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END-OF-LIFE VEHICLE RECYCLING - A REVIEW OF THE STATE-OF-THE-ART

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Subject review

End-of-life vehicle (ELV) waste flow is an important environmental concern, because of its rapidly increasing amount and special composition of hazardous substances. Its recycling is a matter of country's attitude towards supporting the environment preservation and it has emerged as a novel area of scientific research. In this paper, we presented a holistic view of the environmental engineering issues of the ELV recycling by covering a wide range of peer-reviewed journal papers. The purpose of this review paper is to give an extensive content analysis overview of the literature published in the period 2003 ÷ 2012. In addition, the major classification scheme and a distribution list of journal papers published in the considered period are created to identify the primary publication outlets. Finally, on the basis of the performed review, several important recommendations for the future research are highlighted and discussed.

Keywords: *content analysis, end-of-life vehicle, environmental engineering, general discussion, mathematical modelling, review*

Recikliranje vozila na kraju životnog ciklusa – pregled najsuvremnijih znanstvenih radova

Pregledni članak

Otpadni tok vozila na kraju životnog ciklusa predstavlja važan ekološki problem, zbog količine koja je u stalnom porastu i posebnog sadržaja opasnih tvari. Njegovo recikliranje je stvar državnog stava o potpori očuvanju okoliša i ono se pojavila kao novo područje znanstvenog istraživanja. U ovom radu, predstavljen je sveobuhvatni pregled tema ekološkog inženjerstva, koje su vezane za recikliranje vozila na kraju životnog ciklusa, pokrivanjem značajnog broja recenziranih radova. Cilj ovog preglednog rada je davanje širokog pregleda analize sadržaja radova objavljenih u razdoblju 2003 ÷ 2012. Pored toga, glavna shema klasifikacije i lista raspodjele radova objavljenih u časopisima u promatranom razdoblju kreirane su kako bi njihova primarna odredišta mogla biti identificirana. Konačno, na bazi izvršenog pregleda, nekoliko važnih preporuka o budućem istraživanju je istaknuto i prodiskutirano.

Ključne riječi: *analiza sadržaja, ekološko inženjerstvo, matematičko modeliranje, opća diskusija, pregled, vozilo na kraju životnog ciklusa*

1 Introduction

Waste management is an important topic among environmental issues today and at present, the vehicle sector generates about 5 % of the world's industrial waste, whether from vehicles or the plants which produce them. End-of-life vehicle (ELV) is a specified vehicle which is discarded or is to be discarded by its registered owner as waste. It is composed of many different materials that have a large impact on the environment such as mercury, cadmium, hexavalent chromium, anti-freeze, brake fluid and oils [1].

In the early 1990's ELVs have been identified by the EU as priority waste stream. Nowadays, ELVs are a major stream of waste in the EU [2]. Recycling and reuse of ELV parts and components, and metal recovery is important to governments, manufacturers, suppliers, dismantlers and vehicle recycling factories. The shortening of the vehicles' average life to about 10 ÷ 12 years in the EU produced in the last 15 years an impressive enhancement of ELVs number. As a result, ELV recycling is a matter of country's attitude towards supporting the environment preservation and it is emerged as a novel area of scientific research.

From a waste management point of view, the concerns related to ELVs are twofold: on the one hand, about 25 % of this waste flow has to be considered hazardous, and on the other hand about 75 % of this waste flow (mainly steel and aluminium) can be easily recycled [1]. In that sense, modern ELV recycling not only is supposed to help protect the environment and natural resources, but is also expected to work economically. However, the management of ELV recycling process is complex and requires a multi-faceted approach in order to recover, re-use, and recycle the materials.

In this paper, we presented a holistic view of the environmental engineering issues of the ELV recycling by covering a wide range of previously published journal papers. The purpose of this review paper is to give an extensive content analysis overview of the literature published in the past ten years. The literature is organized into two main sub-areas; namely, general discussion and mathematical modelling research papers.

The remaining part of the paper is organized as follows: Section 2 provides a review methodology. Section 3 presents the obtained results of the review. This particular section is divided further into sub-sections in order to highlight various fields of the environmental engineering issues that are of most importance to this particular review paper. Section 4 presents the major classification scheme and a distribution list of journal papers published in the period 2003 ÷ 2012. The last Section 5 presents the paper's main conclusions and recommendations.

2 Review methodology

In this paper, content analysis method is adopted for literature review. Content analysis is an observational research method that is used to systematically evaluate the symbolic content of all forms of recorded communication and also helps to identify the literature in terms of various categories [3].

