ARCHIVES OF TRANSPORT
Volume 54, Issue 2, 2020

ISSN (print): *0866-9546*
e-ISSN (online): *2300-8830*
DOI: *10.5604/01.3001.0014.2971*

A COMPARATIVE STUDY ON END-OF-LIFE VEHICLES NETWORK DESIGN

Agnieszka MERKISZ-GURANOWSKA
Poznan University of Technology, Institute of Transport, Poznan, Poland

Abstract:

This paper investigates the current research in the field of the end-of-life vehicles (ELV) recycling network. The optimisation of the location of a network facilities in forward logistics in the automotive industry has received a lot of attention for many years but the reverse logistics for ELVs has been a subject of investigations since the beginning of 21st century. ELV recycling network design gained in popularity after the European Union and other countries like Japan, South Korea and recently China introduced legal obligations to organize a collecting or recycling network for used vehicles.
When regulations are introduced, there is a need for a systemic solution to the problem, especially since the obligation to create a collection network is often accompanied by requirements related to its accessibility for vehicle owners or efficiency of operation. With the growing scope of legal regulations, companies or organisations responsible for the network are forced to redesign the existing recycling infrastructure in a given area so that it meets specific requirements. Initially, the most important criterion was network availability. Currently, the same importance is attached to economic, environmental and social aspects in order to meet the sustainability criteria.
In this paper, forty one peer-reviewed published studies focused on network design were classified. Its main purpose is to provide an extensive review of state-of-the-art research published in the period 2000-2019. The scope of the review is limited to network design problems including facility location and flow allocation problems. Only papers that present mathematical models are considered. Studies on the ELV network design are classified based on: type of supply chain, type of network, optimisation problem, type of facilities, modelling technique, single/multi objectivity, objective function, period of time, solution approach and scope of implementation. The final part of the paper includes discussion of the methodology of the reviewed studies and some recommendations for future research area.

Keywords: *end-of-life vehicles, ELV reverse logistics, ELV recycling network, ELV network design*

To cite this article:

Merkisz-Guranowska, A., 2020. A comparative study on end-of-life vehicles network design. Archives of Transport, 54(2), 107-123. DOI: https://doi.org/10.5604/01.3001.0014.2971

Contact:

agnieszka.merkisz-guranowska@put.poznan.pl [https://orcid.org/0000-0003-2039-1806]

1. Introduction

The article presents a comparative study of research on the organisation of the end-of-life vehicles recycling network. Since the introduction of the EU Directive 2000/53/EC imposing the obligation to organise a vehicle collection network, not only European scientists have begun to attach more and more attention to the issues of ELV network design. If there are no rules in a given area regarding the organisation of the network, it develops on a market-driven basis. This is how the network works in the United States, Canada or Australia. However, when regulations are introduced, there is a need for a systemic solution to the problem, especially since the obligation to create a collection network is often accompanied by requirements related to its accessibility for vehicle owners or efficiency of operation. The approaches used vary greatly depending on who is responsible for organising the network. The main differentiator of approaches is also whether the network is designed as an open loop or as a closed loop network, in which the same entities are responsible for the distribution of new cars and collection of ELVs from owners. Assuming an open loop reverse logistics network, four types of entities deal with recycling of ELVs: collection points, dismantlers, shredders and material recycling facilities. ELV owners transfer vehicles to collection points or dismantlers. The task of collection points is to temporarily store vehicles, issue certificates confirming that the vehicle has been handed over for recycling and then deliver ELVs to dismantlers. At the dismantler, the vehicle is dried and hazardous elements (e.g. batteries) are removed. Then parts and subassemblies for reuse (directly or after remanufacturing) as well as subassemblies and parts intended for material recycling (e.g. plastic bumpers, windscreens, wire harnesses) are disassembled. After dismantling, the hulk is compressed and transferred to a shredder, whose task is mainly to recover metals. The recycled materials separated in dismantlers and shredders are transferred to specialised material recycling facilities. If the traditional logistics network (forward logistics) is combined with reverse logistics, ELVs collection and new vehicles sales take place at the same facility, and components and recycled materials are reused in the production of new cars.

With the growing scope of legal regulations, companies or organisations responsible for the network are forced to redesign the existing recycling infrastructure in a given area so that it meets specific requirements. Initially, the most important criterion was network availability. Currently, the same importance is attached to economic, environmental and social aspects, so that vehicle reverse logistics network meets the sustainability criteria. The same approach is also used to model other aspects of vehicle life cycle (Jacyna and Merkisz, 2014; Sendek-Matysiak, 2019). The general requirements for location of ELV recycling network entities were described in a work by Merkisz-Guranowska (2009) and the set of criteria representing the base for evaluation of possible location for ELV recycling centers were defined in a work by Pavlovic et al (2011). Recycling network design is part of a wider research area called reverse logistics. A number of papers have been published on the issue of product recovery network. Characteristics that differentiates a reverse logistics system from a traditional supply chain system were presented by Jayaraman et al (2003) and Fleischmann et al. (2000). A comprehensive review of literature on the design of network for reverse logistics as well as of closed loop supply chain involving reverse logistics based on the methods to provide solution was given by Aravendan and Panneerselvam (2014).

2. Review methodology

The article presents the state of research in the area of ELV recycling network by analysing the content of 41 peer-reviewed published papers. The main goal was to analyse the applied approaches to network design in the most important publications from the period 2000-2019. The publications were identified using the Web of Science, Scopus, Google Scholar, as well as Elsevier/ScienceDirect, Emerald, Springer Online Journals, Taylor and Francis Group – Online Journals, Wiley Online Library – Journals databases, based on keywords: ELV reverse logistics, ELV recycling network, ELV network design. Review articles on similar topics (Cin and Kusakci, 2017; Karagoz et al., 2020; Gan and He, 2014; Simic and Dimitrijevic, 2019; Simic, 2013) were also a great help in reaching relevant publications.

