t}^{E}$) and non-ferrous metals recycling facilities ($y_{s,n}^{F}$) and the industrial shredders to the non-ferrous metals recycling facilities ($y_{m,n}^{G}$) and ferrous metals recycling facilities ($y_{m,z}^{H}$).

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.

These limitations are related to:

- The need to forward all ELVs to the recycling network.
- Assuring that the throughput of individual network entities will not be exceeded.
- Adjusting the flows at the input and output of individual entities so that all the ELVs and waste are forwarded to the entities in the subsequent stages of the technological cycle.
- Assignment of network entities, which means that each entity can collaborate with only one enterprise of a given type in a subsequent stage of the technological cycle.
- Assuring that if a location of a given entity is not selected no ELVs or waste will be directed to that entity.
- Assuring that at a given distance from the source a return station or a dismantler will operate.
- Expressing decision variables related to the ELV flows in positive integer numbers.
- Expressing decision variables related to the waste flows in non-negative numbers.

- Expressing decision variables related to the determining of the locations of network entities and assigning of enterprises in binary numbers.

3.3. Bicriteria model of the recycling network construction

A bicriteria model of a construction of a recycling network is similar to the network reorganization model. Here we have two partial evaluation functions, one of which, as in the above described model, is assigned to the participants of the network and the other reflects the preferences of the vehicle owners. The difference is that in this case the location of the entity could be designated in any municipality and is not limited only to the existing enterprises.

For the dismantlers and the industrial shredders instead of binary variable indicating the selection of the location a variable expressed in a real positive number was entered that determines the throughput potential for a given location. If the variable assumes zero the dismantler or the industrial shredder in a given location will not be created and a positive value means that the location will be chosen and at the same time the throughput potential is determined. For the return stations the variable remains a binary variable, as the return stations do not have a determined throughput potential. They can collect a number of vehicles that corresponds to the throughput potential of the collaborating dismantler.

The objective is to ascertain the decision variables that determine:

- The locations of the return stations ($\mathrm{x}_{\mathrm{p}}^{\mathrm{PZ}}$).
- Throughput potential assigned to a given location of a dismantler ($\tilde{\mu}_s^{SD}$) i and industrial shredder ($\tilde{\mu}_m^{MP}$).
- The flow quantities: between the sources and the return stations ($\mathrm{q}_{\mathrm{i,p}}^{\mathrm{A}}$), the sources and the dismantlers ($\mathrm{q}_{\mathrm{i,s}}^{\mathrm{B}}$) and at the input to the return stations ($\mathrm{q}_{\mathrm{p}}^{\mathrm{PZ}}$), the dismantlers ($\mathrm{q}_{\mathrm{s}}^{\mathrm{SD}}$), the industrial shredders ($\mathrm{q}_{\mathrm{m}}^{\mathrm{MP}}$), the plastic recycling facilities ($\mathrm{q}_{\mathrm{t}}^{\mathrm{ZRT}}$), the non-ferrous metals recycling facilities ($\mathrm{q}_{\mathrm{n}}^{\mathrm{ZRN}}$) and ferrous metals recycling facilities ($\mathrm{q}_{\mathrm{z}}^{\mathrm{ZRZ}}$).
- 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 i.e.: return stations to the dismantlers ($\mathrm{y}_{\mathrm{p,s}}^{\mathrm{C}}$), the dismantlers to the industrial shredders ($\mathrm{y}_{\mathrm{s,m}}^{\mathrm{D}}$), plastic recycling facilities ($\mathrm{y}_{\mathrm{s,t}}^{\mathrm{E}}$) and non-ferrous metals recycling facilities ($\mathrm{y}_{\mathrm{s,n}}^{\mathrm{F}}$) and the industrial shredders to the non-ferrous metals recycling facilities ($\mathrm{y}_{\mathrm{m,n}}^{\mathrm{G}}$) and ferrous metals recycling facilities ($\mathrm{y}_{\mathrm{m,z}}^{\mathrm{H}}$).