This particular review is limited to the papers published only in the peer-reviewed journals. In that sense, grey literature is completely excluded from this review paper. Search engines were used to explore ACS Publications, ASCE Library, ASME Digital Library, Cambridge JOURNALS, EBSCOhost, EmeraldInsight, Google Scholar, IEEE Xplore, Inderscience, IntegraConnect, IOPScience, J-STAGE, JSTOR, ProQuest, RSCPublishing, SAGE journals, ScienceDirect, SciVerse, SpringerLink, and WILEY databases for literature. In addition, the references cited in each relevant literature were examined to find out additional sources of information.

3 Result of literature review

Due to the increasing importance of the subject of ELV recycling, a considerable number of journal papers have been published in the past ten years.

Recently, several review papers have been published. Kumar and Sutherland [4] provided an overview of studies on the vehicle recovery infrastructure and identified the following limitations in the available mathematical models: inadequate description of the complex material flows and economic transactions within the infrastructure, minimal consideration of market factors and lack of consideration for government policies. Ilgin and Gupta [5] gave an overview of the literature on environmentally conscious manufacturing and product recovery and concluded that more studies are needed to better control the effects of uncertainties. Go et al. [6] presented a review on ELVs, recycling, disassembly methods and the related fields. Mayyas et al. [7] investigated the sustainability research within the vehicle industry through a review of different studies in the vehicles' life cycle, disposal and end-of-life (EoL) analyses, and the different sustainability metrics and models used to quantify the environmental impact.

As can be seen from contents analysis of published review papers, the scope of every previous review is limited to a specific area of the ELV recycling problem consideration. In this paper, we presented a holistic view of the environmental engineering issues of the ELV recycling by covering a wide range of previously published journal papers. The literature is organized into two main sub-areas; namely, general discussion and mathematical modelling research papers. In each main sub-area, papers are classified into appropriate categories and sub-categories.

3.1 General discussion

In this sub-section of the paper, the general discussion papers related to environmental engineering issues of the ELV recycling are classified into three categories: (1) *Vehicle recycling practices world-wide*; (2) *Legislation-oriented research*; (3) *Remanufacturing and materials recycling*.

3.1.1 Vehicle recycling practices world-wide

Kim et al. [8] surveyed using some questionnaires the ELVs recycling and recovery rates, and management status in Korea to aid the establishment of policies for the ELV management. Sakkas and Manios [9] applied generalized cost modelling approach to obtain a momentary snapshot of the current vehicle recycling practice in Greece. Nakajima and Vanderburg [10] described and analyzed the German ELV take-back system in terms of its impact on the environment and the vehicle producers involved, and found that it is not one that maximizes the value recovered from ELVs. Forton et al. [11] discussed issues and drivers at play on ELV management in the UK, and outlined their actual effects on vehicle recycling practice. Edwards et al. [12] described the recovery infrastructure and practices in the UK's vehicle recycling sector and concluded that the achievement of the EU ELV Directive (2000/53/EC) eco-efficiency quotas is dependent on accessibility of post-shredder separation technology. Zameri and Blount [13] provided a brief snapshot of vehicle recycling practices in EU, United States, Japan and Australia. Dalmijn and De Jong [14] outlined the development of ELV recycling in Europe and concluded that exporting ELVs to China is more economical than processing in the EU. Joung et al. [15] analysed status of ELV recycling in Korea and concluded that installation of advanced sorting equipment in a vehicle shredding facility could maximize its separation efficiency and increase the attained recycling rate. Chen and Zhang [16] provided insight into thinking within China about ELV recycling problem and reported on the progress of process-related activities. Chen et al. [17] thoroughly described the principles and characteristics of the ELV recycling system in Taiwan and concluded that improving and optimising the process of tactical and operational planning is necessary to make recycled materials more competitive. Altay et al. [18] discussed the current situation of vehicle recycling in Turkey and revealed that adoption of specific regulation may create a new employment area. Cheng et al. [19] examined the operational characteristics of recycling and treatment industry for ELVs in Taiwan and its relationship to recycling performance by using production capacity, power efficiency, and recycling rate as indicators. It is suggested that vehicle shredding facilities, need to optimise their operation schedule to enhance recycling rate of ELVs. Wang and Chen [20] explored development strategies for the used automotive electronic control components recycling industry in China. They analysed its strengths, weaknesses, opportunities and challenges. They pointed out that this ELV recycling industry responded well to all the factors and proposed new development strategies.