Only peer reviewed journal papers were included in the analysis. Books, diploma thesis and reports were not covered in the review. This approach resulted from the fact that publications in journals can be traced using scientific databases, while it is difficult

to identify and overview all other major writings on selected topic.
As a literature review method the content analysis was applied to determine the approach to ELV recycling network design, identify methods used by researchers and define the scope of application of presented models.

3. Literature reviews covering the aspects of ELV recycling network management

Several review papers on ELV recycling have been published (Table 1). They cover a wide range of papers published in the period 2000-2019.
An extensive analysis in terms of both the covered period of time and the number of papers was carried out in the work of Karagoz et al. (2020). The review includes papers on ELV management research published in the period 2000-2019. A total of 232 studies were collected, categorized, reviewed and analysed. The publications were classified into four major categories: literature survey, recycling production and planning, network design and regulations review.
Simic and Dimitrijevic (2019) provided a content analysis overview of peer-reviewed international journal papers related to ELV management and more specifically to logistics network design models. They investigated the papers published in the period 2013-2019 and classified them based on their modelling technique, solution approach and type of supply chain. They also created the distribution list to identify primary publication sources.
Cin and Kusakci (2017) focused on reviewing articles that included the mathematical formulations of models for optimizing ELV recycling networks. Network design proposals were analysed based on: type of logistics network, number of criteria, optimisation model, methods to handle uncertainty and solution approach. Publications were grouped using an artificial neural network tool – Self Organizing Maps to show the frequencies of the characteristics. The scope of the analysis was limited to 23 papers that were published in the period 2005-2016.
Simic (2013) reviewed the environmental engineering issues of the ELV recycling by covering a wide range of peer-reviewed journal papers published in the period 2003-2012. The literature was organized into two main areas: general discussion and mathematical modelling research papers. In the general discussion sub-section, papers were classified into three categories: vehicle recycling practices worldwide; legislation-oriented research and remanufacturing and materials recycling. In the second subsection, papers in which authors used various methodological approaches to model different aspects of ELV processing systems were classified into four categories: life cycle assessment; location; production planning and material selection.

Table 1. Summary of review papers on ELV recycling network

Authors	Scope of review	Period covered	Number of reviewed papers
Karagoz et al. (2020)	Literature survey Recycling production and planning Network design Regulations review	2000-2019	232
Simic and Dimitrijevic (2019)	ELV logistics network design models	2013-2019	17
Cin and Kusakci (2017)	Design of the ELV logistics networks	2005-2016	23
Gan and He (2014)	Status quo and countermeasures of ELV recycling Choice of ELV recycling mode ELV recycling logistics system ELV recycling logistics network design	2002-2013	38
Simic (2013)	Vehicle recycling practices world-wide Legislation-oriented research Remanufacturing and materials recycling Life cycle assessment Location Production planning Material selection	2003-2012	94

Gan and He (2008) presented a review on ELV reverse logistics research with focus on studies published by Chinese researchers. They assigned the publications to the following areas: status quo and countermeasures of ELV recycling, choice of ELV recycling mode, ELV recycling logistics system and ELV recycling logistics network design. The authors stated that research studies on ELV recycling are mainly based on qualitative analysis. In the part concerning the design of the ELV recycling network, studies were divided depending on the mathematical model, the method or software used to solve the model, one- or multi-period optimisation, one- or multi-product optimisation, and the type of processing (remanufacturing, recycling, reuse).

As can be seen from content analysis of published review papers, the authors covered a wide range of issues related to the ELV recycling network. The scope of three reviews (Karagoz et al., 2020; Gan and He, 2014; Simic, 2013) is much broader than this review and covers all issues related to ELV management including recycling processes, production planning, legislation, material flows or types of ELV treatment. Simic and Dimitrijevic (2019) and Cin and Kusakci (2017) focused on recycling network design models but their reviews are limited both in period and the number of analysed papers. Publications on network design were classified in analysed reviews based on the type of supply chain, solution approach and their modelling technique including the type of the mathematical model, the number of criteria and the methods of handling uncertainty.

In this paper the scope of the review is limited to network design problems including facility location, facility location/flow allocation and flow allocation problems. Only papers that present mathematical models are considered. The papers were classified based on: type of supply chain, type of network, optimisation problem, type of facilities, modelling technique, single/multi objectivity, objective function, period of time, solution approach and scope of implementation. Comparing with other reviews the criteria functions are described and compared and types of facilities that are subject of optimisation are presented. Also the scope of implementation has been added to provide additional information about the reviewed studies.

The publications containing mathematical optimisation models were analysed in detail, publications related to recommendations and qualitative assessment were not taken into account. Not included are also publications that only describe how the organisation of ELV recycling networks in a country or area looks like or should look like, as well as comparative analyses of network organisations. Such information can be found, among others, in the works of Kanari et al. (2003), Sakkas and Manios (2003), Arora et al. (2019), Manomaivibool (2008), Sakai et al. (2014), Wang and Chen (2013), Chen et al. (2010), Mamat et al. (2016), Zhao and Chen (2011), Kumar and Sutherland (2008). Optimisation of management of specific facilities of the recycling network, e.g. dismantlers or shredders (Choi et al., 2005; Simic and Dimitrijevic, 2013), was also not taken into account.

4. Research papers on ELV recycling network design

In this section detailed information on original research papers on the ELV recycling network design is given.