For the partial objective function f_1 expressing the profitability of the network we seek a maximum value of the function that is:

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

$$- \sum_{s \in S} (sgn(\tilde{\mu}_s^{SD}) k_s^{SS} + k_s^{JZS} q_s^{SD}) - \sum_{m \in M} (sgn(\tilde{\mu}_m^{MP}) k_m^{SM} + k_m^{JZM} q_m^{MP}) -$$

$$
\begin{aligned}
&-\sum_{p\in P}\sum_{s\in S} q_p^{PZ}\left(d_{p,s}^{C}k_{p,s}^{TZC}+k_{p,s}^{TSC}\right)-\sum_{s\in S}\sum_{m\in M}\chi^{D}q_s^{SD}(d_{s,m}^{D}k_{s,m}^{TZD}+k_{s,m}^{TSD})- \qquad (5)\\
&-\sum_{s\in S}\sum_{t\in T}\chi^{E}q_s^{SD}[d_{s,t}^{E}k_{s,t}^{TZE}(\mu_s^{SD})+k_{s,t}^{TSE}(\mu_s^{SD})]-\\
&-\sum_{s\in S}\sum_{n\in N}\chi^{F}q_s^{SD}[d_{s,n}^{F}k_{s,n}^{TZF}(\mu_s^{SD})+k_{s,n}^{TSF}(\mu_s^{SD})]-\\
&-\sum_{m\in M}\sum_{n\in N}\chi^{G}q_m^{MP}[d_{m,n}^{G}k_{m,n}^{TZG}(\mu_m^{MP})+k_{m,n}^{TSG}(\mu_m^{MP})]-\\
&-\sum_{m\in M}\sum_{z\in Z}\chi^{H}q_m^{MP}[d_{m,z}^{H}k_{m,z}^{TZH}(\mu_m^{MP})+k_{m,z}^{TSH}(\mu_m^{MP})]
\end{aligned}
$$

and for the partial objective function f_2 assuming the form as below we seek the minimum value:

$$
f_2=\sum_{i\in I}\sum_{p\in P} q_{i,p}^{A}\left(d_{i,p}^{A}k_{i,p}^{TSA}+k_{i,p}^{TZA}\right)+\sum_{i\in I}\sum_{s\in S} q_{i,s}^{B}\left(d_{i,s}^{B}k_{i,s}^{TZB}+k_{i,s}^{TSB}\right) \qquad (6)
$$

The sgn function in the cost notation returns the value of the natural numbers through determining of the sign of the given value so that for $\mu>0$ sgn = 1, and for $\mu=0$ sgn = 0.

Similarly to the model of network reorganization the solving of the optimization task must comply with several limitations resulting from the specificity of the functioning of the recycling network, legal regulations and other requirements imposed on a recycling network.

These limitations are related to:

- The need to forward all ELVs to the recycling network.
- Assuring that the maximum throughput potential of the dismantlers and the industrial shredders will not be exceeded.
- Adjusting the flows at the input and output of individual entities so that all the ELVs and waste are forwarded to the entities in the subsequent stages of the technological cycle.
- Assignment of network entities, which means that each entity can collaborate with only one enterprise of a given type in a subsequent stage of the technological cycle.
- Assuring that if a location of a given entity is not selected no ELVs or waste will be directed to that entity.
- Assuring that at a given distance from the source a return station or a dismantler will operate.
- Expressing decision variables related to the ELV flows and throughput potentials of the dismantlers and the industrial shredders in positive integer numbers.
- Expressing decision variables related to the waste flows in non-negative numbers.
- Expressing decision variables related to the determining of the locations of the return stations and assigning of enterprises in binary numbers.

4. Network Optimization on the Polish Example

The above presented mathematical models have been used for the optimization of a recycling network in Poland. In the task of network reorganization the locations of entities are selected out of the actually existing locations. In Poland at the end of 2010 there were 117 return stations, 689 dismantlers, 7 industrial shredders, 26 nonferrous metals recycling facilities, 18 plastic recycling facilities and 16 ferrous metals recycling facilities (steelworks). Because it has been assumed that all end-of life vehicles 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 tasks 20 additional potential locations of the industrial shredders have been indicated. In the network construction task the potential locations are selected from all the existing 2478 municipalities.

