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ASSESSMENT METHOD OF END-OF-LIFE VEHICLES RECYCLING NETWORK EFFICIENCY

Agnieszka Merkisz-Guranowska

Poznan University of Technology
Faculty of Machines and Transportation
Piotrowo Street 3, 60-965 Poznan, Poland
tel.: +48 61 6475958, e-mail: agnieszka.merkisz-guranowska@put.poznan.pl

Abstract

Recycling is a final stage closing the life cycle of vehicles. The quality of this process affects the combined impact of automobiles on the environment. Recycling networks differ in the level of efficiency due to the differences in how the recycling system is organized, their environment, and the characteristics of the entities taking part in recycling process. The article presents an algorithm of a method for assessing the effectiveness of a vehicle-recycling network, which can be used in a comparative analysis of networks, or for evaluating changes over time. A set of indicators relating to the technical, economic, environmental, and social aspects was proposed.

The article presents the variety of aspects involved in assessing, the efficiency of a vehicle-recycling network the best solution seems to be the inclusion of selected indicators for the assessment model, which will also act as a tool to assess the state of the network and conduct rankings of available solutions. The model for assessing the efficiency has to be preceded by determining the purpose and scope of the assessment and analysis of available evaluation tools.

Keywords: *recycling network, end-of-life vehicles, system efficiency, indicators*

1. Introduction

The car became a symbol of the progress of civilization, and the volume of the vehicle fleet is one of the indicators of economic development of a country. The dynamic development of the automotive industry unfortunately also entails negative consequences, both for humans and for the environment. These effects include, among others, waste generated by vehicles both at the stage of production, operation, as well as their end-of-life. One of the ways to reduce waste is its recovery, so its economic use. The condition for the effective treatment of vehicles is to create a recycling network, whose objective is receiving end-of-life vehicles (ELV) from their owners and processing them for recovery.

The most developed recycling networks operate in the European Union (EU), Norway and Japan. The organization of the networks, even among EU countries, where the Directive 2000/53/EC on end-of-life vehicles [7] is applied, is significantly different. Recycling systems differ mainly in: the scope of the recycling legislation, the obligations imposed on manufacturers and importers of vehicles and other network entities, solutions for financing of the recycling process, the requirements for dismantlers and shredders, incentives for the last owners to transfer ELVs to the official network, methods of monitoring the market, network coverage, meaning the number and type of companies involved in the handling of ELVs, and the range of activities associated with the recovery and recycling of vehicles, i.e. the degree of dismantling and shredding. These differences eventually translate into the level of efficiency of the entire system. In connection with the diversity of operating networks, tools that can be used for a comparative analysis and evaluation of the effectiveness of recycling solutions are highly sought after.

2. Efficiency assessment tools

2.1. The efficiency of a recycling network

In the common meaning efficiency refers to the economic rationality and means the ratio of the results achieved to the costs incurred [9]. In the literature, in addition to economic efficiency, also organizational efficiency and technical efficiency are defined. Organizational efficiency refers to the functioning of the organization (also the system) and determines the ability to adapt to changes in the environment and the effective use of resources to achieve the objectives [3]. Technical efficiency is related to maximizing the volume of production using given expenditures.

The efficiency of the system is determined on one hand by the results of its operation, namely the degree of achieving the objectives of the system, and on the other hand by the ability to use existing elements of the system (the quantity of the resources involved) to achieve the objectives.

2.2. Efficiency evaluation methods

Among the methods of assessing the efficiency of a network, the following methods can be highlighted:
– quantitative (quantifiable): indicators, parametric, non-parametric,
– qualitative (descriptive),
– mixed.

Quantitative methods lead to the determination of numerical parameters (in appropriate units) characterizing the studied phenomenon or object researched. Using qualitative methods does not specify numerical values, and the aim of the research is in-depth knowledge of the phenomenon and relationships occurring in the system. Qualitative methods give subjective results; however, in situations where certain phenomena cannot be measured they are the only tool that can be used. An example of qualitative methods is the expert's method, which delegates the development of the evaluation system to a group of professionals in the field. Mixed methods combine qualitative (descriptive) and quantitative approach mostly by quantifying the phenomena described (e.g. The Analytic Hierarchy Process, SWOT analysis).