Ahn et al. (2005) proposed a combination of optimisation and simulation procedures to determine the location of collection points and dismantlers and to allocate the flows between facilities (including shredders). The main purpose of the study was to provide car manufacturers with a decision support tool enabling the design of ELV recycling network in order to minimize the total network cost. Alsaadi and Franchetti (2016) also proposed network optimisation for the manufacturer assuming the minimisation of total network costs. They assumed that the collection of ELVs was handled by vehicle distribution centres, and locations were sought for dismantlers and processing facilities that operate as shredders. Another closed loop network design approach was presented by Mora et al. (2014). The optimisation is carried out for locations of distribution and collection centres that sell new cars and collect ELVs and dismantlers and material flows in the network with the goal of minimizing the total cost. The key feature is the modular approach to the vehicle structure and the inclusion of remanufacturing activities for vehicle module reuse. The developed model was used for a real case study in Italy and a sensitivity analysis was carried out to identify the parameters most affecting the optimisation results. Qi and

Hongcheng (2008) worked on facility location in reverse logistics in the automotive industry with focus on remanufacturing activities and assuming that the recovered products are sent to the original manufacturers. The authors used a mixed integer linear programming (MILP) method with the objective of minimizing total network costs to determine locations of dismantlers and processing facilities. Shankar et al. (2018) developed a model for the closed loop supply chain network with a multi-echelon inventory, multi-period planning and multi-product scenario that was applied for an Indian car manufacturer. The method enables to plan the transport of parts produced from primary raw materials and from secondary raw materials based on demand, collection rates and capacity of facilities and provides the optimal amounts of flows of both end products (new products, recycled products and used non-recycled products) and raw materials. Various strategies were analysed, such as a centrally coordinated system and a system of third-party logistics providers, different qualities and the scope of warranty. Zarei et al. (2010) formulated an optimisation problem for the design of a closed loop recycling network. They assumed that the new vehicle distributors are also responsible for collecting the ELVs. In this case the optimisation is based on simultaneous minimisation of costs of forward and reverse logistics as both logistic networks are integrated. Solution methodology was based on the use of genetic algorithm to achieve high-quality results.

Network design from the third-party logistics provider perspective was presented in the paper (Mahmoudzadeh et al., 2011a). This approach was chosen due to economies of scale and reduction of supply uncertainty, which is greater for a single car manufacturer. The mathematical model is a capacitated facility location allocation problem formulated as mixed integer linear programming with the aim of minimizing the total costs of the network. The goal is to determine the collection points, their capacity and the flows between entities. A similar model including dismantlers' location is developed in the study (Mahmoudzadeh et al., 2011b). Another modification of this model was presented in a paper by the same authors (Mahmoudzadeh et al., 2013). ELVs were divided into three quality groups depending on the age of the vehicle. The main problem is to determine the optimal locations of scrap yards acting as dismantlers and the flows in the network. Third party logistics provider manages all ELVs to be dismantled in a year, indicating to the owner the place and time of delivery of the vehicle to the processing site. The model was implemented to assess different scenarios for the recycling network in Iran. Demirel et al. (2016) proposed a MILP model for network design to assess the allocation of ELV flows to collection points and dismantlers and to determine the facilities location that comply with regulations in force in Turkey. The goal was to minimize the total cost of network but the objective function also included revenue obtained from selling reusable parts, as well as selling ferrous and non-ferrous materials to recycling facilities or material suppliers. Balci and Ayvaz (2017) proposed a MILP model to select locations of dismantlers and shredders and to determine the amount of material transported between the facilities. The goal was to minimize the total cost of the system including transport cost, the fixed cost of opening facilities and the cost of ELV and waste treatment. The presented model was applied to ELV recycling network design problem in Istanbul. Merkisz-Guranowska (2010) also used a MILP model to optimize the location of collection points, dismantlers and shredders with the aim of network cost minimisation. This model was developed and applied to optimize the ELV recycling network in Poland (Merkisz-Guranowska, 2011a, 2011b). Due to the complexity of the problem, a solution methodology was proposed that is based on the evolutionary algorithm which allows obtaining good quality solutions within a reasonable time of algorithm operation.

Deng et al. (2018) developed a simulation–optimisation model for the location, path and inventory problem of ELV recycling systems. The ExtendSim software was used to optimize the location of the recycling centre and the path between the collection point and the recycling centre or the processing centre. A bi-level programming model for locating distribution centres for ELV parts and mapping network flows in ELV recycling network in order to obtain a trade-off between the opening cost and transport cost is presented in the paper by Sun et al. (2018). Distribution centres collect the parts dismantled by dismantlers and forward them by collective transport to recycling facilities.

Tian et al. (2009) formulated a non-linear mixed integer facility location model to determine the optimal number and location of ELV collection points with the objective of total cost minimisation. A hybrid algorithm has been proposed to solve the model combining the Lagrangean relaxation to solve the capacity constraints and the tabu search to find the optimal number of facilities for the ELV collection network. Another research focused on facility location is presented by Vidovic et al. (2011). The model has the objective of maximizing the number of ELVs collected by pre-defined number of dismantlers while respecting the existing characteristics of demand and the allowable distance limits. The authors developed an innovative approach based on dividing dismantlers' service zones into sub-zones in order to minimize aggregation errors. This modification was included in the traditional formulation of the problem of maximum coverage of the area. The model has been applied on the example of the city of Belgrade. One approach assumed maximum distance between the source and dismantler and second approach assumed minimum and maximum distances between the ELV owner and dismantler.