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

- The network operates in compliance with the Polish law – with the End-of-life Vehicles Recycling Act in particular [12]. The return stations, the dismantlers and the industrial shredders must meet the requirements related to the technical equipment specified in the following regulations [8,9,10].
- The number of end-of-life vehicles is 824 733 per annum i.e. 5% of the vehicle fleet in the country. The end-of-life vehicles are assigned to municipalities that are treated as ELV sources.
- 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 1010 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 proposed.

In order to find solutions of the objective function for the presented bicriteria models 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 i.e. 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. 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%. 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 i.e. it grows by 20%. The number of industrial shredders in all solutions remains 13.

For the network construction model for extreme weights ($u_2 = 1$ and $u_2 = 100$) we can obtain an owner cost reduction of 50% but at the same time the profitability will drop by 63%. In none of the obtained best solutions for individual weights were there return stations and the number of dismantlers was 177 to 822. The network accessibility for the vehicle owners changes in the same range as the number of the dismantlers i.e more than 4.5 times. The number of industrial shredders for the solutions with the number of dismantlers below 200 is 13 and for the other solutions it is 14.

In the network reorganization task 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. The results for the individual weights have been presented in figure 1. Each marked point reflects the best solution found for a given weight u_2.

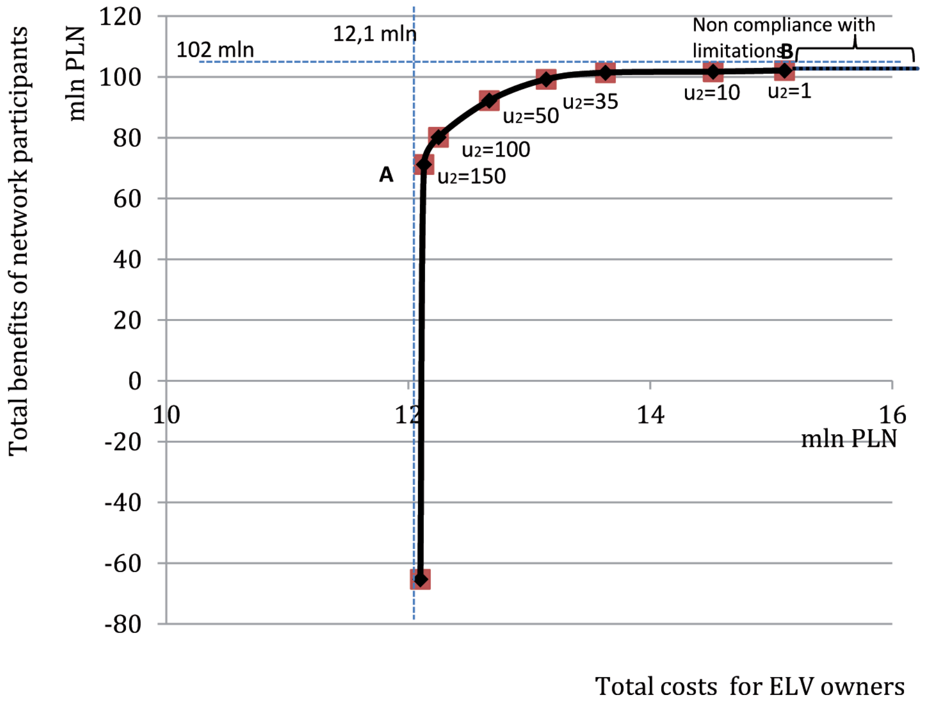

Fig. 1. The results of the multicriteria optimization task for a network reorganization depending on the value of u_2

The top owner cost boundary is the level of PLN 15,1 million i.e. the value obtained as a result of optimization for weight u_2 =1. The number of network entities proposed in this solution is the lowest. Further cost reduction for the network would be possible only if the limitations related to the maximum distances between the sources and the return stations/dismantlers were not maintained and along further reduction of the number of the dismantlers the all-ELV-processing condition would not be fulfilled. In an extreme case in the network only one dismantler would operate.