In the assessment of recycling network, quantitative methods are most commonly used. Indicator methods rely on the use of indicators, which describe the relationship between different characteristics. The choice of indicators depends on the purpose of the evaluation. The use of indicators is based on selecting a certain set of data and its treatment properly to use it in the decision-making process. The use of indicators allows monitoring the trends that occur in the system, and also allows for an assessment of the effectiveness of actions taken [17]. One selected indicator can be used, as well as a set of indicators or a synthetic indicator containing multiple aspects of the evaluation at the same time.

Indicators of waste management are the basis for comparative analysis and determining the direction of changes in an effort to create better systems [18]. Initially single indicators were used, most commonly cost indicators (assuming a certain system performance) or environmental indicators based on the degree of recycling [8, 10]. Due to the disadvantages of using a purely economic approach or based only on the recycling indicator, with time it has become more common to use multiple indicators simultaneously. The motivation behind it is that it is not possible to evaluate complex systems fulfilling social, environmental and economic functions with just one indicator. Such an approach was used, among others, in the papers: Chavez et al. [5], Arendse and Godfrey [2], the OECD [15], Mendes et al. [13], Wilson et al. [19], Armijo et al. [1] Olugu et al. [16]. A review of these researches has been done in papers [5, 8]. The common element of these publications is that they identify the multifaceted nature of assessment of waste management, and the need to consider all: the technical, economic, environmental, but also social aspects [5, 19].

Parametric methods are focused on solving optimization problems. They can be used when evaluating systems with a well-defined structure, which determines the choice of the estimated parameters. Parametric methods use both deterministic and stochastic models. Parametric models use the tools of financial analysis or econometric models in the assessment of a recycling network.

Financial analytical models can be based on the costs [4] or on the profitability of the system. A method using a profitability assessment is the commonly used cost-benefit analysis [6, 11, 14].

Another economic tool that can be used to evaluate recycling networks is the marginal cost analysis [14]. The purpose of this analysis is to identify at what amount of recycled waste the system is cost-effective, and thus economically viable. The main advantage of using the methods of economic analysis is a clear presentation of the results, because all effects are summed up into a single monetary value. This makes it easy to determine which scenario is the most efficient in terms of resources used. However, the disadvantage of these models is the difficulty in estimating the monetary cost of environmental and social impacts, which are often intangible.

The most commonly used nonparametric method in the evaluation of the efficiency is the *Data Envelopment Analysis* (DEA). The main advantage of the DEA method (and more broadly, the nonparametric approach as a whole) is that it does not require knowledge of the functional relation between costs and effects. Based on empirical values of costs and effects, the nonparametric methods use a linear programming procedure to determine such weight values for which the efficiency indicator is at maximum. The optimization carried out individually for each object is based on the data on costs and benefits of the full tested set, and the resulting value of the efficiency of the object is the relative efficiency i.e. it is determined in relation to other objects. The DEA method was used in evaluating the efficiency of a Portuguese recycling network by Marques et al [12] among others.

3. The method of assessing the efficiency of a recycling network

3.1. Method algorithm

The proposed procedure for assessing the efficiency of recycling networks includes 4 main phases:

1. Identifying the different scenarios of organization of recycling systems – the choice of variants used to assess the efficiency.
2. Identifying the indicators – determining the purpose and the scope of the assessment, reviewing of available indicators, establishing the criteria for the evaluation of indicators, evaluating the indicators, selection of a set of indicators chosen for the efficiency assessment.
3. Determining the value of the indicators – gathering source data, determining the numerical values of indicators, normalization of the indicators.
4. Creating a comparable ranking of recycling networks – determining the total sum of the evaluated variants, assigning variants to performance categories, ranking of the variants.

The first step is to select the variants for the assessment of the network. In the analysis, we assume that there is a set of network variants $\boldsymbol{W}$ designated as:

$$\boldsymbol{W} = \{1,2,\dots,w,\dots,\overline{W}\}, \tag{1}$$

where the requirement for comparative analysis is defining at least two variants of the recycling network, i.e. $\overline{W} \geq 2$.

Another very important step is the selection of indicators relevant to the assessment of the system. These indicators provide partial criteria for assessing the efficiency of the network. Overview of indicators should include an analysis of literature and opinions of experts in the field of vehicle recycling network organization and waste management as a whole.

