Systematic Design for Recycling Approach – Automotive Exterior Plastics

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Abstract

Car components are getting more advanced when meeting customer requirements. At the same time, the requirements of having cars that are easily dismantled and recycled also increase. At Volvo Cars, there is a need to have car components adapted to ease disassembly, where one example is exterior plastic components. However, end-of-life processes of car dismantling are seldom thought of when designing exterior plastic components. Therefore, this paper aims to develop a systematic design approach to support the Design for Recycling of exterior plastic components from an end-of-life perspective. We investigated challenges, factors, and practices that affect the recycling of the cars’ exterior plastic components. In addition, we studied end-of-life and eco-design tools that are used in industry and meet the requirements established by Volvo Cars. This was then used to develop a systematic design approach to support Design for Recycling. It encompasses three steps: 1) checking the investigated component against the identified end-of-life practices (helps to identify problems and generates solutions for design improvements), 2) comparing the generated design improvements in terms of the environmental aspect (contributes to environmentally-driven decisions), and 3) evaluating the economic recycling benefits of the design improvements. The approach can be used within the automotive industry to improve the Design for Recycling of exterior plastic components and contribute to achieving a more circular economy.

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1. Introduction

The rapid growth of the automotive industry relates to the increasing rate of resource use in the manufacturing stage, leading to increasing waste at the end-of-life (EoL) stage [1]. Due to the large consumption of material and energy, the environment is impacted negatively [2]. The use of plastic materials in automobiles has increased considerably over the years due to weight reduction [3]. Even though some of the plastics are recyclable, other plastic materials are not easy to recycle and hence go to landfills. This shifts the environmental burden from the use stage to the EoL stage [4]. As a result, many countries with especially strict regulations, for example, the End of Life Vehicle (ELV) Directive [5], are moving towards waste management solutions [6].

The advancement of automotive technologies towards electronification has created complications for dismantling and accessing parts [7]. Dismantling and accessibility of the parts are considered the main challenges for recycling ELVs because they are time-consuming and cost-inefficient activities [4].

The circular economy (CE) concept is one of the solutions for the plastic waste generation problem as it aims for material value recovery. It also maintains economic benefits while tackling waste generation and resource scarcity challenges [7]. One of the strategies used for CE is recycling to close the loop. In relation to this, Design for Recycling (DfR) is an eco-design approach used to facilitate closing the loop. Hence, a synergy exists between eco-design and CE strategy [8].

There are several EoL and eco-design tools developed to assist in Design for Disassembly (DfD), which is one part of the DfR strategy [9]. Although DfD would not be enough to satisfy DfR, it is necessary to consider other factors and...
practices that relate to the EoL phase. 
For all the reasons mentioned above, there is a requirement in the automotive industry to have an efficient and effective design approach that supports decisions regarding environmental aspects to facilitate plastic recycling of exterior components at the EoL stage.

2. Methodology

Developing a systematic design approach to support DfR requires first understanding the context and the challenges with recycling cars’ exterior plastic parts. Secondly, it requires identifying the factors and the practices that affect the recycling of exterior plastic parts. Thirdly, there is a need to explore examples of eco-design tools/methods that have already been developed and then investigate the possibility of using a combination of these tools to develop our systematic approach.

A combination of research methods is used in this paper, and a triangulation approach is used to increase the credibility of the results. Results from a literature review are compared with those from the case study, which includes an interview study and a field study. This is done to identify challenges, factors, practices, and eco-design tools/methods. This is followed by developing the systematic approach through analyzing and mapping the different results together. Finally, the approach is tested on an exterior plastic part of a Volvo car (front bumper).

The literature review is conducted to explore the knowledge which already exists. The literature review is used to establish a theoretical background on DfR in conjunction with the CE. In addition, the literature review is used to identify challenges, factors, practices, and eco-design tools/methods by following the literature review approach used by Petersen et al [10]. The literature review process starts with defining the review scope and then searching for papers in the Scopus and Web of Science databases. This is followed by screening the papers to identify the most relevant ones. The next step is to create a classification scheme by categorizing the papers based on their contents. The last step is to extract, analyze and map the data for a better understanding of the challenges, factors and practices, and eco-design tools/methods.

The interview study was conducted because it is a suitable method to collect data in qualitative research. A semi-structured interview was used because it meets the flexibility requirement according to [11]. The interview study follows instructions by [12] for conducting an interview, and the interview questions are mainly exploratory questions with some follow-up and interpretive questions. Three interviews were held to collect data from five experienced stakeholders and employees. In two of the interviews, the participants asked a colleague to join to provide useful information based on their experience.