Some studies refer only to flow distribution without indicating the location of recycling facilities. Boon et al. (2003) applied a goal programming technique to assess material flows and profitability of ELVs treatment at dismantlers and shredders for microcars, electric and hybrid vehicles. Farel et al. (2013) developed a model to determine the optimal material flows for the ELV glazing recycling scheme. The model is mapped using real data from French industrial partners, and a linear programming technique was used to optimize the network for maximum profit. Özceylan et al. (2017) presented a closed loop supply chain based on a case study of ELV management in Turkey. They developed a linear programming model enabling the integration of return flows of used parts and recycled materials into forward supply chain. Several scenarios for different numbers of ELVs, sales prices and numbers of facilities were discussed to show the performance of the proposed model and its application in the automotive industry.

Several studies by Simic are focused on ELV allocation management under uncertainty. In a work (Simic, 2015) the author developed a two-stage interval-stochastic programming model. The goal is to ensure maximum profit for network managers (e.g. provincial authority) and minimize the risk of disruption in recycling plants acting as shredders. Uncertainties are expressed as probability density functions or discrete intervals. The model can support the analysis of scenarios related to different levels of economic penalties (a monetary compensation for recycling plants from the system manager) when the target of ELV allocation levels are not met. This model was improved and extended in a work (Simic, 2016a) to reflect the dynamics of decisions regarding the allocation of ELVs from a multi-regional waste management system to many recycling plants within a multi period context. The amounts of ELVs collected in each planning period are random variables, and the corresponding ELV allocation plan is dynamic. A semi-hypothetical case study was carried out to demonstrate the potential and applicability of the proposed method. In a paper (Simic, 2016b) an interval-parameter two stage stochastic full-infinite programming model for ELV allocation management under uncertainties was formulated. The main assumptions regarding network management by the central authority responsible for the allocation of ELVs to plants and a system of penalties are the same as in previous models. In the first stage, the initial decision is made on the basis of uncertain information about future ELV supply. In the second stage, when the number of ELVs available for treatment is known, the initial allocation is adjusted to minimize costs. The interval approach to linear programming is an extension of classic linear programming that takes into account uncertain environment. Full-infinite programming can reflect the dynamic features of modelling parameters presented as intervals. It can cope with functional intervals in objective function (i.e. economic parameters) and constraints (i.e. levels of safety stocks), thereby effectively dealing with complex uncertainties regarding unit revenues, unit penalties and minimum allocation levels. Similar approach based on an interval-parameter chance-constraint programming model for uncertainty-based decision-making for ELV industry under rigorous environmental regulations and maximized profit is presented in the paper (Simic, 2016c). The goal of the model is to search for optimal patterns of obtaining ELVs from many regions, planning production and inventory in vehicle recycling plants, and allocating sorted materials in accordance with environmental protection regulations. Simic (2018) developed another method to provide a compromise solution between the expected profit and the risk associated with levels of ELVs availability. The formulated model can produce optimal solutions with pre-defined decision-making risk preferences and confidence levels. The values of costs and revenues are not fully known, hence they are treated as interval values and ELV numbers are random variables with known probabilities.

Some authors applied heuristic algorithms to solve recycling network design problems. Cruz Riviera and Ertel (2009) applied an uncapacitated facility location model with solution method based on the Lagrangian relaxation to find the optimal number of treatment facilities for the ELV recycling network in Mexico. Transport costs were considered as a determinant factor for the recycling network design although the objective function covered both transport cost and facilities fixed cost. It was assumed that collection points act as dismantlers so the network structure was simplified. Another example of the use of heuristics methods for the optimisation of the facility location is work by Gołębiewski et al. (2013). The authors developed a non-linear programming model (as the ELV number was random) for selecting the location of dismantlers. The model was implemented using genetic algorithms and illustrated on the example of the Masovian region in Poland. The cost of transport, storage and dismantling of ELVs and the fixed cost of dismantlers were minimized in the optimisation function. Heuristic approach has been used by Mansour and Zarei (2008) in their research on the optimisation of the ELV recycling network in order to meet legal requirements expressed as maximum accessible distance for vehicle owners. The search procedure was based on the greedy algorithm. The design of the network was presented from the point of view of manufacturers with the objective of minimum expenditure for the ELV collection (minimisation of the cost of transport and storage of ELVs and the fixed cost of establishing facilities). The novelty of the approach was that the authors proposed a multi-period optimisation model for the location of collection points and dismantlers.

Lin et al. (2018) proposed another MILP model for the problem of facility location and flow allocation in the ELV recycling network considered as non-deterministic polynomial complete problem with the increase in the number of candidate locations. To solve the problem an original approach based on artificial bee colony metaheuristics was used. The proposed method is applied to two different scale case studies. Another multi-period model was presented by Ene and Öztürk (2015) to manage network structure and return flows related to disassembly, refurbishing, shredding, recycling, disposal and reuse of vehicle parts in a dynamic, multi-stage approach and assuming limited capacity of facilities. The uncertainty about the ELV number was taken into account by analysing three scenarios: pessimistic, optimistic and expected.

