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LAYING THE FOUNDATIONS FOR A DFR TOOL FOR AUTO COMPONENTS

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Abstract

Environmentally innovative products are to be considered in the context of their life cycle, and within the framework of the legal-economic strategies that govern both product and the infrastructures that interact with it. The auto-industry has been particularly involved in this process and, in particular, EU directive 2000/53/EC, that restricts the use of some materials and stipulates minimum reuse and recovery rates for end-of-life vehicles, which motivates the use of dedicated design for recycling (DfR) tools.

This paper assesses existing methodologies for economical optimisation of disassembly activities, and this allowed identifying the need for a new approach based on precedence relations between disassembly operations. This requires all the operators integrating the end of life vehicle processing chain to be considered, namely: dismantler, shredder and operator for shredder residue separation. The new methodology is under implementation in a software tool, which is illustrated in the text.

The foundations for a DfR tool to be used in the auto industry are discussed and a methodology for disassembly activities optimisation that makes use of environmental and economical information is presented and illustrated in a case study.

Keywords: design for recycling, disassembly optimization, end-of-life vehicles

1. Objectives

The main objective of this paper is to discuss the principal drivers of a design for recycling (DfR) tool, in the context of emerging technologies for end of life vehicle (ELV) processing, namely shredder residue (SR) recycling.

2. Introduction

In the last decade, extended product responsibility has driven environmental concerns to the product life cycle level and has been a major driver for the introduction of environmentally innovative products and services. The auto-industry has been particularly active in designing more efficient engines or making use of lighter materials, which contributed to reduce the environmental burden associated to the use of a car. However, the use of light materials in cars is to be considered with care by designers, if the end-of-life is to be considered. This is because the EU directive 2000/53/EC restricts the use of some materials and stipulates minimum reuse and recovery rates for end-of-life vehicles:

- Until 01/07/2003: vehicles put on the market cannot contain lead, mercury, cadmium or hexavalent chromium, with the exception of some cases referred in the annex of the Directive.
- Until 01/01/2006:
  - reuse and recovery of 85% on a mass basis (recycling 80%) for vehicles produced after 1980.
  - reuse and recovery of 75% on a mass basis (recycling 70%) for vehicles produced before 1980.
- Until 01/01/2015 – reuse and recovery of 95% on a mass basis (recycling 85%).

This directive also encourages vehicle manufacturers to promote the prevention of waste, through the application of the following eco-design strategies:

- Reduce the use of hazardous substances in new vehicles,
- Improve the ease of dismantling, in order to increase the rate of reuse, recycling and recovery of end of life vehicles;
- Integrate an increasing quantity of recycled material in vehicles, in order to develop the markets for recycled materials.

It is clear that these constraints to car design are to be considered in the context of the life-cycle infrastructure in which the product or service lives, and the legal-economic strategy that governs both product and infrastructure. This paper looks at only one necessary element, design for recycling tools, but the approach adopted is dynamic, in the sense that eco design strategies that can be implemented: design for disassembly, reuse, re-manufacture or recycling are related to the emergence of new systems for managing end of life products, through the development of a new software tool whose main parameters are discussed under the framework previously analysed and considering the currently available practices.

The current understanding about DfR of complex products with non metallic materials has been, until now, closely related with the practice of design for disassembly, which allows for the separation and use of recycled materials in substitution of their virgin correspondents. However the costs associated to disassembly are leading to the development of new SR separation technologies that require a new approach to DfR.

This requires a new systematization of the available information on ELV treatment technologies that considers the two strategies, disassembly and SR recycling, and this promote the development of DfR optimization methodologies. The analysis of this process towards the development of a new DfR tool constitutes the main motivation for this paper.

The rest of this paper has been organized into four main sections; the next section discusses available methods for economical optimization of disassembly activities, then methodology proposed for economical optimization of disassembly activities is presented and a case study is analysed. Finally, the main conclusions of the paper are presented.

3. Methods for economical optimization of disassembly activities

In the past, different methodologies for economical optimization of disassembly activities were presented, e.g. [1 to 6]. From these, the method suggested by Lambert [1] is formulated in such terms that it is of general application and thus is discussed here in more detail.

This methodology is based in a product's connection diagram, as illustrated in figure 1, where the precedence relations for removing each part constitute a major input parameter. From this information, all the feasible disassembly sequences are identified and represented making use of a transition matrix T_{ij} [2] (other similar representations of all the feasible dismantling sequences include more graphic based methods such as the AND/OR graph [3] or Petri Nets [4]). An element t_{ij} of the transition matrix is equal to -1 if a disassembly action j destroys the group i (group of components, for example F+H), or to 1 if action j creates the group i (being the remaining elements equal to zero). Economic information is considered by assigning a cost to each action (vector C_j), e.g. proportional to dismantling time, and a revenue to each group or part (vector R_i), which may be associated to the part reuse or to the value of the recycled material.

