END-OF-LIFE VEHICLES RECYCLING NETWORK DESIGN

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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.

In order to fulfil the ecological requirements and also efficient management of the whole recovery process, the conceptual framework of a reverse logistics network is presented. The collecting of vehicles, dismantling and following processes of shredding and treatment in material recycling facilities are considered jointly. Then a mathematical model is developed which minimizes the costs of setting up the network and also the relevant transportation costs. Because of the complexity of the model, a solution methodology based on the evolutionary algorithm is proposed which enables achieving good quality solutions in a reasonable algorithm run time. In particular, the participants and the flows in the recycling network and visualisation of the results for flows between dismantlers and plastic recycling facilities are presented in the paper.

Keywords: *end-of-life vehicles, recycling network, modelling, optimization*

1. Introduction

One of major aspects of modern society is focus on consumption. For a long time issues of profitability, performance and growing production were predominant in developed countries economies. This approach changed when in the last quarter of the 20th century the world has come to a situation in which society felt that a change in attitude towards the environment was an absolute necessity, hence the implementation in more and more countries of the concept of sustainable development. Sustainable development ties together concern for the environment protection with the social and economic challenges facing humanity. One of the solutions that governments and industry have come up with is the collection, recycling and reuse of products and materials. This development is not only stimulated by a growing responsibility towards the environment and regulations from the government. More and more companies see valuable commercial opportunities in collecting, recycling and reusing products and materials.

Vehicle recycling constitutes one of the cases of reverse logistics. A growing interest in product recycling, including, but not limited to, end-of-life vehicles (ELV) resulted in that today the issues of recycling network formation are treated in a more comprehensive way and with more attention. One of the consequences of the modified approach is the use of model of multi criteria decision support, whose task is to optimize the processes in a recycling network or the optimization of the entity location. In both cases the main objective is proper management of rare resources irrespective of the fact whether these are financial or tangible assets of the network entities or materials contained in the recycled products. The first introduced innovations in recycling were related to the material recovery technologies and the modifications introduced in the vehicle design in terms of their future dismantling and processing. Recently, particularly in developed economies an equally important issue is the efficiency of the network organization ensured through optimization of the participating entities locations and used resources.

Developing of the ELV recycling network has so far been based on the market principles. Such a status quo changed when the EU member states adopted a directive2000/53/EC on end of life vehicles [3]. This directive introduced a requirement of forming recycling networks in the EU member states that would guarantee each vehicle owner the opportunity to return their vehicles for recycling. This same directive also imposed network efficiency indicators in the form of a minimum recovery and recycling performance. Also, the growing society awareness and global implementing of sustainable development in modern economies have led to a situation where the design of a recycling network cannot be merely based on the recycling entity's decision to exist in the market and its individual profit and loss account. Such entities take their decisions based exclusively on the profitability analysis that cannot be the only criterion deciding about the location of the network entities.

Irrespective of the motivation for the network design, it should not be of random nature. The decision related to the entity location should consider the highest possible number of factors. The location and functioning of the entities must be based on informed decisions in many aspects related to both technical and economic conditions (network profitability), legal (requirements related to the network organization), social (network availability, inconveniences related to the activity of certain network entities), and environmental (the necessity to reduce the negative impact of vehicles on the environment and minimization of the impact of the network itself). Hence, the creation of the network and a location of new entities will assure a maximization of benefits both from the point of view of the network participants and the vehicle owners not to mention other entities. Taking so many elements into the equation complicates the decision making process. For this reason there is a necessity to develop tools supporting the decision making and considering various aspects related to the problem at hand.

2. Literature studies

The issues of design of an end-of-life vehicle recycling network are a part of a wider research area - reverse logistics. Reverse logistics can be defined as the process of planning, implementing and controlling the efficient, cost effective flow of raw materials, in-process inventory and finished goods from manufacturing, distribution or point of consumption to a point of recovery or point of proper disposal for the purpose of recapturing of the value or proper disposal [2,7].