3.1.2 Legislation-oriented research

ELV recycling industries world-wide have been greatly affected by the implementation of various ELV-oriented legislative measures. Hence, in this review paper, the legislation-oriented research papers are classified into four sub-categories: (1) *Comparative analysis of legislations*; (2) *EU ELV Directive*; (3) *Japanese and Chinese legislations*; (4) *Extended producer responsibility issue*.

(1) *Comparative analysis of legislations* - Kanari et al. [21] described the ELV recycling practice in the EU and compared the Japanese Law on recycling of ELVs with the EU ELV Directive. Gesing [22] reviewed issues and technologies in recycling with a focus on ELVs and compared the vehicle recycling regulations in the United States, EU and Japan. Sakai et al. [23] compared the Japanese framework for the recycling of ELVs with the EU ELV Directive. Che et al. [24] made a comparative

analysis of ELV recycling legislations between Japan, Korea and China and provided several practical insights in an effort to promote international cooperation in these three countries.

(2) *EU ELV Directive* -The emergence of vehicle abandonment, pollution, and waste in the EU has resulted in the creation of the 2000/53/EC Directive on ELVs. The EU ELV Directive has raised the profile of ELVs waste flow as an issue and led to the creation of recycling/recovery solutions that would not otherwise have existed. It represents the first embodiment of extended producer responsibility (EPR) in vehicle recycling and provides an example of a success framework for other industries to follow. Smith et al. [25] examined how the abandoned vehicle problem is likely to develop with the implementation of EU ELV Directive. Mazzanti and Zoboli [26] explored how the introduction of free take-back instrument can influence the behaviour of industrial actors towards different innovation paths considering the EU ELV Directive as a representative case. Gerrard and Kandlikar [27] identified that positive effects of implementing EU ELV Directive are changes in the material composition of new vehicles, increased design for disassembly (DfD) and design for reuse (DfRu), increased levels of recycling of ELV materials and improved information provision. Smith and Crotty [28] examined the impact of the EU ELV Directive on UK vehicle component manufacturers using questionnaire tool. Santini et al. [29] reported on a campaign trial performed in Italy which involved 18 dismantlers, a vehicle shredding facility and 630 ELV representatives. They outlined that EU ELV Directive recovery rate has not been achieved due to the structural weakness of the Italian municipal solid waste incinerators (MSWIs) framework. Blume and Walther [30] discussed the legislative influence on the German vehicle industry and concluded that EU ELV Directive's future eco-efficiency quotas are the main driving force for material flow innovations. Nicolli et al. [1] provided an econometric analysis of the effect of the EU ELV Directive in inducing innovation in vehicle recycling area. They confirmed that it has played a pivotal role in inducing technological innovations.

(3) *Japanese and Chinese legislations* - In an attempt to reduce waste originating from ELVs, the Japanese Government introduced the Law on recycling of ELVs. It was enforced in January 2005 and automobile manufacturers and importers were required to collect and recover air bags, chlorofluorocarbons/hydrofluorocarbons and automobile shredder residue (usually defined as the residual material left after the majority of the metal content of a vehicle has been removed) generated during the process of recycling ELVs. Therefore, the main purpose of the Japanese ELV Law is to create a new recycling system for the proper processing and disposal of ELV waste flow and its efficient use as resources. On the other side, the vehicle number of China is on constant rise, so the treatment of the ELV becomes a serious environmental and social problem. However, present situation in Chinese vehicle recycling industry greatly differs from practices in the EU and Japan, as a direct consequence of the much cheaper labour cost. In that sense, most of the reusable parts and interior materials can be disassembled before hulk shredding operation. Chen [31] reviewed the Chinese ELV legislation, the ELV dismantling industry, the challenges and opportunities of ELV recycling and the state-of-the-art of remanufacturing of ELVs in China. Chen [32] gave a detailed overview of the Chinese Motor vehicle product recovery technology policy and concluded that the challenges of implementing this policy are enormous. Zhao and Chen [33] gave a brief overview of Japanese and Chinese legislations about ELVs, and also made a comparison of Japanese and Chinese vehicle recycling systems.

(4) *Extended producer responsibility issue* -In the EU, ELVs are a prioritised waste stream and are managed on the basis of economic EPR. Forslind [34] examined how the existing Sweden's vehicle recyclers, aimed at creating economic incentives and financing EoL management, are affected by EPR. Manomaivibool [35] explored the impacts of network management on the environmental effectiveness of the programmes for the management of ELV in the UK and in Sweden from an EPR perspective. Wilts et al. [36] noticed that existing product-orientated EPR approaches with mass-based recycling quotas, such as EU ELV Directive, do not create adequate incentives to supply waste materials containing precious metals to a high-quality recycling. They analysed incentive effects on EPR for the ELVs and precious metals, and developed a proposal for an international covenant on metal recycling as a policy instrument.