The analysis of the data obtained from the interviews was led by the research aim. The collected data was read to acquire an overall understanding. Then, the materials that could contribute to achieving the aim of this paper were identified using a conventional content analysis method described in [12].

The field study was conducted at a dismantling facility to identify practical challenges with the recycling of cars’ exterior plastic components. The facility was selected based on its certification, size, and capacity. A dismantling exercise was performed on two exterior plastic parts, which are, front and rear bumpers of different Volvo Car models. The bumper was selected because it is considered the biggest plastic exterior part, it carries different plastic types, and it is seen as a challenge for Volvo Cars. The field study was documented and recorded by means of notes and pictures. The notes and the pictures were analyzed, and results were drawn.

The results were analyzed from applying the research methods following three steps described by Gustavsson and Säfsten [12], which are, data display, data reduction, and making a conclusion. We started by looking at the EoL factors from an EoL perspective and connected them to the associated EoL principles that might contribute to eliminating the negative impact of these factors. Then, we attempted to find the appropriate eco-design tools that can enforce the EoL principles and therefore improve the EoL phase: Recycling strategy.

3. Theoretical framework

3.1. Life cycle perspective

The life cycle of a product refers to the phases that a product goes through during its entire life. The life cycle of a product consists of raw material extraction, manufacturing/production, distribution, use and ends with the end of life (EoL) phase. The product's life cycle is in this paper described according to a product life cycle model adapted from Johansson et al [13]. This model divides the life cycle into three main phases: beginning of life (BoL) includes several sub-phases: the extraction of raw materials, design, production, and the assembly of products, middle of life (MoL) contains distribution, installation, and use sub-phases. It also includes some activities like upgrading, maintenance, repairs, remanufacturing, and reuse, and end of life (EoL) is the post-use phase, including recycling, upcycling, energy recovery, and landfilling.

3.2. Circular economy

The current linear economy model causes waste generation, depleting of natural resources, and emitting pollutants into the eco-system [14]. The CE attempts to integrate economic activities and the environment to achieve sustainable development [15]. A general definition of a CE is, according to Morseletto [16], “an economic model aimed at the efficient use of resources through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socio-economic benefits.”.

For an efficient transition to a CE, recycling should target improving environmental performance. In other words, recycling should be a core concept of a product’s design, and the target should be set on the recycling content in products instead of the recycling target [16].
We identified 22 challenges with recycling cars' exterior plastic components. We categorized the challenges into four categories.

Under the category **product structure**, some examples of the challenges identified are identifying and separating components of an exterior plastic part, access to the parts or its components, long dismantling time, and complexity of the product architecture.

Under the category **joints**, challenges include the use of unliberated or hard to liberate joining techniques such as welds and adhesive bonds, loss or damage of material during dismantling, an excessive number of joints, requirements for the use of multiple tools to liberate the joints, use of different joining techniques, and inaccessibility to the joints.

The challenges identified under the category **material** are the use of various types of plastics, heterogeneity of plastic materials, low demand of recycled materials, use of incompatible materials such as adhesive tapes, labels, use of non-recyclable plastics such as thermoset plastics, use of surface coatings and paints, and functional requirement affecting material choice.

Finally, the challenges found in the **other challenges** category are DfR (is not included in industrial processes), aesthetic demand (paint, coating, etc.), high treatment costs such as dismantling and transportation, inadequate access to dismantling information, and the number of personnel required for dismantling.

We found that the challenges are interconnected, and one should consider them equally to improve the EoL phase: Recycling strategy.

4.2. Recycling cars’ exterior plastic components principles

We identified 52 practices and guidelines that affect the recycling of cars’ exterior plastic components. We categorized these practices and guidelines into seven categories based on the targeted area of the practice/guideline. These categories are:

- **P1**: Hazardous and toxic materials
- **P2**: Material identification
- **P3**: Material choice
- **P4**: Joining techniques
- **P5**: Recycling inhibitors
- **P6**: Ease of disassembly
- **P7**: General considerations

The environmental impact of the hazardous and toxic materials (P1) has an important effect on the EoL phase, as highlighted by [17] and [18]. In addition, [19] points out the importance of avoiding hazardous materials to avoid their negative impact on the environment during the treatment at the EoL phase. They also mention the criticality of following the regulations and the legislation when it comes to the use of hazardous materials.

Identification of materials (P2) is key for the EoL phase. More focus is placed on marking and labeling plastic parts [19-21]. We found that the guidelines regarding the identification of plastic materials are either mandatory or recommended by some eco-labeling standards. Furthermore, we found that the biggest number of guidelines/practices address the material choice (P3). Some guidelines within P3 recommend having one type of plastic along with the product, while others suggest using compatible plastic to reduce the disassembly cost at the EoL phase ([20], [22]). In addition, some guidelines give recommendations on the preferred plastic properties [23].