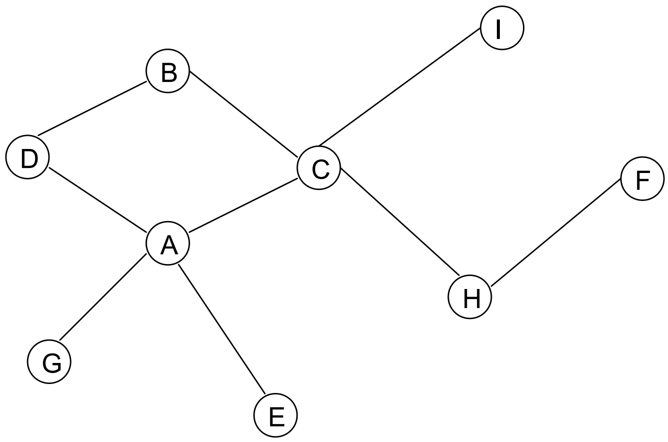

Figure 1. Example of a product's connection diagram, representing parts (circles) and their connections (lines), e.g. part A is directly connected to parts D, C, G and E.

The optimal disassembly sequence is calculated making use of linear programming optimization to minimize the total net cost:

$$\sum_i \sum_j (T_{ij} \; r_i + c_j) \; x_j \tag{1}$$

subject to:

$$\sum_j T_{ij} \; x_j \leq 0 \tag{2}$$

with:

$$x_0 = 0 \tag{3}$$

In order to ensure the removal of given parts, near optimum disassembly sequences can be calculated. In this case, constraints are added to the minimization problem that disable the "previous" optimum solution and a new optimum sequence is calculated [5]. Here, other optimization methods, such as Petri Net based optimization algorithms, may be used, as presented in [4].

The method suggested by Lambert [1,2,5], may require a significant amount of computational time and some expert user intervention in the optimization process, namely when adding constraints for near optimum analysis.

An advantage of this method resides in the possibility of comparing different disassembly sequences which lead to the same final set of removed parts. For example for the assembly

(A B C) this methodology allows, as long as the user, for the comparison of the following disassembly sequences, provides discriminated information:

- separation of (A) and (B C); separation of (B) and (C);
- separation of (A B) and (C); separation of (A) and (B);
- separation of (B) and (A C); separation of (A) and (C);

However, the requirement for very detailed information is to be emphasised, as it is not frequently available. Considering the example given above, comparing the tree parallel dismantling sequences would implicate that tree distinct dismantling times relative to the separation of A were measured and made available. One for dismantling A directly from the assembly, another for separating A from B after dismantling C and, another for separating A from C after dismantling B. Thus, the full assessment of parallel dismantling sequences may require a huge amount of time for collecting all the different dismantling times, which, even for a small set of parts, may prove to be unfeasible.

Alternatively, [6] mentions a different method based in a product's representation, similar to the one used in a typical bill of materials, that considers parts and subassemblies of different levels (see figure 2). Parts are characterized in terms of material composition, removal time and precedence relations. Removal time and precedence relations are also defined for subassemblies. Economic information is considered by assigning a cost and a revenue to each part and subassembly. The cost is proportional to its disassembly time and the revenue (which can be negative) is the highest value from the following: reuse, recycling, shredding and landfill.

The assessment of each disassembly sequence is performed through the evaluation of its final state, which consists in a set of dismantled and non-dismantled parts and subassemblies. For sets that verify precedence relations, total values of profit and recycling rate can be calculated. The optimum disassembly sequence (final state) can be found by enumerating and comparing all the possible sets. For larger sets of parts and subassemblies a genetic algorithm based optimization procedure is used.

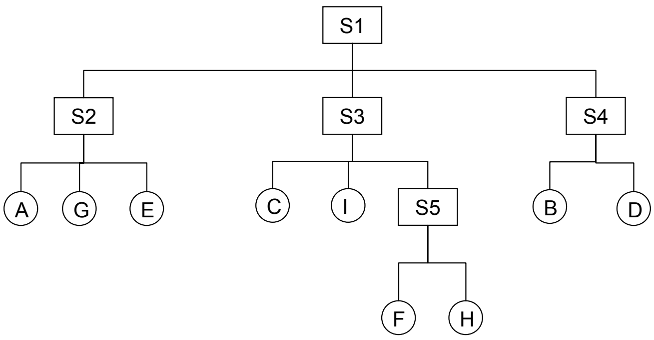

Figure 2. Product representation that considers subassemblies (boxes) and parts (circles).