3.1.3 Remanufacturing and materials recycling

The automotive sector has a well-known history of parts remanufacturing. Vehicle part remanufacturing is transformation of an EoL part into a part with an "as good as new" condition. However, this operation is extensive and includes its disassembly, cleaning, recovery and re-assembly. Seitz [37] reviewed the driving forces and motivations behind passenger car engine remanufacturing including: ethical and moral responsibility, legislation, profitability, aftermarket reasons, market share and brand protection, and customer orientation. Marsh [38] analysed potentials for fibre reinforced plastic recovery from ELVs and proclaimed the foundation of the European Composites Recycling Services Company. Agbo [39] quantified the raw materials potential of used vehicles imported in Nigeria, which is important destination for European used vehicles. Nakamura et al. [40] used a hybrid input-output analysis approach to quantify the quality- and dilution losses associated with the recycling of ferrous materials from ELV due to the mixing of copper. Hatayama et al. [41] discussed on how the recycling of aluminium will change till 2050, focusing on the introduction of next-generation vehicles and modern scrap sorting technology. They demonstrated the limitations of the traditional, profit-oriented recycling systems and confirmed the validity of introducing modern scrap sorting systems. Moreover, the case study results indicated the effectiveness of scrap sorting in the future: if scrap sorting is carried out for ELVs, it reduces the primary aluminium requirement by 15 ÷ 25 %.

3.2 Modelling approach

In this sub-section, papers in which authors used various methodological approaches to model different aspects of very complex systems for ELV processing are presented and thoroughly analyzed. The following categories are created: (1) *Life Cycle Assessment*; (2) *Location*; (3) *Production planning*; (4) *Material selection*.

3.2.1 Life Cycle Assessment

Although Life Cycle Assessment (LCA) has been established as the most broadly used methodology to assess the environmental sustainability of a products, applying LCA to support vehicle parts/components design decision making remains a significant issue of future research. Castro et al. [42] performed LCA of the average passenger vehicle of the Netherlands with emphasis on the dismantling and recycling practice in this country. Schmidt et al. [43] compared 3 sets of theoretical vehicle weight scenarios from LCA perspective: 1000 kg vehicle scenario with two lightweight (900 kg and 750 kg vehicle) scenarios. Having in mind that a weight reduction is primarily achieved by the substitution of materials that are typically going to ELV recycling processes, the authors identified and emphasized the trade-off between the eco-efficiency targets given by the EU ELV Directive and the lightweight design options. Munoz et al. [44] used LCA to compare a plastic door panel with a prototype panel, based on compatible polyolefins. The following scenarios are analyzed: land-filling, energy recovery in a MSWI, energy recovery in a cement kiln, and mechanical recycling. Finkbeiner et al. [45] applied LCA to improve the environmental performance of the Mercedes-Benz S-Class vehicle and reported that the use of parts made from renewable materials was increased by 73 %. Ribeiro et al. [46] used LCA methodology to evaluate two scenarios describing a multi-material car component which is part of the automotive brake system. Jeong et al. [47] focused on the ELV treatment system in Korea by using LCA methodology in order to evaluate its environmental performance and to identify the potential improvement opportunities. Alonso et al. [48] created LCA and Life Cycle Costing (LCC) case studies of two selected automotive electrical and electronic system (EES) components (an engine wire harness and a smart junction box) to define optimum design and EoL scenarios. The analysed EoL scenarios included: status quo car recycling, disassembly for specific EES component recycling and advanced post-shredder recycling. Smith and Keoleian [49] developed LCA model to investigate the energy savings and pollution prevention that are achieved in the United States through remanufacturing a midsized automotive gasoline engine. Puri et al. [50] researched three material alternatives (steel, aluminium and glass-fibre polypropylene composite) and three EoL strategies (land-filling, energy recovery and mechanical recycling) for an Australian automotive component, namely an exterior door skin. Lewicki [51] applied LCA method to evaluate consequences of increased vehicle recycling in Poland considering four scenarios: 25 %, 33 %, 50 % and 75 % from all ELVs will be recycled, respectively. Lazarevic et al. [52] reviewed plastic waste management in the context of a European recycling society and concluded that uncertainty analysis was disregarded in available LCA-based studies. Alves et al. [53] used the LCA to demonstrate the possibility to use jute fibres to produce a structural frontal bonnet of an off-road vehicle. Their results pointed out the advantages of applying natural composites in vehicle enclosures. Gaidajis et al. [54] used LCA method to analyze three waste management scenarios of used oil filters deriving from ELVs in Greece, namely maximum recycling, simple infiltration without special facilities and landfill. LCA results have shown that recycling is preferable for every impact assessment method used. Arena et al. [55] presented a streamlined LCA model that can be used to evaluate the strengths and weaknesses of alternative designs along multiple environmental dimensions in the early stages of developing a new vehicle, or to help carmakers in reporting the environmental performance of their vehicles to external stakeholders. However, one should keep in mind that this approach is validated only by a multi-disciplinary panel of experts.