Xiao et al. (2019) developed a MILP model for the ELV recycling network. The key future of the approach was the inclusion of the environmental cost criterion in the objective function. The model aims to achieve economic and environmental balance by considering both the economic efficiency and reduction of carbon dioxide emissions. As a result of the model application dismantler locations and their capacity are given together with the material flows between various entities, including collection points, dismantlers and different recycling facilities. An extensive mathematical programming model including three objective functions related to sustainable recycling network development is presented in the paper by Dehghanian and Mansour (2009). Life cycle analysis (LCA) has been applied to investigate the environmental impact of different end-of-life options. Analytical hierarchy process has been used to calculate social impacts including employment opportunities and local development and the economic aspect is measured by industry profit maximisation. Model implementation was carried out on the example of scrap tires in Iran but after adjusting the environmental impacts of end-of-life product treatment options, the model can be used for the ELV recycling network design. Another multi criteria model is given in a study by Harraz and Galal (2011). The paper presents a method of designing a sustainable network for the ELVs recovery in Egypt based on mixed integer goal programming. Two types of facilities were considered: collection and disassembly centres and refurbishing centres belonging exclusively to automotive sector suppliers. The profit maximisation, the minimisation of waste disposed and the maximisation of recycled material are adopted as objective criteria and represent the economic and environmental dimension of sustainability. Merkisz-Guranowska (2012) formulated two bi-objective mixed-integer linear programming models, one for the reorganisation of the existing ELV recycling network and one for the design of a new network, which were applied to optimize the network in Poland. The first objective function reflected the preferences of vehicle owners (minimizing the costs of transferring ELV to the recycling network) and the second one the preferences of network facilities (maximizing profit). Similar model, a bi-objective mixed-integer linear programming model for network efficiency improvement, was presented in a work (Merkisz-Guranowska, 2013). The results for different values of the preferences expressed as criteria weights were shown based on the recycling network in Poland.

Some authors include aspects of uncertainty in their research. Phuc et al. (2017) developed a fuzzy MILP model for the design of multi period, multi-echelon and multi-product recovery networks. They considered different types of ELVs. Economic parameters (transport costs, costs of opening entities, processing costs and sales prices) and ELV supply and quantity of products recovered from vehicles were treated as fuzzy (non-deterministic) values. The optimisation relates to both network design decisions and tactical decisions in ELV treatment including locations of collection points, inspection centres, repair centres, dismantlers, shredders, and ASR processing centres. The flow quantity between each pair of facilities is also optimized based on the realisation for each period of time. A numerical example illustrating the possibilities of the proposed model was presented. Yildizbaşi et al. (2018) proposed a fuzzy multi-period MILP model to optimize production and distribution planning for the closed loop supply chain based on the Turkish automotive sector. Three decision makers were considered: manufacturer, dismantler and customer. To deal with compromise solutions, four different types of interactive fuzzy programming approaches were used to solve the problem with three criteria functions corresponding to each decision maker. Three approaches assumed no cooperation between decision makers, and one assumed such a cooperation. Subulan et al. (2015) formulated a multi-objective, multi-stage and multi-product mixed programming model with integer and fuzzy numbers to optimize the lead-acid battery closed loop supply chain in Turkey. Unlike most of the existing models of closed loop logistics chain network design, which are usually cost or profit oriented, the model also includes a new goal, which is the maximisation of the collection of used batteries by opening new plants. Another two objective functions relate to the network total cost minimisation and plant flexibility maximisation. The optimisation consists in choosing a location among: regional distribution centres of new batteries, collection points for used batteries, hybrid plants performing both functions (distribution and collection) and recycling facilities. The fuzzy values used in the model relate to the policy makers' goals such as the maximum acceptable cost of network or minimum level of collected batteries. Ma and Li (2018) proposed a two-stage stochastic programming model for solving the problem of closed loop supply chain for lead-acid batteries with random demands and returns. The mathematical model includes a risk restriction constraint and a reward-penalty mechanism. In the first stage, locations of manufacturing facilities that carry out the recovery operations and their capacity levels were selected. In the second stage, flows were determined and allocated. Two solution methods, a parallel enumeration method and a genetic algorithm are designed to solve the proposed model. Kusakci et al. (2019) assumed that ELV supply in the network is uncertain and should be considered as fuzzy value. Their study aims at developing a fuzzy mixed integer location-allocation model for ELV reverse logistic network. All costs, prices and ratios of material flow of each subcomponent are known and handled as deterministic parameters while only the amount of ELVs generated in the analysed districts is variable. The model has been applied for Istanbul metropolitan area.

The publications presented above have been divided according to several criteria. The first one is the type of supply chain. Closed loop (CL) refers to a supply chain where forward and reverse logistics are integrated while open loop supply chain means that there are separate facilities that collect and process end-of-life vehicles. In some cases, despite the fact that the authors defined their model as closed loop (Cruz Rivera and Ertel, 2009; Phuc et al., 2017), the model was considered in the classification of the studies as open loop. The ELV reverse logistics is always a part of circular economy contributing to resource reuse (provided that the vehicles are recycled or recovered). Only the same facilities used in both forward and reverse logistics were determinant to consider recycling network as closed loop.

Papers are classified also regarding the type of network. Manufacturer network (MN) integrates the production of new vehicles and recovery of used ones. Based on the Extended Producer Responsibility, the manufacturer is responsible for free take back and recovery of its ELVs and must bear all or a significant part of the collection and treatment costs. Third party logistics (3PL) provider is responsible for establishing an independent network and for the management of the ELV flow on behalf of the manufacturers. In some cases, the local authority (A) is responsible for the ELV management. If authors did not define (ND) the network administrator (manufacturer, authority or 3PL provider) the recycling industry in general should be in charge of network design and optimizing material flows between facilities.

The type of optimisation problem was also determined. Location allocation problems (LA) refer to methods that are used to select locations and to determine flows between them. Facility location (FL) problems focus only on optimal number of facilities that have to be placed within network and the last type of problem – flow allocation (FA) – maps flows between recycling network facilities.