The designing and 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. Even though many works treat on the optimization of the location of the recovery network entities few of them concern end-of-life vehicle recycling networks. 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 [6] have set a goal to identify the sources of costs related to the obligation imposed by the EU regulations and develop a model that would include the optimization of the end-of-life vehicle reverse logistics showing the number, location and throughput of the return stations, dismantlers and the flow among the entities. What makes this model different is that the modelling 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. 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 end-of-life vehicle recycling network in Mexico has been presented in the work by Cruz-River and Ertel [1]. In this model it has been assumed that the return stations are also dismantlers, i.e. the structure of the network has been simplified. The basic feature that distinguishes this model is that the locations of the regional distribution centres are not selected from among the initially set potential locations but are indicated by the model.

In Poland the issue of designing the ELV recycling network was brought up by Gołębiewski and Choromański [4, 5]. They used one of heuristics methods, genetic algorithm, for the optimization of dismantler's locations in selected areas.

The above-presented works are focused on designing of a separate network for the recovery 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 end-of-life vehicle recycling network has been presented in the work of Zarei et al. [9]. 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 of joint distribution and return entities, the costs of developing of the dismantlers and the costs of transport of end-of-life vehicles and materials.

Also Schultmann et al. [8] 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 functioning location of the entities and the material flows based on the German end-of-life vehicle recycling network.

3. Recycling network model

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 i.e. 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.

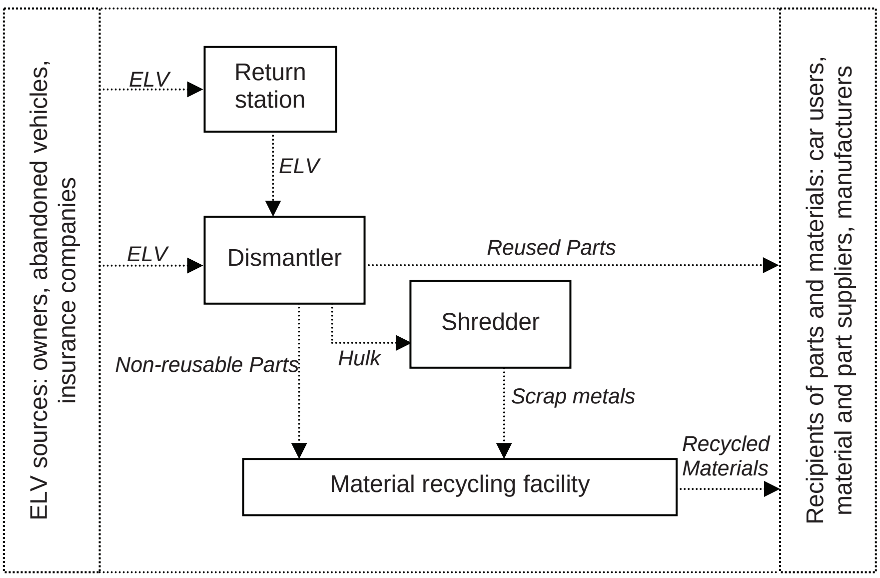

Fig. 1. The participants and the flows in the recycling network

The parts that are good for further use go directly to the sales channels and the other 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 on the market.

4. Formulation of the optimization task

For the creation and optimization of the structure of the recycling network it is necessary to use decision aiding optimization methods. Mathematical modelling is one of the most effective ones. Picking the optimum solution requires determining a decisive criterion that is the indicator of the quality of the solution (the solution that is the optimum one from a set of feasible decisions). The optimization criterion is a reflection of the preference function of the entity making a decision. Depending on the number of preference functions included as partial functions of the criterion, the optimization tasks can be divided into single and multi criteria ones.

Single criterion optimization tasks are more frequently used because of their simpler process of formation and simpler realization as well as quicker and easier finding of optimum solutions. The most frequent objective functions in single criteria optimization tasks are the minimization of costs or the maximization of profit.

Below an example formulation of an optimization task will be presented, whose subject is the optimization of the location of entities of an ELV recycling network.

The assumptions to the creation of the network are as follows:

- The optimization pertains to the return stations (*p*), dismantlers (*s*) and industrial shredders (*m*);
- The selection of the final location is done from among the indicated admissible locations. The sets of potential locations of the return stations, dismantlers and industrial shredders are given;
- The sources of ELVs (i) are municipalities;
- The ELV's owners shall not travel more than 50km to return their vehicles to the recycling network;
- All returned vehicles have to be subsequently forwarded to the dismantlers;
- The plastic recycling facilities (*t*) and non-ferrous metals recycling facilities (*n*) are selected for the collaboration with the dismantlers. Only those processing facilities were selected that generated the highest costs for the stations. The model does not include materials that do not generate costs related to their forwarding to the recycling facilities and for which the return network is sufficiently dense and does not influence the location of the dismantler (tires, batteries, used oil);
- The shredders collaborate similarly with the non-ferrous materials recycling facilities (*n*) and additionally with the ferrous materials recycling facilities (*z*).