3.2.2 Location

Different approaches for solving location problems in ELV recycling research area can be found in the literature, because facility location is considered as strategic level design problem.

Schultmann et al. [56] used a capacitated two-level facility location problem to determine the optimal design of reverse logistics (RL) network for spent vehicle batteries. Schultmann et al. [57] combined recycling sites location planning with collection and reprocessing of ELV's dismantled thermoplastics problem. They develop a symmetric capacitated vehicle routing problem with one depot (i.e. the reprocessing site) to generate a tour schedule with minimal cost for ELV RL network. Mansour and Zarei [58] presented a multi-period RL optimisation model for location of ELV collection centres and vehicle dismantlers. In this paper, a system for collecting the ELVs was based on a maximum accessible distance. Cruz-Rivera and Ertel [59] used an uncapacitated facility location model to determine the locations of ELV collection facilities in Mexico. In this paper, transport costs were considered as a determinant factor for the collection network design. Dehghanian and Mansour [60] proposed a multi-objective programming model for designing recovery network of EoL products and illustrated it on Iranian scrap tire case. The mixed-integer linear programming (MILP) model designed for locating of ELV recycling network entities is presented in Zarei et al. [61]. They assumed that the distribution of new vehicles and collecting the ELVs can be performed simultaneously in the same facilities, called distribution-collection centres. Merkisz-Guranowska [62] formulated a MILP model to determine the optimum locations of the key participants of the ELV recycling network (collection points, dismantlers and industrial shredders) in terms of total costs of the network. Harraz and Galal [63] developed a mixed integer linear goal programming model for location-allocation of the ELV recovery facilities and examined the effect of the model parameters on the network design. Vidovic et al. [64] presented modelling approach that could be used to locate collection facilities for ELVs. In order to minimise aggregation errors, they developed a novel approach to partition service zones into sub zones and incorporated this modification into the traditional formulation of maximal covering location problem. The proposed approach was illustrated on the Belgrade city area. Merkisz-Guranowska [65] proposed bicriteria models aiming at the reorganization and construction of an ELV recycling network on a given area that were subsequently used for the network optimisation in Poland.

3.2.3 Production planning

In general, production planning models can be classified into two sub-categories: (1) *Deterministic models*; (2) *Stochastic models*.

(1) *Deterministic models* - The literature provides a significant number of different deterministic mathematical models. Choi et al. [66] proposed a mixed integer programming (MIP) model for tactical process planning in the case of traditional United States vehicle shredding facilities. Williams et al. [67] expanded mathematical formulation from [66] in order to make short-term tactical decisions regarding to what extent to process and reprocess materials through multiple passes in eddy current sorter. In addition, their MIP model determines whether to combine materials for shipments. Qu and Williams [68] formulated the vehicle reverse production planning and pricing problem in a nonlinear programming model, developed an approximate supply function for hulks ordering when adjacent shredders price independently, and compared market with an optimised pricing strategy in three trends for ferrous metal and hulk costs: constant, increasing and decreasing. Li et al. [69] presented a coupled upgrading and production mathematical programming model to identify economically efficient sorting strategies and their impact on scrap usage in the case of an individual recycling firm. The model is applied to a cast/wrought alloy sorting for typical EU secondary aluminium production from four scrap types: aluminium-intensive (AI) vehicles, shredded extrusion, old rolled, and commingled. Simic and Dimitrijevic [70] presented a tactical production planning problem for vehicle recycling facilities in the EU legislative and global business environments. They analyzed influence of the EU ELV Directive on the vehicle recycling facilities business and concluded that future eco-efficiency quotas will not endanger their profitability. In addition, they recommended that the control of the recycling system efficiency should be done at the system level because it will in no way jeopardise the EU ELV Directive objectives. Simic and Dimitrijevic [71] expanded linear programming modelling framework proposed in [70] in order to incorporate vehicle hulk selection problem and to answer the following questions: Can a modernly equipped vehicle recycling facility conduct profitable business? Are EU ELV Directive's eco-efficiency quotas actually attainable? How will the commenced change in vehicle design influence vehicle recycling facilities? To do so, they provided a production planning model of a modernly equipped vehicle recycling facility and tested it extensively using real data. They came to the conclusion that vehicle recycling facility transformation, from traditional to modernly equipped, is not only necessary but completely justified and that the final success of the EU ELV Directive is realistic.