Another criterion of analysis was the type of facilities whose location is optimized. The key players in an open loop ELV recycling network are: collection points (CP), dismantlers (D), shredders (SR) and recycling facilities (RF) such as refurbishing plants or material recycling facilities. For the open loop supply chain researchers also considered distribution and collection centres (DCC), inspection centres (IC) and manufacturing facilities (MF). In some case the authors used other names for facilities i.e. Cruz Rivera and Ertel (2009) were identifying strategic locations for ELV collection centres that carried out also dismantling activities and in this study are considered as dismantlers. Mahmoudzadeh et al. (2013) optimized the location of dismantlers even if they called the facilities scrap yards. Vidovic et al. (2011) also optimized the location of dismantlers but described them as collection points. In the summary table (Table 2) the name of the optimized facility depends on its activity and not on the name used in the original paper.

As all reviewed publications contained mathematical optimisation models, the modelling technique was analysed. Linear programming (LP) is used to find the best solution from a set of parameters that have a linear relationship while nonlinear programming (NLP) considers constraints or objective functions that are nonlinear. A mixed-integer linear programming (MILP) and mixed integer nonlinear programming (MINLP) assume that some of the decision variables are constrained to be integer values at the optimal solution. To solve problems with multiple and often conflicting criteria in a decision making process, some authors used goal programming (GP) as an optimisation technique.

Mathematical models use single objective function (S) or multiple objectives (M) to perform optimisation. Objective functions mostly relate to cost minimisation or profit maximisation. Some models assume the optimisation over one specific period of planning (single period optimisation – SP) and others solve the problem within a multi-period planning horizon (MP).

The methods used to solve the presented mathematical models can be divided into exact (E) and approximate (heuristic – H). Exact methods enable obtaining optimal solutions while heuristic methods allow obtaining satisfactory solutions but are often only an approximation of optimal solutions. They are implemented when exact methods are too slow or fail to find any exact solution. Heuristic methods include, among others: genetic algorithms (GA), tabu search (TS), greedy algorithm (GRA) and artificial bee colony (ABC).

Finally, the implementation scope was assessed. Problems with less than 180 candidate sites for facility location were considered small-scale problems (SS) and those with at least 180 candidate sites were considered large scale problems (LS).

Detailed information on the 41 peer-reviewed studies on the ELV recycling network design is given in Table 2.

5. Discussion

In the first ten years following the first regulations regarding the obligation to establish an ELV recycling network (EU Directive 2000/53/EC of September 2000), only nine papers were published. Most of the studies have been published since 2011, thirty-two in total.

Table 2. Classification of the studies

Year	Author(s)	Type of supply chain	Type of network	Optimisation problem	Type of facilities	Modelling technique	Single/ Multi objective	Objective function	Period of time	Solution approach	Scope	Type of product
2003	Boon et al.	OL	ND	FA	CP, D	LP	S	Profit max	SP	E	SS	ELV
2005	Ahn et al.	OL	MN	LA	CP, D	MILP	S	Fixed and transport cost min	SP	H (GA)	Yes*	ELV
2008	Mansour and Zarei	OL	MN	LA	CP, D	MILP	S	Logistics cost min	MP	H (GRA)	SS	ELV
2008	Qi and Hongcheng	CL	MN	FL	D, RF	MILP	S	Total cost min	SP	E	No	ELV
2009	Cruz Rivera and Ertel	OL	ND	LA	D	MILP	S	Fixed and transport cost min	SP	H (LR)	LS	ELV
2009	Dehghanian and Mansour	OL	ND	LA	RF	MILP	M	(1) Profit max (2) Social impact max (3) LCA impact min	SP	H (GA)	SS	Tyres
2009	Tian et al.	OL	ND	FL	CP	MINLP	S	Total cost min for CP	SP	H (LR,TS)	SS	ELV
2010	Merkisz-Guranowska	OL	ND	LA	CP, D, SR	MILP	S	Total cost min	SP	-	No	ELV
2010	Zarei et al.	CL	MN	LA	DCC/D	MILP	S	Fixed and transport cost min	SP	H (GA)	SS	ELV
2011	Harraz and Galal	OL	ND	LA	D, RF	GP, MILP	M	(1) Profit max (2) Min of waste disposed (3) Max of material recycled	SP	E	SS	ELV
2011a	Mahmoudzadeh et al.	OL	3PL	LA	CP	MILP	S	Total cost min	SP	E	SS	ELV
2011b	Mahmoudzadeh et al.	OL	3PL	LA	CP, D	MILP	S	Total cost min	SP	E	SS	ELV
2011a	Merkisz-Guranowska	OL	ND	LA	CP, D, SR	MILP	S	Total cost min	SP	H (GA)	LS	ELV
2011b	Merkisz-Guranowska	OL	ND	LA	CP, D, SR	MILP	S	Total cost min	SP	H (GA)	SS	ELV
2011	Vidovic et al.	OL	ND	FL	D	MILP	S	Network coverage max	SP	E	SS	ELV
2012	Merkisz-Guranowska	OL	ND	LA	CP, D, SR	MILP	M	(1) Transport cost min for ELV owners (2) Profit max	SP	H (GA)	LS	ELV
2013	Farel et al.	CL	ND	FA	-	MILP	S	Profit max	SP	E	LS	Glass
2013	Gołębiewski et al.	OL	ND	LA	D	NLP	S	Total cost min	SP	H (GA)	SS	ELV
2013	Mahmoudzadeh et al.	CL	3PL	LA	D	MILP	S	Total cost min	SP	E	LS	ELV
2013	Merkisz-Guranowska	OL	ND	LA	CP, D, SR	MILP	M	(1) Transport cost min for ELV owners (2) Profit max	SP	H (GA)	LS	ELV
2014	Mora et al.	CL	MN	LA	DCC/D	MILP	S	Total cost min including revenue	MP	E	SS	ELV
2015	Ene and Öztürk	OL	ND	LA	D, SR	MILP	S	Profit max	SP	E	SS	ELV
2015a	Simic	OL	A	FA	SR	LP	S	Profit max for authority	MP	E	SS	ELV
2015	Subulan et al.	CL	ND	LA	DCC, CP, RF	GP, MILP	M	(1) Total cost min (2) Network coverage max (3) Flexibility max	SP	E	SS	Batteries
2016	Alsaadi and Franchetti	OL	MN	LA	D, SR	MILP	S	Fixed and transport cost min	SP	E	No	ELV
2016	Demirel et al.	OL	ND	LA	D, SR	MILP	S	Total cost min including revenue	SP	E	SS	ELV
2016a	Simic	OL	A	FA	SR	LP	S	Profit max for authority	MP	E	SS	ELV
2016b	Simic	OL	A	FA	SR	LP	S	Profit max for authority	MP	E	SS	ELV
2016c	Simic	OL	A	FA	SR	MILP	S	Profit max for authority	MP	E	SS	ELV
2017	Balcı and Ayvaz	OL	ND	LA	D, SR	MILP	S	Total cost min	SP	E	SS	ELV
2017	Özceylan E. et al.	CL	MN	FA	-	MILP	S	Profit max	SP	E	LS	ELV
2017	Phuc et al.	OL	ND	LA	CP,D, SR, IC, RF	MILP	S	Total cost min	MP	E	SS	ELV
2018	Deng et al.	OL	ND	LA	CP, D	MILP	S	Total cost min	SP	E	SS	ELV
2018	Li et al.	OL	ND	LA	CP, D	MILP	S	Total cost min	SP	H (ABC)	SS	ELV