The decision variables are the location variables indicating the location of the analyzed entities where:

- x_p^P – denotes a binary variable that equals 1 if locating the return station in a *p*-th location or 0 in an opposite case;
- x_s^S – denotes a binary variable that equals 1 if locating the dismantler in a *s*-th location or 0 in an opposite case;
- x_m^M – denotes a binary variable that equals 1 if locating the industrial shredder in a *m*-th location or 0 in an opposite case.

During the tasks-solving process the following quantitative variables are also determined:

- f_{ip}^A – the number of ELVs transported between sources (*i*) and return stations (*p*),

- f_{is}^{B} – the number of ELVs transported between source (*i*) and dismantler (*s*),
- f_{p}^{P} – the number of ELVs transported to *p*-th return station,
- f_{s}^{S} – the number of ELVs transported to *s*-th dismantler,
- f_{m}^{M} – the mass of waste transported to *m*-th shredder,
- f_{t}^{T} – the mass of waste transported to *t*-th plastic recycling facility,
- f_{n}^{N} – the mass of waste transported to *n*-th non-ferrous metal recycling facility,
- f_{z}^{Z} – the mass of waste transported to *z*-th ferrous metal recycling facility.

The objective function reflects the preferences of the participants of the recycling network. It has been assumed that the main objective of the entities is the minimization of the total costs of creating and functioning of the recycling network that are constituted by such costs as: operating costs of the entities, costs of transport of ELVs, costs of transport of hulk and waste .

For the dismantlers and the industrial shredders the operating costs are composed of overheads (k^{SS} and k^{SM} respectively) and variable costs (k^{ZS} and k^{ZM} respectively). The overheads reflect the expenditure for start-up and equipping of the entity (depreciation) and cover other costs generated in relation to keeping of the system ready for operation (i.e. personnel wages). The level of the overheads depends on the maximum capacity of the entity (μ_s^S and μ_m^M) but it does not depend on the actually processed mass of waste or number of ELV. The unit variable cost denotes a cost of processing of a single ELV or 1 kg of waste. Hence the total variable costs grow proportionally to the actual throughput. In the case of return stations variable costs have not been determined as these entities do not process ELVs but forward them directly to the dismantlers and their total costs equal to the overheads (k^{SP}). What is more, the return stations do not have a maximum capacity and overheads have the same value for all return stations.

The costs of transport of ELVs are the sum of the unit costs of the ELV transport (k^{TELV}), the number of the vehicles transported between the entities and the distance between the sources and the return stations (d_{ip}^{A}), the sources and the dismantlers (d_{is}^{B}) and the return stations and the dismantlers (d_{ps}^{C}). The costs of transport of waste between the entities that are the sum of unit costs of transport of waste (k^{TD} for hulk, k^{TE} for plastic waste from dismantlers, k^{TF} for non-ferrous metal waste from dismantlers, k^{TG} for non-ferrous metal waste from shredders and k^{TH} for ferrous metal waste from shredders), the mass of waste and the distance between the entities i.e. the dismantlers and the shredders (d_{sm}^{D}), the dismantlers and the plastic recycling facilities (d_{st}^{E}) and the non-ferrous metal recycling facilities (d_{sn}^{F}) and finally the shredders and the non-ferrous and ferrous metals recycling facilities (d_{mn}^{G}, d_{mz}^{H}). The mass of waste transported from dismantlers and shredders to different entities is calculated based on conversion factor (χ). A conversion factor of waste processed at dismantler is χ^D for hulk, χ^E for plastic waste and χ^F for non-ferrous metals. For shredders χ^G refers to conversion factor for non-ferrous metals and χ^H refers to conversion factor for ferrous metals.