Joining techniques (P4) might complicate the recycling process and increase its cost [24]. The guidelines that we found mainly address minimizing the variation of the joining methods and integrating the joints with the parts wherever possible [30].

Recycling inhibitors practices (P5) are mainly recommendations to avoid the use of materials that might contaminate the plastic, for example, ink, coating, and paint [23], [26]. Moreover, some guidelines address the cases where using such contaminants is not avoidable [25].

We found that ease of disassembly (P6) is addressed in more general terms, and the guidelines and practices mainly address how to make the disassembly an easy and fast process. Some of these guidelines highlight the importance of ease of access and liberating the joints, and protecting the joints from external factors (e.g., corrosion) [19]. Also, we found some guidelines regarding clear direction for disassembly and assembly and using only one tool throughout the disassembly process [26].

Regarding general considerations (P7), they are guidelines and practices that indirectly affect the design of plastic parts. The seven principles are interconnected, and they should be equally considered to improve the EoL phase: Recycling strategy. The detailed guidelines/practices can be found in [27].

4.3. Recycling cars’ exterior plastic components factors

We found 31 factors that affect the recycling of cars’ exterior plastic parts. We can categorize these factors into five categories, F1: Cost-related factors, F2: Design-related factors, F3: technology-related factors, F4: Data and information-related factors, and F5: Other factors.

Collecting and transporting ELVs, disassembly processes, and reprocessing materials are the main factors that negatively influence recycling costs ([28], [29]). However, other factors have positive effects on recycling costs, such as the revenue from using recycled materials and the benefits from the reduction of waste generation [29].

The main design factors that affect the recycling of exterior plastic are related to fastener selection, how easy they are to access, and how easy it is to liberate the attached materials ([21], [30], [31]). In addition, [32] considers the lack of having DfD or DfR as a key factor that influences the recycling of exterior plastic parts.

Being familiar with the technology cycle of the product is a key factor when it comes to the EoL phase [33]. Moreover, products should be designed to take into consideration the limitation of the available recycling technologies.

The data is a critical element of the decision-making process, and the lack of data makes it hard to achieve a circular model and to follow the material flows [34]. In addition, raising awareness among and educating the public, suppliers, and other stakeholders is important to enhance the EoL phase [35].

The EoL factors are interconnected, and they are equally important when it comes to improving the EoL phase: Recycling strategy. The detailed factors can be found in [27].
4.4. End-of-life and eco-design methods/tools

A total of 66 methods/tools were found from the literature review, out of which 30 are EoL methods/tools and 36 eco-design methods/tools. The EoL methods/tools are classified into eight categories based on their outcome or purpose and consist of design improvement, recyclability rate, disassembly rate, degradation rate, disassembly sequence, disassembly time, cost benefits, and EoL treatment options. The eco-design tools are categorized into three categories, also based on their outcome or purpose, and consist of environmental assessment and design improvements, and economic assessment.

These tools are analyzed based on their inputs, outputs or purpose, life cycle consideration, consideration of recycling strategy for EoL, consideration of other sustainability aspects such as economic and social aspects, the time required to use the tool, area of tool use in the product development (PD) process, and the industry where the tools were used as a case study on a product. From the analysis, the tools were found to be mainly used in the electronic and electrical equipment (EEE) sector, but these tools can still be used in the automotive industry based on the purpose of the tools.


To develop a systematic approach, we must realize the factors, principles, and tools together and understand how they work collectively to enhance the EoL phase. Fig. 1 illustrates the relationships between factors, principles, and tools.

There is also a need to analyze the eco-design tools against the automotive industry requirements represented by Volvo Cars. A detailed analysis can be found in [27]. We identified the following five requirements that the approach should:
1. be efficient and effective,
2. support the decision-making process,
3. generate requirements for other departments (e.g. R&D),
4. support DfR, and
5. consider environmental and economic aspects.

The systematic design approach should contain all the factors that affect the EoL phase. However, the technology factors are an aspect that can not be addressed directly from a design perspective, but the industry can still work with other actors through conducting research and investigating new technologies that contribute to improve recycling at EoL.

As regards the design factors, the main aspect is a product design that supports the recycling process at the EoL phase. This requires understanding the current design and identifying areas for improvements. We found that the checklist is a qualitative methodology and easy to understand and use. Furthermore, the checklist facilitates generating new design ideas [41] and can be modified to target the EoL to understand its environmental impact.