The next step is to select the final number of indicators from the previously identified set. Choosing indicators should be guided by the objective of the evaluation as well as data availability. It is assumed that the set of evaluated indicators $\boldsymbol{I}$ of the analysed variants of the recycling network is:

$$\boldsymbol{I} = \{1,2,\dots,i,\dots,\overline{I}\}. \tag{2}$$

At this stage the validity of indicators, i.e. their appropriate weight $c(i)$ should also be determined. Determining the weight (also called the weighting factors) of each, one of the indicators must reflect the importance of that indicator for the overall assessment of the system efficiency. It is assumed that:

$$\forall i \in \boldsymbol{I} \ \ c(i) \geq 0 \wedge c(i) \leq 1 \ and \ \sum_{i \in \boldsymbol{I}} c(i) = 1 \ . \qquad (3)$$

Evaluation of indicators and assigning them weight is based on the opinions of stakeholders (people involved or interested in the functioning of the system) who assess the relevance and validity of each of the identified indicators or on the expert method, in which case experts from the fields associated with the operation of a recycling network rate the weight of the indicators.

In the next stage of the method, all variants of the network from the point of view of the individual indicators are assessed. Estimation of the indicators requires the collection of data and the determination of the values of indicators. The assessment of a variant of the network organization w from the point of view of the chosen indicator i, for the purpose of further consideration will be denoted as $f(w, i)$.

The condition for conducting a comparative analysis of variants of the recycling network and to ensure comparability between indicators is the normalization of the evaluation obtained on the basis of indicators. The evaluation of variants determined by individual indicators can be expressed in different units and use maximized criteria (the higher the value the higher the efficiency) or minimalized criteria (the lower the value, the higher the efficiency). One of the scaling methods, i.e. the method of point aggregation or the method of quotient normalization can be used to normalize the indicators. In this case, the second of these methods is used. Thus:

– in case of maximized criteria:

$$e(w, i) = \frac{f(w,i)}{max_{w \in \boldsymbol{W}}\{f(w,i)\}}, \qquad (4)$$

– in case of minimized criteria:

$$e(w, i) = \frac{min_{w \in \boldsymbol{W}}\{f(w,i)\}}{f(w,i)}. \qquad (5)$$

The value of $e(w, i)$ determined by the formula (4) or (5) is the normalized evaluation of the variant *w* from the point of views of the indicator *i*.

The next step after the normalization of the evaluation is to determine the synthetic assessment values of specific variants of the network, according to the formula:

$$\boldsymbol{F}(w) = \sum_{i \in \boldsymbol{I}} c(i) \cdot e(w, i), \qquad (6)$$

where $\boldsymbol{F}(w)$the synthetic assessment of variant w. Categorization of solutions is also performed, i.e. assigning of the degree of efficiency to individual total values. Thus, a recycling network can receive an assessment of the efficiency in the form of:

– excellent – the total evaluation score is 75% of the maximum value or above,
– good – the total evaluation score is in the range 61 to 75% of the maximum value,
– average – the total evaluation score is between 40 and 60% of the maximum value,
– unsatisfactory – the total evaluation score is 40% of the maximum value or below.

In the last stage of the procedure, a ranking system based on the total value of normalized indicators was created. The variant of the network organization that is best according to the accepted performance indicators is the variant w^*, which follows the relation:

$$w^*: \boldsymbol{F}(w^*) = max_{w \in \boldsymbol{W}}\{\boldsymbol{F}(w)\}. \qquad (7)$$

3.2. A set of indicators

Indicators are an essential element of the assessment of a recycling network. More specifically, they are used to measure efficiency, to identify the strengths and weaknesses of the system, and for setting goals and actions for the future. Indicators available in literature were assessed against the following criteria:

- indicators are adequate for the purpose of the evaluation – the results obtained with the use of an indicator reflect the purpose of the evaluation faithfully, or as close as possible,
- usefulness for the evaluation of the recycling network – the indicators must be relevant to the assessment of the recycling network and allow the evaluation of changes in the network,
- reliability – in order to ensure the validity of the measurements, the indicators must be based on reliable information,
- objectivity – there are no uncertainties in the interpretation of the indicator, and constructing the indicator was done using generally accepted definitions,
- simplicity – the indicator ought to be simple in design and easy to interpret,
- usability – the data necessary for the calculation of the indicator value can be obtained in a timely manner and at a reasonable cost,
- comparability – the data used to calculate the indicators should allow for evaluation of different systems.

The described method uses 10 indicators relating to economic, environmental, social and technical aspects. Most indicators were selected from the environmental group, since the main purpose of a recycling network is appropriate waste management and reduction of the environmental impact of ELVs. The indicators selected for use in the algorithm are described in Tab. 1-10.