2018	Ma and Li	CL	MN	LA	CP, MF	MINLP	S	Profit max	SP	E+ H(GA)	SS	Batteries
2018	Shankar et al.	CL	MN, 3PL	FA	-	MILP	S	Profit max	MP	E	SS	ELV
2018	Simic	OL	A	FA	SR	MILP	S	Profit max for authority	MP	E	SS	ELV
2018	Sun et al.	OL	ND	LA	DC	MILP	S	Fixed and transport cost min	SP	E	SS	ELV
2018	Yildizbaşi et al.	CL	ND	LA	D	MILP	M	(1) Total cost min for manufacturers (2) Profit max for dismantlers (3) Cost min for customers	MP	E	SS	ELV
2019	Kuşakcı et al.	OL	ND	LA	D, SR	MILP	S	Total cost min including revenue	SP	E	SS	ELV
2019	Xiao et al.	OL	ND	LA	D	MILP	S	Total cost + environmental cost min	SP	E	SS	ELV

*without giving results

OL: Open loop, CL: Closed loop, A: Authority, MN: Manufacturer's network, 3PL: Third party logistics provider, LA: Facility location/ flow allocation, FL: Facility location, FA: Flow allocation, CP: collection points, IC: inspection centers, D: dismantlers, SR: shredders, RF: Recycling facilities, DCC: distribution and collection centers, DC: Distribution center, MF: Manufacturing facilities, LP: Linear programming, NLP: Nonlinear programming, MILP: Mixed integer linear programming, MINLP: Mixed integer nonlinear programming, GP: Goal programming, S: Single objective, M: Multi objective, min: minimisation, max: maximisation, SP: Single period, MP: Multi period, E: Exact, H: Heuristic, GA: Genetic algorithm, GRA: Greedy algorithm, ABC: Artificial bee colony, TS: Tabu search, SS: Smal scale, LS: Large scale

Most of the above-presented works focused on designing a separate network for the recovery logisticsA quarter of the research problems were formulated as a closed-loop supply chain optimisation, the approach to network design was dominated by open loop assumptions. Because of the differences in the new and end-of-life streams of products it is rare to integrate the reverse logistics with the new vehicle distribution network. The closed loop recycling network requires common facilities for both forward and reverse logistics and existing recycling network facilities (except collection points that are sometimes integrated with car dealers) are not combined with forward logistics entities. The authors of nine publications assumed that the car manufacturers should be in charge of the ELV recycling network design and in six models the network was designed as a closed loop supply chain. Only four research models assumed explicitly that the network is organized by the third-party logistics provider and one author (Simic, 2015; 2016a-c; 2018) developed several models for flow allocation in recycling network managed by local authority. Twenty-nine models integrate material flow allocation (including ELVs and/or waste from vehicles) and facility location problems. Three refer only to facility location and nine focus on flow allocation exclusively. Location problems were related mainly to the location of dismantlers and collection points, 26 and 15 models respectively, 11 took into account the location of shredders. The location of recycling plants was much less frequently referred to (5 cases). The popularity of the location of the dismantlers is related to the fact that these entities are the basic link in the car recycling network and the effectiveness of the entire system depends to a large extent on their activity. In turn, collection points are the most important from the point of view of car manufacturers, who in many countries are responsible for the organisation of the ELV collection network, and not for the organisation of the entire recycling network. For a closed loop recovery logistics network, three models assume the operation of collection and distribution centres, which are a joint entity for forward and reverse flows. For closed loops, in individual cases, the authors also located inspection centres and manufacturing facilities. The most extensive model taking into account the location of as many as five types of entities was proposed by Phuc et al. (2017). Mostly, two entities were subject to location (12 models), the problem of choosing a location of one entity was presented in 10 models, and locations of 3 types of entities were optimised in 6 models.