Therefore, we adopted CSPD [36] and the eco-strategy wheel checklist [37], and integrated EoL principles to develop a checklist dedicated to the EoL phase of cars’ exterior plastic parts. In addition, we added some additional questions to the developed checklist to make sure that no problem shifting could occur due to implementing the new ideas.

In addition, there is a need to measure the positive impact of the new ideas to be able to make a decision regarding which one should be prioritized. We found that Quality Function Deployment for Environment (QFDE) [38] can be used for decision-making purposes because EoL requirements can be added to the tool. Moreover, QFDE makes the decision-making process quantitative, giving more confidence to the user, and it provides a visual representation of the results, making the results easier to understand.

SDRA-EP (Fig. 2) consists 3 steps, in Step 1, the checklist is used to identify problems, areas for improvement, suggest design improvement options, and check if any of the suggested options might cause potential problem shifting.

This is followed by Step 2, where QFDE is used to compare the design improvement options which are generated in Step 1. Step 2 carries out the comparison in terms of the options’ effects on customers and the environment. Then a cost-benefit analysis is performed in Step 3 to measure the economic benefits of the design improvement options.

5. Discussion

SDRA-EP makes the recycling process of cars’ exterior plastic components more effective and cost-efficient. This is in line with [39] regarding the purpose of using DfR tools.

Our systematic design approach deals with most exterior plastic components’ recycling challenges. It facilitates the identification of the plastic components and contributes to reducing the number of plastic types used in a product. Moreover, SDRA-EP helps to address dismantling-related challenges, which lead to cost and time reduction.

Some challenges are not addressed by the approach, for example, ELV transportation cost and aesthetic demand. Those challenges might affect the transition towards a CE, and therefore the user of the approach should be aware of such challenges and their consequences.

SDRA-EP addresses most of the EoL factors, but there are still some factors that are not being addressed by the approach. The user should be aware of such factors to achieve the transition towards a CE (e.g., collection cost, ELV purchase, and technology factors). Our approach meets the automotive industry requirements. SDRA-EP is time-efficient, and it is a simple approach that helps identifying potential improvement areas and generate improvement suggestions.

SDRA-EP considers the environmental and economic aspects of the entire life cycle of the exterior plastic parts. Our approach can be used to give design-related feedback from the aftermarket to the R&D department to make the product more recycling friendly, while other DfR tools/approaches are usually used in the design phase ( [40], [41] ). In other words, SDRA-EP opens communication channels between upstream and downstream stakeholders.

Furthermore, other tools/approaches mainly focus on calculating the recyclability rate of a product through improving the disassembly process. SDRA-EP, in contrast, considers the disassembly process as one of several aspects that contributes to improving not only the recyclability rate but also the rate of the recycled materials in a product.
SDRA-EP has some limitations that the user should be aware of. The approach does not consider the social aspect, it has a certain level of subjectivity, and it requires a user with a dynamic mindset. Further studies and tests should be carried out on SDRA-EP to understand these limitations and further develop the approach.

6. Conclusion

The systematic design approach (SDRA-EP) proposed in this paper aims to support DfR on automotive exterior plastic parts on a conceptual level. This approach will be helpful for initiating and supporting DfR for new and developing old products. It also helps towards achieving a CE. The pathway of the challenges in relation to the factors helps the approach to be used effectively and efficiently by using a combination of eco-design and EoL tools, meaning the approach considers these factors and therefore helps to solve the challenges, especially in terms of DfR. This approach has been studied in a case with Volvo car’s front bumper, thereby validating the approach.

Regarding challenges, we identified 22 challenges and categorized them into four categories. The user must be aware that this approach needs to be used for different exterior plastic parts as the challenges will be unique to each specific part and know that these challenges are interconnected.

For EoL factors and practices, we identified 52 practices that we categorized into seven principles. For factors, we found 31 that we categorized into five-factor categories. The principles influence the factors and hence improve them by means of the eco-design tools. Similar to the challenges, the principles and factors are found to be interconnected.

The approach SDRA-EP is developed based on the requirements from the automotive industry, especially Volvo Cars, by using a combination of EoL tools and eco-design tools. This approach will benefit in many ways, such as improving cost-effectiveness, life cycle considerations, ease of use, increasing ease of recycling, helping generate ideas for improvement, and helping environmental and economic driven decisions.

Despite the benefits, drawbacks with this approach were also found. It do not consider social aspects, and the usage has subjectivity at a certain level. SDRA-EP can be further investigated and developed, and a workshop can be arranged in the future with users from different industries to evaluate the approach. The outcome of the workshop will help to concretely validate the benefits of the approach, as in our paper, SDRA-EP was tested with only one company (Volvo Cars). In addition, room for improvement could be identified from the workshop to continue developing the approach and minimize its limitations.
References