The results obtained with this method may be highly dependent on the way the information on parts, subassemblies and precedence relations is entered by the user, and therefore, the solution is biased by the structures of the dismantling sequences that are made available when the problem is parameterised.

As an illustration of this drawback, consider a set of 4 parts (A B C D), linked as presented in figure 3, where precedence relations are not established, including the respective disassembly times for breaking each connection. The user could measure 12 s for disassembling part C, as it requires breaking the links from C to A and B, and 15 s for disassembling part A. Based in this values, for the disassembly of parts C and A, this method may compute a disassembly time of 27 s, where breaking the connection between A and C was accounted twice.

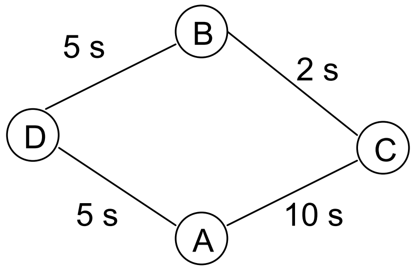

Figure 3. Set of four parts and dismantling times for breaking the associated connections

The previous analysis of existing methodologies for economical optimization of disassembly activities, shows that there are methods available to formulate any disassembly problem, but did also show that their use may be limited either by the amount of data to be gathered by disassembly experiments or by the bias induced on the formulation of the problem.

In particular, the method presented in [1] assesses all the possible disassembly sequences, but may require a significant amount of computational time and expert user intervention. The method described by [6] uses a simplified product description based in parts and subassemblies. However its results may be highly dependent on the way the information on parts, subassemblies and precedence relations are defined namely when assemblies with several connections are considered.

The necessity of reducing computation time and user intervention, while ensuring that the information on parts connection is considered in the optimization of the disassembly sequence, motivated the development of the method suggested in the next section.

4. Proposed methodology for economical optimization of disassembly activities

The methodology suggested here is based in the product's connection diagram and emphasis is given to the relations of precedence for the disassembly operations that cut the connections between the parts.

The method suggested here is supported by a software, illustrated in figure 4, that is under development, where information is collected by requiring the user to completely disassembly the main assembly until only individual parts are left, while registering the operations and the parts connected by the connections eliminated. It is considered that one operation may cut more than one connection (ex: removal of a screw that connects four parts).

The evaluation of each disassembly sequence is performed considering its final state, which corresponds to a set of performed and non-performed operations. The feasibility of each set is assessed confirming that all the performed operations comply with precedence relations.

Economic information is considered by assigning a cost to each operation and a revenue to each separated part and group of connected parts. Cost is proportional to the disassembly time and the revenue (which can be negative) is the highest value associated to possible end of life scenarios. These may include reuse, recycling, shredding with or without shredder residue separation and landfill. Regarding reuse and recycling, the following rules are considered:

- Reuse is considered only for user specified parts and groups of parts that correspond to subassemblies with reuse value;
- Recycling is considered only for parts or groups of parts composed by a single material;