The total costs (*KC*) will be minimized, hence the objective function will have the form:

$$KC = \sum_{p=1}^{P} k^{SP} x_p^P + \sum_{s=1}^{S} (x_s^S k^{SS}(\mu_s^S) + k^{ZS} f_s^S) + \sum_{m=1}^{M} (x_m^M k^{SM}(\mu_m^M) + k_m^{ZM} f_m^M) +$$

$$+ \sum_{i=1}^{I}\sum_{p=1}^{P} f_{ip}^{A} d_{ip}^{A} k^{TELV} + \sum_{i=1}^{I}\sum_{s=1}^{S} f_{is}^{B} d_{is}^{B} k^{TELV} + \sum_{p=1}^{P}\sum_{s=1}^{S} f_{p}^{P} d_{ps}^{C} k^{TELV} + \sum_{s=1}^{S}\sum_{m=1}^{M} \chi^{D} f_s^S d_{sm}^{D} k^{TD} +$$

$$+ \sum_{s=1}^{S}\sum_{t=1}^{T} \chi^{E} f_s^S d_{st}^{E} k^{TE}(\mu_s^S) + \sum_{s=1}^{S}\sum_{n=1}^{N} \chi^{F} f_s^S d_{sn}^{F} k^{TF}(\mu_s^S) +$$

$$+\sum_{m=1}^{M}\sum_{n=1}^{N}\chi^{G} f_{m}^{M} d_{mn}^{G} k^{TG}(\mu_{m}^{M}) + \sum_{m=1}^{M}\sum_{z=1}^{Z}\chi^{H} f_{m}^{M} d_{mz}^{H} k^{TH}(\mu_{m}^{M}) . \tag{1}$$

The creating of the recycling network requires a variety of constraints to be taken into account. The equation (2) refers to the collection of all ELVs from the sources. The other limitations Eqs (3), (4), (5), (6), (7), (8) are limitations related to the flows according to which the sum of flows at the entity input must equal that at the output using the conversion factor.

$$\sum_{p=1}^{P} f_{ip}^{A} + \sum_{s=1}^{S} f_{is}^{B} = f_{i}^{I}, \quad \forall i = 1\ldots I, \tag{2}$$

$$\sum_{i=1}^{I} f_{ip}^{A} = f_{p}^{P}, \quad \forall p = 1\ldots P, \tag{3}$$

$$\sum_{i=1}^{I} f_{is}^{B} + \sum_{p\in P^{S}(s)} f_{p}^{P} = f_{s}^{S}, \quad \forall s = 1\ldots S, \tag{4}$$

$$\chi^{D} \sum_{s\in S^{M}(m)} f_{s}^{S} = f_{m}^{M}, \quad \forall m = 1\ldots M, \tag{5}$$

$$\chi^{E} \sum_{s\in S^{T}(t)} f_{s}^{S} = f_{t}^{T}, \quad \forall t = 1\ldots T, \tag{6}$$

$$\chi^{F} \sum_{s\in S^{N}(n)} f_{s}^{S} + \chi^{G} \sum_{m\in M^{N}(n)} f_{m}^{M} = f_{n}^{N}, \quad \forall n = 1\ldots N, \tag{7}$$

$$\chi^{H} \sum_{m\in M^{Z}(z)} f_{m}^{M} = f_{z}^{Z}, \quad \forall z = 1\ldots Z . \tag{8}$$

Then, limitations were introduced related to the throughput potential Eqs (9), (10), (11), (12), (13). 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 with which they are in collaboration.

$$f_{s}^{S} \le \mu_{s}^{S}, \quad \forall s = 1\ldots S, \tag{9}$$

$$f_{m}^{M} \le \mu_{m}^{M}, \quad \forall m = 1\ldots M, \tag{10}$$

$$f_{t}^{T} \le \mu_{t}^{T}, \quad \forall t = 1\ldots T, \tag{11}$$

$$f_{n}^{N} \le \mu_{n}^{N}, \quad \forall n = 1\ldots N, \tag{12}$$

$$f_{z}^{Z} \le \mu_{z}^{Z}, \quad \forall z = 1\ldots Z . \tag{13}$$

Another limitation eons (14), (15) 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 should not travel more than a certain distance (d^{max}) to return an ELV to the recycling network.

$$d_{ip}^{A} \le d^{\max}, \quad \forall i = 1\ldots I, p = 1...P, f_{ip}^{A} \ne 0, \tag{14}$$

$$d_{is}^{B} \le d^{\max}, \quad \forall i = 1\ldots I, s = 1...S, f_{is}^{B} \ne 0 . \tag{15}$$

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.