(2) *Stochastic models* - Most of the production environments are characterized by uncertainties. These uncertainties affect and complicate the production planning and control. Van Schaik et al. [72] proposed a dynamic optimisation model to describe the relationship between particle size reduction and liberation during shredding and recycling of ELVs. Through various simulations the authors illustrated the liberation behaviour of vehicles and provided insight into the mutual compatibility of processes and material streams at various stages of the ELV recycling chain. Shredding mill represents the core element of every vehicle recycling facility. Castro et al. [73] presented a simulation model that describes the relationships between vehicle design and the liberation level attained by shredding. The authors used distribution functions for modelling the breakage and liberation in the developed model. The obtained results showed that during product design the materials and joints among them can be chosen to obtain the best possible liberation and the lowest possible contamination. A detailed model to optimise the performance of the ELV recycling system, in which quality, separation physics and thermodynamics are addressed simultaneously, is suggested in [74]. The proposed model combines several dozens of processes (usually located on a single vehicle recycling facility) and flows to optimise the recycling of ELVs. Ignatenko et al. [75] extended optimisation model of the ELV recycling system proposed in [74] in order to add thermal treatment processes and energy recovery constraint enacted with EU ELV Directive. The obtained results showed that EU ELV Directive has the negative impact on the performance of the material and energy processing system in its totality. More detailed, by imposing an energy recovery constraint, the required complexity of processing routes increases, and the energy and material recovery performance is negatively affected.

3.2.4 Material selection

Selection of materials for a vehicle application is affected by numerous factors including weight, composition, cost, recyclability and so on. In this part of the paper, the material selection related papers are divided in two sub-categories: (1) *Design for X*; (2) *Recycling infrastructure effectiveness*.

(1) *Design for X* - Design for X (DfX) represents a wide collection of specific design guidelines such as design for assembly, design for manufacture, design for recycling (DfR), DfD, DfRu, design for environment, design for life-cycle (i.e. life-cycle engineering), design for quality, design for maintainability, design for reliability, etc. Good overview of the concepts, applications, and perspectives of various DfX methods can be found in [76]. The vehicle and its sub-systems can be adopted within the DfX principles to help analyze its environmental impact from specific design aspects such as disposal-ability and recycling efficiency. Therefore, in order to deal with the environmental criteria in vehicle

design process, a number of tools and methodologies were presented by researchers. Villalba et al. [77] proposed the recyclability index in order to incorporate it in the evaluation and optimisation of disassembly and DfD. Tonnelier et al. [78] developed a quantitative evaluation tool and a base of rules (called Precorec) that allow engineers to improve the recycling rate of parts or subassemblies of the vehicle. The objective of this tool is to quantify the recovery potential of a function (RPF) in terms of mass of recovered material, scenario for EoL and profitability on the completely defined parts and subassemblies. However, this RPF tool needs detailed and complete information: thus, it could only be used near the end of the design process. Ruhrberg [79] proposed the copper flow model to assess the recycling efficiency rate of copper from several EoL products, including ELVs. Ferrao and Amaral [80] proposed a new DfR tool based on the product's connection diagram to provide economically optimum recycling strategies, by combining dismantling, shredding and post-shredding activities, for achieving specific recycling and reuse rates. Applicability of the developed tool is illustrated on a car seat case study. Santini et al. [81] used a DfR software named ProdTect® to carry out a study on the impact that pre-shredder dismantling step could have in achieving 85 % recyclability rate in 2015. However, they investigated only recyclability rate, while total and energy recovery rates have not been considered. Nazmi et al. [82] developed artificial neural network (ANN) based DfRu tool to predict the critical stress life of a vehicle door so that the optimal reusability can be identified. The optimisation results showed that ANN application produced good reliability of the analyzed ELV part. Lu et al. [83] proposed an easy to operate method that can be used to predict the residual strength and life of reused parts of ELVs. Hedayati and Subic [84] proposed a decision-making support framework for recovery of ELVs to provide the integrated sustainable treatment option. It consists of four main stages: benchmarking study, development of the primary set of options, evaluation of options, and systems modelling. A case study illustrating the application of the proposed framework in an Australian context is provided. Agarski et al. [85] applied two multi-criteria assessment methods to assess environmental performances of passenger motor vehicles. Approach was described through a case study that included assessment of five Toyota Auris car models. The question of the vehicles' certification relating to their recyclability is closely analysed by Millet et al. [86]. They developed a method based on an Impact of module on recycling rate indicator which allows establishing rules for identifying the vehicle which presents the worst recycling case within a range. The proposed method aims to control the recycling rate at the end of the design process and to evaluate the impact of design choices on the recyclability or recoverability rates of vehicles.