Tab. 1. The characteristics of the indicator of ELV collection points in relation to the country's area

Aspect	Characteristics
Indicator	The equipment in ELV collection points in relation to the country's area.
Purpose	Allows the assessment of infrastructure availability in a given area.
Interpretation	The higher the indicator value, the greater the vehicle collection network and higher saturation of infrastructure.
Formula	$I_{ECP} = \frac{N_{CP}}{S} * 10000\ km^2,$ (8) N_{CP} – number of points collecting ELVs, i.e. places where the owners of ELV may hand the vehicle over to a recycling network, S – country land area in km^2.
Range of values	0-10 very low, 11-20 low, 21- 60 satisfactory, 61-100 average, >100 high.

Tab. 2. The characteristics of the indicator of dismantlers in relation to the number of ELVs

Aspect	Characteristics
Indicator	Number of vehicle dismantlers to the number of ELVs.
Purpose	Allows the assessment of the required processing capacity of the dismantling stations.
Interpretation	The higher the indicator value, the greater should be the processing capacity of the dismantlers.
Formula	$I_{D\_ELV} = \frac{N_{ELV}}{N_D},$ (9) N_D – number of dismantlers, N_{ELV} – number of ELVs in the country.
Range of values	0-300 very low, 301-500 low, 501-700 satisfactory, 701-1000 average, >1000 high.

4. Conclusions

Given the variety of aspects involved in assessing, the efficiency of a vehicle-recycling network the best solution seems to be the inclusion of selected indicators for the assessment model, which will also act as a tool to assess the state of the network and conduct rankings of available solutions.

Tab. 3. The characteristics of the indicator of the recycling system profitability for the owners of ELV

Aspect	Characteristics
Indicator	Profitability of the system for the owners of ELV.
Purpose	Allows the assessment of financial benefits and incentives from the point of view of the owner of the ELV.
Interpretation	Indicator of a positive value indicates a net financial benefit to the owner of the ELV. The higher the value, the greater the financial benefits. A negative value means that the ELV owner partially covers the operating costs of the recycling network.
Formula	$$I_{OP} = CV_{ELV} - \sum_{t=1}^{n} FV_{ELV}, \quad (10)$$ CV_{ELV} – the value of the compensation received for the transfer of ELV to the network, FV_{ELV} – the value of the fee paid towards the recycling system by the vehicle owner, t – the service life of the vehicle, where $t = (1, \ldots, n)$.
Range of values	< –30 very low, from –30 to 0 low, 0 satisfactory, 0-50 average, >50 high.

Tab. 4. The characteristics of the indicator of ELV recovery

Aspect	**Characteristics**
Indicator	ELV mass recovery.
Purpose	Determines the degree of ELV mass recovery.
Interpretation	The higher the ratio, the greater the efficiency of the system and the more waste that is used economically. In EU countries, the minimum required by law recovery rate is 95% of the mass of the vehicle.
Formula	$$I_{RV\_ELV} = \frac{M_{PR}+M_{MR}+M_{ER}}{M_{ELV}} * 100\% , \quad (11)$$ M_{ELV} – ELV mass when entering the recycling network, M_{PR} – mass of waste designated for product recycling, M_{MR} – mass of waste designated for material recycling, M_{ER} – mass of waste designated for energy recovery.
Range of values	0-60% very low, 61-70% low, 71-80% satisfactory, 81-90% average, >90% high

Tab. 5. The characteristics of the indicator of shredding recovery from ELV

Aspect	**Characteristics**
Indicator	Recovery of the elements sent to shredding.
Purpose	Determines the degree of recovery of vehicle elements designated for shredding (i.e. the vehicle body after the dismantling of parts and components), thus the efficiency of industrial shredders.
Interpretation	The higher the indicator value, the greater the efficiency of the industrial shredders and less waste from ELVs needing disposal.
Formula	$$I_{RV\_SHRED} = \frac{M_{MRS}+M_{ERS}}{M_B} * 100\% , \quad (12)$$ M_{MRS} – mass of waste from the industrial shredder designated for material recycling, M_{ERS} – mass of waste from the industrial shredder designated for energy recovery, M_B – mass of the vehicle body designated for shredding.
Range of values	0-60% very low, 61-70% low, 71-80% satisfactory, 81-90% average, >90% high

Constructing a model for assessing the efficiency must be preceded by determining the purpose and scope of the assessment and analysis of available evaluation tools (e.g. indicator sets). The indicator values of systems with high efficiency can be treated as the so-called benchmark values.