The above formulated optimization task enables an optimum selection of the locations of the key participants of the end-of-life vehicle recycling network (return stations, dismantlers and industrial shredders) in terms of total costs of the creation and keeping of the network. The selection takes place from the indicated set of admissible locations of the infrastructure elements. The solving of the task also provides the answer to the question of the material flow among the individual network entities.

5. Results of the optimization task

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 achieving 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.

Summarizing the solutions proposed by the software we could draw the following conclusions:

- Out of the existing entities the software selected 3 return stations (3% of the existing ones) and 389 dismantlers (57% of the existing ones) and all existing shredders.
- The majority of the costs of the whole system are the operating costs of the entities (93% of the total costs) while the transport costs have a 7% share in the total costs.
- More than a half of the transport costs is the cost of transporting of the hulk from the dismantlers to the industrial shredders (53%) and out of the total operating costs the costs of industrial shredders constitute 54% and the dismantlers nearly 46%.

The results of the task indicate that the transport of waste does not play a significant role in the total costs of functioning of the system. What is important is that the use of all entities be optimized i.e. in the network there should be as few entities as possible with their capacity maximized.

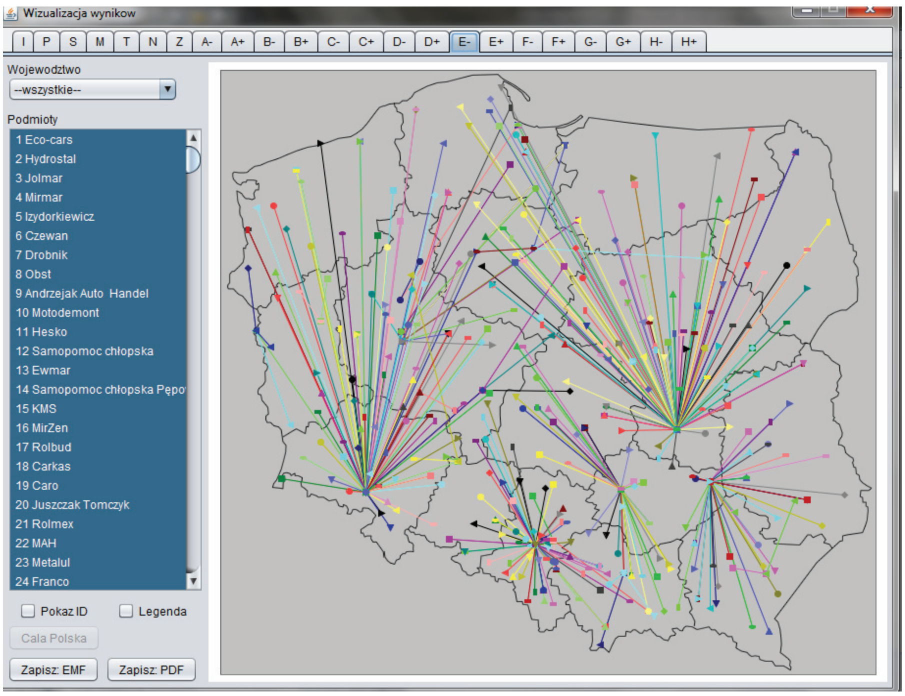

Fig. 2. Visualisation of the results for flows between dismantlers and plastic recycling facilities

6. Conclusions

Designing of a vehicle recycling network is a complex issue. The decisions related to the locations of the recycling entities should take into account as many factors as possible (technical, economic, environmental and legal). If so, the formation of a selected fragment of the network shall ensure maximization of the benefits from both the point of view of the network participant and that of the vehicle owners not to mention other stakeholders.

Complex problems require proper tools facilitating the decision making process. That is why, recently, single and multi criteria decision support design methods have been used for the designing of the recycling network. A novelty in the decision support in modelling of recycling networks and optimization of the network entity locations is the use of the heuristic methods (i.e. genetic algorithms) that gain in popularity among researcher and decision makers.

The here described example application of optimization of the recycling network entities location is a useful tool for the designing of network as well when creating a new network as extending the existing network by new entities.

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