(2) *Recycling infrastructure effectiveness* - The vehicle recycling infrastructure is an independent business that collects, processes and manages ELVs in an environmentally responsible manner and makes available vehicle parts for reuse and remanufacturing, facilitates the metal separation for recycling and allocates the disposal of waste. Boon et al. [87] used Goal Programming method to assess the materials streams and recycling process profitability for several clean vehicles cases. Van Schaik and Reuter [88] critically reviewed the vehicle recycling rate used in the EU ELV Directive and proposed two novel definitions of the vehicle recycling rate based on the various distribution functions for the lifetime, car weight and composition. Bandivadekar et al. [89] created a simulation model for material flows and economic exchanges (MFEE) to examine the effects of changes in vehicle material composition on the United States automotive recycling infrastructure. They noticed that the Japanese automobile shredder residue (ASR) recycling quota of 70 % and EU recycling/recovery quotas by 2015 are unachievable without fundamental changes. Amaral et al. [90] developed a system dynamics model of the Portuguese ELV recycling infrastructure and concluded that mechanical separation technologies are less expensive than component/part removal by dismantlers. Ferrao and Amaral [91] developed individual technical cost models of vehicle dismantlers and vehicle recycling facilities to assess the influence of the EU ELV Directive on the profitability of recycling infrastructure. Ferrao et al. [92] used data obtained from a full scale shredding experiment to develop a technical model and access the eco-efficiency performances of several vehicle recycling strategies. They concluded that ASR mechanical separation may enable more extensive recycling and allow the achievement of the present EU ELV Directive's recycling quota. Fuse and Kashima [93] developed an automobile recycling input-output analysis based evaluation method to examine the appropriateness of recycling system scheme for ELVs imported from Japan. Coates and Rahimifard [94] integrated several techniques, such as Activity Based Costing, regression analysis and time studies, and proposed the ELV costing framework. Their framework allows various recycling operators to assess the economic consequences of their investment and processing decisions. Kumar and Sutherland [95] used simulation MFEE model from [89]. They found that with change in vehicle design the profit of shredding facilities will increase over time, due to the additional revenue from the aluminium in AI hulks. Coates and Rahimifard [96] developed a post-fragmentation separation model capable of simulating the value-added processing that a piece of automated separation equipment can have on a fragmented ELV waste stream. The model takes the input composition of the ELV waste stream and determines the most likely route of each material flow.

4 The major classification scheme and distribution list

In this section, the major classification scheme and the distribution list of journal papers published in the period 2003 ÷ 2012 are created to identify the primary publication outlets.

The details of the major classification scheme and the papers that come under each such classification are presented in Tab. 1.

The distribution list of journal papers published in the considered period is presented in Tab. 2.

Table 1 The major classification scheme of journal papers published in the period 2003 ÷ 2012

Classification and sub-classification	Literature	Total
Review papers	**[4-7]**	**4**
General discussion	**[1, 8-41]**	**35**
Vehicle recycling practices world-wide	**[8-20]**	**13**
Legislation-oriented research	**[1, 21-36]**	**17**
Comparative analysis of legislations	[21-24]	4
EU ELV Directive	[1, 25-30]	7
Japanese and Chinese legislations	[31-33]	3
Extended producer responsibility issue	[34-36]	3
Remanufacturing and materials recycling	**[37-41]**	**5**
Modelling approach	**[42-75, 77-96]**	**54**
Life Cycle Assessment	**[42-55]**	**14**
Location	**[56-65]**	**10**
Production planning	**[66-75]**	**10**
Deterministic models	[66-71]	6
Stochastic models	[72-75]	4
Material selection	**[77-96]**	**20**
Design for X	[77-86]	10
Recycling infrastructure effectiveness	[87-96]	10