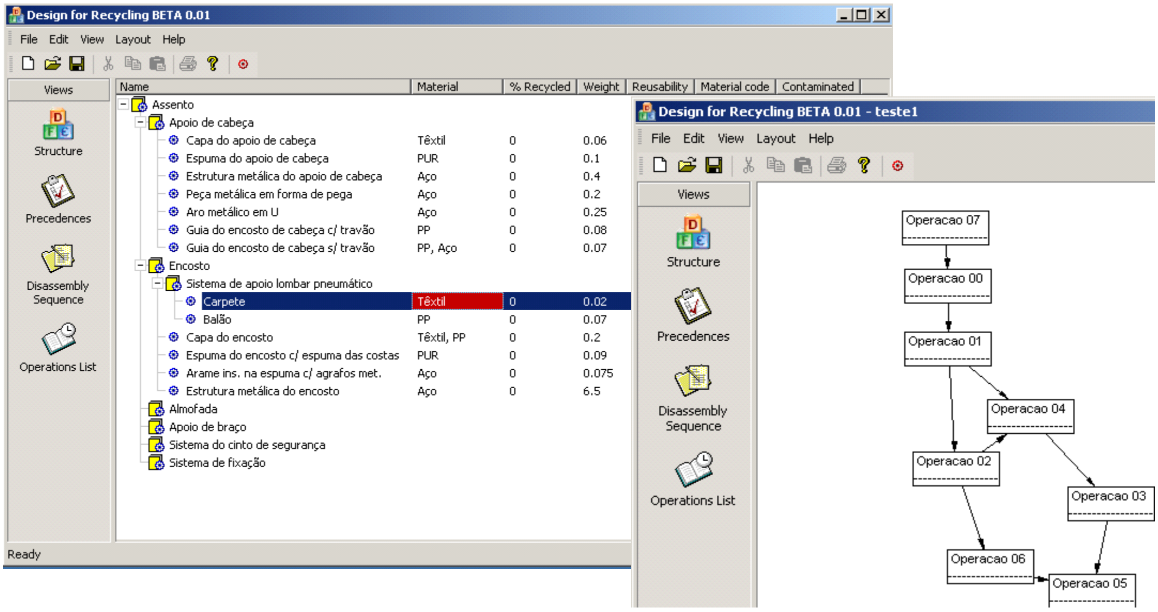

Figure 4. Sample view of the DfR software under development at IST-IN+.

Considering the operations performed, groups of connected parts and separated parts are identified allowing for the evaluation of the total values of profit and recycling rate. The optimum disassembly sequence (final state) can be found by enumerating and comparing all the possible sets.

To assess the economic value and the recycling rate associated to a given disassembly sequence the following parameters are required:

- Operations: time, parts separated and precedence relations by other operations;
- Parts: weight, material composition, subassembly where the part is included and reuse value;
- Subassemblies: higher level subassembly where the subassembly is included and reuse value;
- End of life scenarios: material recycling value, shredding value (dependent on material composition of the group or part), shredding efficiencies for separation of ferrous and non ferrous metals, shredder residue process separation efficiencies for metallic and non metallic materials and landfill cost.

The software is aimed at supporting product design of auto components with increased recycling performance. This objective is to be achieved by calculating the most economical disassembly sequence while ensuring the accomplishment of a pre-specified recycling rate. This requires all the operators integrating the end of life vehicle processing chain to be considered, namely: dismantler, shredder and operator for shredder residue separation.

The dismantler, besides removing hazardous materials, may also disassemble parts for reuse and recycling. The remaining hulk is then sold to a shredder, where it is broken in small pieces (around 10 cm). The pieces containing metals are separated, with different separation efficiencies for ferrous metals and non-ferrous metals. The remaining material mix (plastics, rubber, glass, metals, etc.), designated by shredder residue, which currently is normally sent to landfill, may be further processed in order to separate some of the materials for recycling or recovery. Solutions that manage to separate different material from the shredder residue, allowing for recycling and/or recovery [7], are also modeled.

5. Case study: automobile seat

The methodology suggested in the previous section is illustrated making use of a case study where a car seat is disassembled. This case study is intended to illustrate:

- the type of information required to the user
- the building up of dismantling sequences
- the foundation for process optimisation.

The seat considered is based on a steel structure and includes six main sub-assemblies: head rest, back support, seat support, arm rest, seat belt system and tracks.

The seat includes a total number 39 parts, and weights 25 kg. Table 1 provides a sample view of the product structure, and of the parameters that where used to characterise each part.

Table 1. Product structure

Parts	Subassembly	Weight (kg)	Material composition	Reuse value (€)	Recycling	End of life value (€/ton)
Head rest cover	Head rest	0,05	Foamed textile	None	No	-46
Head rest polyurethane cushion	Head rest	0,26	Polyurethane PUR	None	Yes	0
Head rest metallic structure	Head rest	0,40	Steel	None	Yes	55

The dismantling sequence that resulted from the manual disassembly of the seat resulted in 28 dismantling operations, where the parameters represented as columns in table 2 were registered, and constitute the main input to the disassembly optimisation procedure.

Table 2. Operations structure for dismantling sequence A

#	Operations	Separated parts	Precedence relations	Time (min.)	Disassembled material (kg)	Recycled material (kg)	Disassembled costs (€)
1	Dismount	- Head rest locking-ring - Head rest guides	-	1,5	0,00	0,00	0,38
2	Unsheath	- Head rest cover - Head rest polyurethane cushion	-	1,0	0,05	0,00	0,25
3	Dismount	- Head rest polyurethane cushion - Head rest metallic structure	2	0,5	0,26	0,26	0,12
4	Unscrew and dismount	- Head rest locking-ring - Head rest metallic structure	1, 3	5,5	0,83	0,80	1,38

The dismantling sequence first introduced by the user has environmental and economic consequences that are represented in figure 5, in terms of recycling economics vs. the amount of materials removed and recycled. This dismantling sequence is not optimal, and this is clear if it is compared with an alternative sequence represented in figure 6. Here, for example, the costs required to achieve a recycling target of 80% are reduced by 20%, when an improved strategy is adopted, which is to say, when the dismantling sequence represented in figure 5 is replaced by that of figure 6.