It is related to the fact that having the requirement of processing all the vehicles, the total value of the revenues for the recycling network is constant; hence the maximization of the profits depends on the minimization of the costs. As approximately 93% of the total costs of the system are the entities operating costs (more or less half is the industrial shredders and another half is the dismantlers) and the number of industrial shredders is the same in all solutions the total costs will be dependent on the number of the dismantlers. Hence, the variant that includes the participants utility function in the first place will be characterized by the lowest (by limitations) admissible number of entities. For the network construction the vertical asymptote is the cost of ELV return to the network assuming that the network of return stations and the dismantlers is so large that in each municipality there will be at least one return station or one dismantler. In such a situation there will be no variable costs related to transport and the only cost borne by the owner will be overheads related to the delivery of the vehicle. This minimum collective cost for the vehicle owners will be PLN 8,25 million. A reduction of this cost is only possible if the model parameter was changed and if the transport overheads were reduced. The loss generated by the network, assuming that each municipality has a dismantler (for the solution with 2478 dismantlers and 14 industrial shredders) will be as much as PLN 673,4 million.

The top boundary as in the multicriteria model of network construction will be the value of profit for $u_2 = 1$ on the level of PLN 147,6 million. The results for individual weights have been shown in figure 2. Each marked point reflects the best solution found for a given weight u_2.

Comparing both variants of the multicriteria models network construction model enables better solutions that give better values of the partial objective functions for both the vehicle owners and the network entities (Fig. 3).

The best solutions ensure higher values of total profit of the networks and at the same time higher utility for the vehicle owners through cost reduction of vehicle return for recycling. It is noteworthy that in this model we can also find solutions that render lower number of entities but these entities are larger thanks to which the profit of the network grows. This is done at the expense of the owners as there are fewer dismantlers and they are located farther from the sources, which increases the costs of return of ELVs for recycling.

The model of network construction generally renders more flexible solutions as the horizontal asymptote determining the maximum profit level is placed higher than in the reorganization model and the vertical asymptote determining the minimum cost for ELV owners is placed closer to the starting point of the coordinate system. The model of network construction, thus gives better solutions from the point of view of both partial objective functions but also worse solutions for the vehicle owners (for $u_2 = 1$) or worse for the network entities (for $u_2 \rightarrow \max$). For extreme admissible

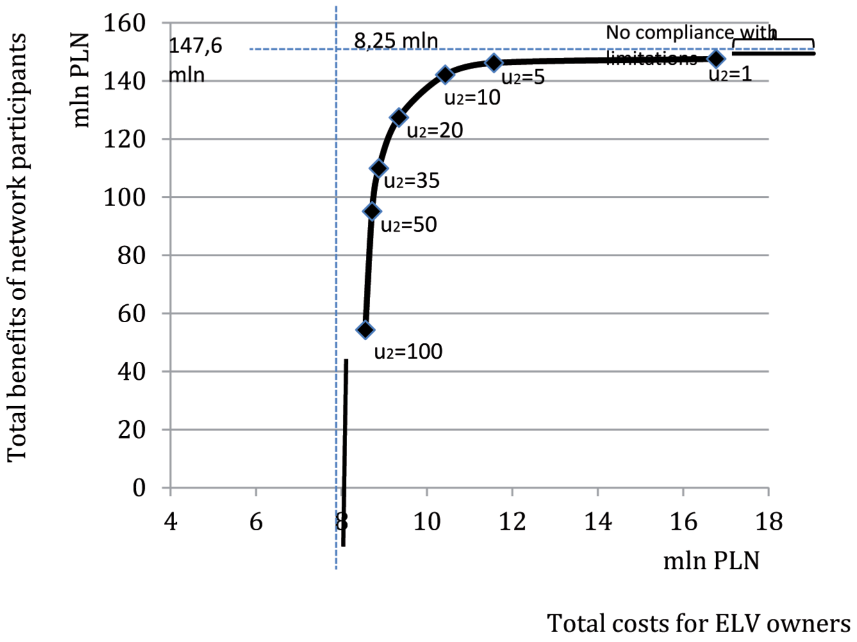

Fig. 2. The results of the multicriteria optimization task for network construction depending on the value of u_2