Tab. 6. The characteristics of the indicator of ELV recycling

Aspect	Characteristics
Indicator	ELV mass recycling.
Purpose	Determines the level of recycling of the ELV vehicle mass.
Interpretation	The higher the ratio, the greater the efficiency of the system and the more waste that is used economically. In EU countries, the minimum required by law recycling rate is 85% of the mass of the vehicle.
Formula	$$I_{REC\_ELV} = \frac{M_{PR}+M_{MR}}{M_{ELV}} * 100\% \,, \quad (13)$$ M_{ELV} – ELV mass when entering the recycling network, M_{PR} – mass of waste designated for product recycling, M_{MR} – mass of waste designated for material recycling.
Range of values	0-50% very low, 51-60% low, 61-70% satisfactory, 71-80% average, >80% high

Tab. 7. The characteristics of the indicator of waste reduction

Aspect	Characteristics
Indicator	Waste reduction.
Purpose	Specifies the reduction of the amount of waste generated by residents thanks to the recycling of ELVs.
Interpretation	The higher the indicator value, the more waste is used economically and less waste is transferred to a landfill.
Formula	$$I_{ELV\_W} = \frac{M_{ELV}*I_{RV\_ELV}}{M_W} * 100\% \,, \quad (14)$$ M_{ELV} – ELV mass when entering the recycling network, I_{RV_ELV} – the ELV recovery rate, M_W – the total mass of waste generated in the country.
Range of values	<0.1% very low, 0.1-0,5% low, 0.51-0.65% satisfactory, 0.66-0.75% average, >0.75% high

Tab. 8. The characteristics of the indicator of the number of ELVs in relation to the vehicle fleet size

Aspect	Characteristics
Indicator	ELV number in relation to the fleet size.
Purpose	Specifies the number of vehicles being withdrawn from service every year and transferred to the recycling network in relation to the entire fleet.
Interpretation	The higher the indicator, the younger the fleet in the country, due to a greater rate of replacement.
Formula	$$I_{ELV\_FLEET} = \frac{N_{ELV}}{N_{FLEET}} * 100\% \,, \quad (15)$$ N_{ELV} – the number of ELVs in the country, N_{FLEET} – the number of registered vehicles.
Range of values	<2% very low, 2-3% low, 3.1-4% satisfactory, 4.1-5% average, >5% high

This allows the organizers of the system to be able to evaluate how the results of the analysed recycling network shape in relation to the reference values. This allows for setting priorities and trends, determining and subsequently taking the necessary steps to improve the functioning of the recycling network as well as to monitor changes over time. Furthermore, a deeper analysis of the

Tab. 9. The characteristics of the indicator of network availability for residents

Aspect	Characteristics
Indicator	Network availability for residents.
Purpose	Specifies the number of inhabitants for every facility designed for taking back or dismantling vehicles.
Interpretation	The lower the ratio, the easier it is for a statistical resident to find a facility to hand over an ELV.
Formula	$$I_{RNA} = \frac{N_P}{N_F}, \quad (16)$$ N_P – country's population size, N_F – number of facilities taking back ELVs, i.e. places where the owners of such vehicles may hand the vehicle over to a recycling network.
Range of values	>100000 very low, 80001-100000 low, 60001-80000 satisfactory, 30000-60000 average, <30000 high

Tab. 10. The characteristics of the indicator of participation rate

Aspect	**Characteristics**
Indicator	Participation rate.
Purpose	Determines the percentage of the population that decides to hand over their ELVs to a national recycling network.
Interpretation	The higher the ratio, the higher the profitability of the network and the fewer ELVs are dismantled illegally or outside the country.
Formula	$$I_{PR} = \frac{N_{ELV\_RN}}{N_{ELV}} * 100\% \,, \quad (17)$$ N_{ELV_RN} – the number of ELVs processed legally in the country, N_{ELV} – the total number of vehicles taken out of service in the country.
Range of values	<51% very low, 51-70% low, 71-80% satisfactory, 81-90% average, <90% high

functioning of the most effective recycling networks makes it possible to identify the best practices and solutions for the recycling of vehicles and apply the selected solutions at the local level.

The presented algorithm of efficiency evaluation assumes that both the evaluation criteria and the analysed variants of recycling networks are known (it excludes the evaluation of systems whose characteristics are determined through the simulations). The most important stage of aiding the decision-making process is in this case the selection of indicators with the expert's method and assessing the available variants.

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