In terms of mathematical formulation of the problem, the linear programming approach dominates (38 models in total), only 3 models use non-linear programming. Two authors who formulated multi-criteria mathematical models combined goal programming and mixed-integer linear programming.

Most reverse logistics problems are formulated as single criteria models (35 in total). Only six studies refer to multi criteria decision support system. In single-criteria optimisation problems, one objective function which reflects decision maker preferences is used to assess solutions. Multi-criteria approach assumes the minimisation / maximisation of several (at least two) objective functions which often express the opposing preferences of many different stakeholders and seek to find best possible solutions regarding all objective functions simultaneously. Harraz and Gallal (2011) adopted the criterion functions relating to environmental and economic aspects, while Dehghanian and Mansour (2009) undertook to develop a method of sustainable recycling network design that includes, in addition to environmental and economic aspects, also a social aspect. The other four multi-criteria models focused on objective functions related to economic aspects but taking into account various entities (recycling network facilities, ELV owners, car manufacturers).

Referring to all analysed models, the most popular criterion relates to cost minimisation and is expressed either as total cost function including cost of establishing facilities, transport and processing cost; or fixed and transport cost function relating to cost of establishing facilities expressed as fixed cost and transport cost; or logistics cost function including cost of transport, cost of establishing facilities expressed as fixed cost and cost of ELV storage. Xiao et al (2019) added the environmental cost of greenhouse gas emissions to the total cost of network. Merkisz-Guranowska (2012; 2013) used the owner's ELV cost function, which referred to the cost of transporting the vehicle to the nearest collection point or dismantler and Yildizbaşi et al. (2018) formulated the cost function for customers which referred to the cost of transporting and purchase price of parts.

The second most used objective function is profit maximisation. This function relates to cost of processing by dismantlers and shredders, cost of buying ELVs and hulks and cost of disposal of non-recovered waste deducted from total revenue of dismantlers and shredders. Simic in all his models (2015; 2016 a-c, 2018) formulated the objective function of profit maximisation for the local authority which includes revenue for allocated ELVs minus penalties for not allocating ELVs to shredders. Some authors instead of using profit maximisation function deducted revenues from costs and minimized the total cost function but still including revenue.

Other objective functions were also used in some models relating to the environmental burden minimisation expressed as minimisation of waste and maximisation of the recovery of the amount of material flow (Harraz and Galal, 2011) or LCA impact minimisation (Dehghanian and Mansour, 2009). In two models the objective function of maximizing the coverage of collected products (vehicles or parts) was formulated. The main goal of the maximal covering problem is locating a fixed number of facilities (at least one) within the acceptable distance while maximizing the amount of demand covered (or the population covered). Subulan et al. (2015) applied flexibility maximisation as one of three partial objective functions. This was measured as the difference between plant capacity and plant capacity use.

Ten out of forty-one models were formulated as multi period problems extending the allocation planning problem to several periods and enabling optimal long-term planning of recycling activities.

To solve the ELV recycling problems most of the authors applied exact methods. Due to the NP-hard nature of the problem, different heuristics have been also proposed to solve the problem in a short computation time. The most frequently applied approximation technique for finding good suboptimal solutions were genetic algorithms which are an example of stochastic search and an optimisation technique based on principles of evolution theory. This solution approach was applied in nine research studies.

Almost all authors implemented the mathematical models to prove their effectiveness in solving problems. Some models were implemented based on the actual data related to an existing recycling network and the analysis of the results of the performed optimisation tasks were presented. In some cases (Simic 2015; 2016a-c; 2018) the model was verified on hypothetical case. Nine implementations referred to large scale problems with more than 180 candidate sites for facility location.

6. Conclusions

The optimisation of the location of a network facilities in forward logistics in the automotive industry has received a lot of attention for many years but the reverse logistics for ELVs has been a subject of investigations since the beginning of 21st century. ELV recycling network design gained in popularity after the EU and other countries like Japan, South

Korea and recently China introduced legal obligations to organize a collecting or recycling network for used vehicles.

The scope of the network design is to determine the number and locations of facilities in the network and the material flows between these facilities.

The most important criterion used in network optimisation is the economic criterion related to maximising profitability or minimising the costs of network operation. Considering the changing approach to managing and using resources, too little research takes into account sustainability requirements. Most models assume exclusively an economic optimisation, and little attention is given to reducing environmental impact and social aspects. It seems that the multi-criteria approach to designing ELV recycling network should be further developed in subsequent studies on network optimisation. A number of authors consider environmental aspects in the constraints of mathematical models, e.g. the condition of solution acceptance is the achievement of the required recovery rate, or the boundary condition is the need to process all collected waste in the network. However, environmental criteria are rarely found as separate criteria in models subject to minimisation or maximisation.

Most of the models presented in the literature assume a static approach, without taking into account changes in processes over time. By using dynamic models, changes in the demand and supply of cars in subsequent periods can be considered in modelling, and thus the storage of vehicles and their waste and processing them in subsequent periods can be taken into account. Similarly, most models assume the deterministic nature of parameters and do not contain elements of randomness and uncertainty. Meanwhile, the economic environment is very variable, and especially the automotive industry is sensitive to changes and external factors. Therefore, the inclusion of uncertain parameters is another important element to consider in network design. The element of risk and uncertainty may relate to the size of ELV supply and the possibility of collecting the vehicles from the market, to material composition of vehicles as well as to variability of economic parameters, such as operating costs and sales revenues.

Models that take into account changes over time, parameter uncertainty, and, above all, the interests of various stakeholders are able to better reflect the reality of recycling network, although applying them to large-scale problems is a challenge for researchers.

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