Table 2 Distribution of journal papers in the period 2003 ÷ 2012

Journal	**Year**									
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Resources, Conservation and Recycling		2		2			2	2	3	4
Journal of Cleaner Production			1		2	2		1	1	2
The International Journal of Life Cycle Assessment	1	1		2	1	1	1			
JOM	1	1	1	1	1		1			
European Journal of Operational Research				1	1	1	1			
Journal of Industrial Ecology	1			1		1			1	
Waste Management		1					2		1	
Journal of Material Cycles and Waste Management					2	1				
Waste Management & Research									1	2
Others (31 journals)	2	3	5	7	1	4	1	3	6	6
Total (40 journals)	5	8	7	14	8	10	8	6	13	14

5 Conclusions and recommendations

Recycling of ELVs is a vivid example for evolution of a resource recycling society. In that sense, as various resources are rapidly being depleted, recycling and recovery of ELVs are considered as one of the most important methods to promote sustainable development. On the other side, the problem of ELV recycling has become very serious in the last few years and more and more efforts are made all world-wide in order to reduce its impact on the environment, recovering materials and energy.

In this review paper, after presenting some background information, we comprehensively analysed the contents of 93 identified peer-reviewed scientific journal papers and classified them in the belonging categories and sub-categories. Previous figure clearly indicate the great relevance and tremendous importance of the analyzed topic in environmental engineering research.

From the distribution list of journal papers (Table 2) it can be concluded that the primary publication outlets for the ELV recycling research area are Resources, Conservation and Recycling; Journal of Cleaner Production; The International Journal of Life Cycle Assessment; JOM; European Journal of Operational Research; Journal of Industrial Ecology; Waste Management; Journal of Material Cycles and Waste Management; and Waste Management & Research; jointly publishing about 59 % of the total journal papers in the whole analysed time period. More detailed, those top-tier peer-reviewed scientific journals published about 61 % of the total identified number of papers in the past 5 years. Additionally, in past several years, numerous scientific journals have extended their aims and scopes to welcome papers from this research area.

On the basis of this review, the following recommendations for further development of the considered scientific research area are presented:

- Even though the application of the LCA methodology on the vehicle recycling problem is broadly reviewed in this paper, it should be noted that its general applicability could be seen as very "slippery". In addition, some authors, like for instance Reuter et al. [74], claim that simplistic LCA and similar environmental modelling approaches cannot provide the required depth to optimise, improve and understand the complete ELV recycling system. However, *integration of socio-economic features with ecodesign and LCA could be seen as very promising* (and robustly enough) *methodological approach for modelling and prediction of complex ELV recycling systems*. In this sense, use of Life Cycle Sustainability Assessment (LCSA) [97], which joins together LCA, Social Life Cycle Assessment (SLCA) and Environmental Life Cycle Costing (LCC) (i.e. LCSA=LCA+SLCA+LCC), could be seen as another field of future interest.
- *Modelling vehicle recycling processes and the uncertainty analysis needs to be simultaneously considered in the process of long term planning, and more research concerning this matter has to be done*. More detailed, a large number of factors in real world processes are influenced by uncertainties, and in a vehicle recycling system, it is difficult to express or obtain the overall modelling data in deterministic form. For instance, the costs of land-filling, incineration and advanced thermal treatment (ATT) are subject to continuous change; processing rates of vehicle recyclers' sorting equipment and efficiency of ATT plants and MSWIs depend on material flow composition; etc.
- One of the major weaknesses of previous research is that little has been done to *document present industry practices in real life case studies or surveys*.
- *The research within production and operations management is particularly needed to consider the effects of legislations on the choice of ELV recycling strategy*. For instance, having in mind that there are countries with contemporary ELV legislation around the world, such as China, Korea and Japan, creation of advanced mathematical models to comply with characteristics of Chinese, Korean and/or Japanese ELV recycling systems can certainly be considered as a field of major interest.
- *The research on novel ASR application represents another avenue for further research*. Nowadays, it is

obvious that the ASR recycling problem constitutes a crucial challenge to the vehicle recycling industry and decision making about it processing have enormous repercussions for other industries. However, the introduction of novel ASR applications might have a very positive influence on the vehicle recycling business, as it provides an opportunity to reduce landfill disposal costs once and for all. In that sense, ASR can be used as a binder and/or aggregate in asphalt for roadways, highways and airfields, applied as a mineral supplement in cement manufacturing, for the production of low-strength components such as housings and covers, used as an alternative fuel to coal in the iron metallurgical industry, utilised as an industrial fuel, and utilised as a secondary fuel in the cement industry.

Finally, we believe that this review will provide a source of reference for researchers/practitioners interested toward the environmental engineering issues of the ELV recycling research, inspire their additional attention and help to advance their work in the future.

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