solutions for which only the preferences of one party are taken into account the network accessibility changes in the range from 177 to 2478 ELV collection points for the model of network construction and in the range from 396 to 806 for the model of network reorganization (Table 1).

Table 1

Comparative analysis of the obtained solutions for a bicriteria model of network construction and reorganization depending on the weight of the partial objective functions

	Network reorganization u_1 =1, u_2 =1	**Network construction u_1 =1, u_2 =1**	**Network reorganization u_1 =1, u_2 →max**	**Network construction u_1 =1, u_2 →max**
Total network profit [PLN]	102 110 000	147 600 000	-65 320 000	-673 373 000
Total owner costs [PLN]	15 110 000	16 770 000	12 100 000	8 247 000
Number of return stations	6	0	117	0
Number of dismantlers	390	177	689	2478
Number of industrial shredders	13	13	14	14

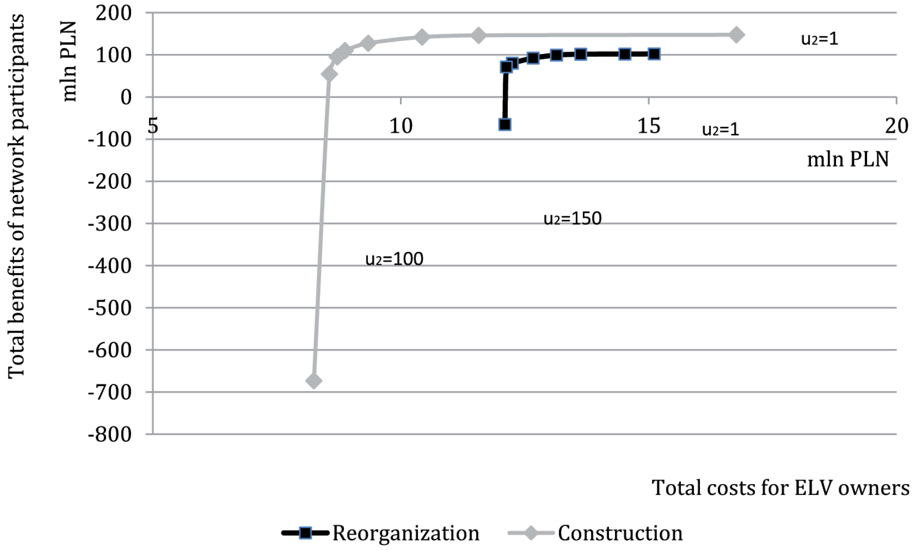

Fig. 3. Comparison of the result of the optimization for the model of network construction and reorganization

5. 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 bicriteria models aiming at the reorganization and construction of a network on a given area that were subsequently 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 as a starting point for the selection of the final solution by the decision maker.

Upon evaluation of the solutions obtained during the optimization with the use of the described models of recycling network we can draw the following conclusions:

- Out of different variants of solutions we can choose one that will satisfy both the ELV owner expectations and the economic interest of the participants of the recycling network.
- The results show that the network should have the smallest number of entities having the maximum throughput potential.
- Polish recycling network has an insufficient number of industrial shredders.

Sufficient disposal of all the end-of-life vehicles requires that the number of industrial shredders in the network grow almost twice.

- In the Polish conditions the operation of return stations is not an advantageous solution because of high overheads related to their functioning directly linked to high investment capital expenditure resulting from the legal requirements.
- The costs of transport do not significantly affect the location of the entities and vital for the optimization are the operating costs of the enterprises.

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