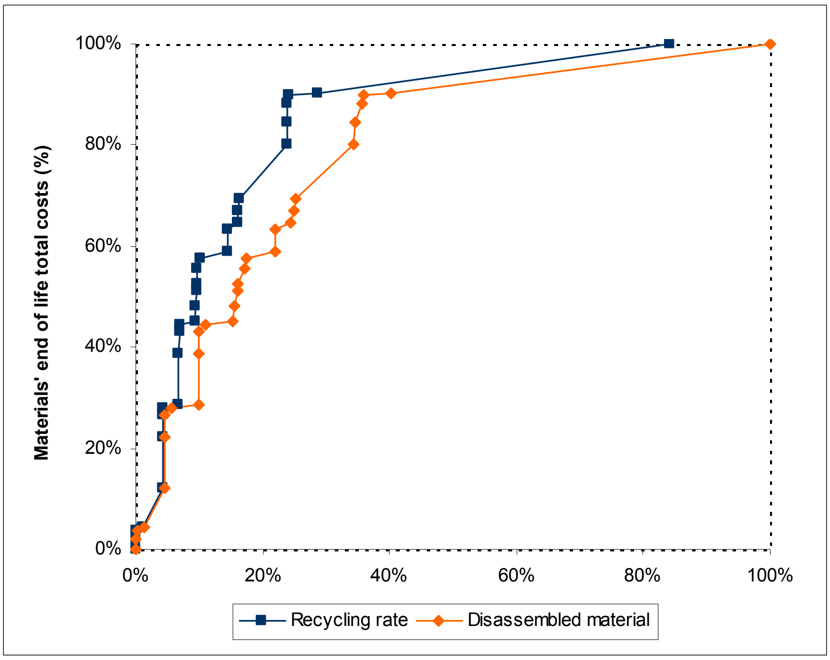

Figure 5. Dismantling sequence A

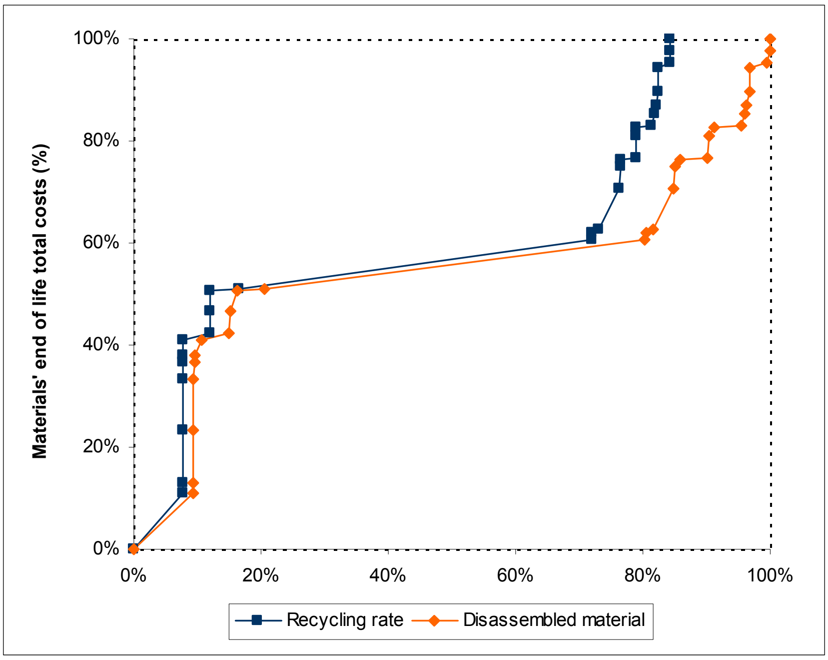

Figure 6. Dismantling sequence B

6. Conclusions

The foundations for a new DfR software tool were discussed and resulted in a new methodology for disassembly activities optimisation. The suggested methodology incorporates environmental and economical information according to a set of specified parameters. This requires all the operators integrating the end of life vehicle processing chain to be considered, namely: dismantler, shredder and operator for shredder residue separation.

The optimisation procedure is demonstrated in a case study that analysis the recyclability of a car seat in economical and material terms.

7. Acknowledgements

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