

THE EVALUATION METHODS OF DISASSEMBLABILITY FOR AUTOMOTIVE COMPONENTS – A REVIEW AND AGENDA FOR FUTURE RESEARCH

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ABSTRACT

Nowadays, automotive manufacturers are facing with impact of the vehicle to the environment. In some European countries, Japan, USA, and Australia, laws require automotive manufacturers to take back their products at the end of their useful life and recycle them. Most of the developed countries also have set new legislation, which is planned to force automotive manufacturers to recover and recycle their products at the end of their life. Disassembly is the first step to recycle automotive components. In general, the designers do not have experience in disassembly and recycling to determine the impact of various design aspects on the disassemblability at the disassembly stage. Based on that, many researchers have proposed several methods in evaluating disassemblability. This paper reviews the evaluation methods of disassemblability which were proposed by the previous researchers and then outlines the functional requirements for a system for evaluating the disassemblability of automotive components based on automotive manufacturer and legislation requirements. In particular, the implication of end-of-life vehicle on current product design practice is also explored. The result of the literature review shows that, in order to successfully implement the concept of end-of-life vehicle especially in terms of disassemblability evaluation, the aspects of recycling and disassembly must be considered more rigorously in the product design process.

Keywords: *Disassembly; disassemblability evaluation method, automotive components, end-of-life vehicle*

1.0 INTRODUCTION

Automotive manufacturing has increased in the last 20 years, reaching about 58 million units (excluding commercial vehicles) in 2000 [1]. At present,

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approximately 75% to 80% of end-of-life vehicles in terms of weight, mostly metallic fractions, both ferrous and non ferrous are being recycled. However, the remaining 20% to 25% in weight, consisting mainly of heterogeneous mix of materials such as resins, rubber, glass, textile, etc., is still being disposed [2].

According to EU Directive [3], the disposal of vehicles is a major source of hazardous waste and toxic emissions. About 25% of a vehicle's weight is classified as hazardous waste. In Europe, about 12 million tones of vehicles reach their end-of-life every year, and 25 percent of them are disposed to the landfill [4].

Now, the automotive manufacturers are facing with the impact of the vehicles to the environment, consumption of energy and resources, waste generation, greenhouse gases, hazardous substance emissions, and disposal are burdens created by vehicle production and use [1].

To reduce the environmental impact of end-of-life vehicles, European Union, Japan, USA, and Australia laws require manufacturer to take back their products at the end of their useful life and recycle them [5]. In order to enhance the recycling rate of the vehicle, it is important to disassemble every part of the vehicle depending on the materials. However, it may be impossible, its cost is too much, and unrealistic. Because of that the disassembly effort should be determined in the vehicle development phase where its properties are fixed.

Base on that, the disassemblability, the degree of easiness of disassembly, becomes important. The environmental impacts of products can be minimized only if the products can be disassembled and recycled easily [6] and the cost effectiveness of recycling will be increased if disassembly is made easier [7].

2.0 LEGISLATION

2.1 European Union (EU)

In September 2000 after much consultation, the European Commission produced End-of-Life Vehicles (ELV) directive. The EU ELV directive is the legislation enacted by the European Commission to minimize pollution resulting from vehicles that have reached the end of their useful life [4].

The EU Directive states that the vehicle manufacturers and material and equipment manufacturers must meet the following objectives [3]:

1. Endeavour to reduce the use of hazardous substances when designing vehicles.
2. Design and produce vehicles which facilitate the dismantling, re-use, recovery and recycling of end-of-life vehicles.
3. Increase the use of recycled materials in vehicle manufacture.
4. Ensure that component of vehicles placed on the market after 1 July 2003 do not contain mercury, hexavalent chromium, cadmium or lead.

According to the EU Directive [3] the requirements for dismantling, reuse and recycling of end-of life vehicles and their components should be integrated in the design and production stages of new vehicles and producers should ensure that vehicles are designed and manufactured in such a way as to allow the quantified targets for reuse, recycling and recovery to be achieved.

2.2 Japan

On 1 January 2005, the End-of-Life Vehicle Recycling Law was fully enforced in Japan. This law is intended to promote environmental conservation and the effective use of resources by implementing measures to ensure the proper and smooth recycling of end-of-life vehicles. Under the law, automobile manufacturers are obliged to collect and properly dispose of the following three items: chlorofluorocarbons (CFCs) that are used as air conditioner refrigerants and would destroy the ozone layer and contribute to global warming if emitted into the air; airbags that are difficult to dispose because of their explosive nature and automobile shredder residue (ASR) that remain after the collection of useful materials from end-of-life vehicles. The target of the Japan law for recycling is to establish recycling system with the goal of attaining 95% recycle rate by 2015.

2.3 USA

In USA, there is no specific legislation regarding the management of end-of-life vehicles. All materials, either waste, materials or recycled materials are considered as a solid waste. So the recycling industry has received much less interest. Currently, there is no shortage in waste disposal sites because of abundant land. This situation can make the costs of waste disposal low. Further more, there is no standard waste legislation for whole of the US. Every state has its own legislation, so the target and implementation varies from state to state.

However, Ford, Daimler Chrysler and General Motors have provided a special program to study how to improve recyclability rate and methods to decrease the current ASR burden [8]. The USA Environmental Protection Agency (EPA) is trying to promote the recycling concept among the vehicle manufacturers [9].

2.4 Australia

Based on the Australian Department of the Environment and Heritage [10], there is no specific the end-of-life vehicle directive in Australia. But some progress has been made towards encouraging end-of-life vehicle recycling through informal encouragement of recyclers and dismantlers.

A joint project between the Department of Environment and Heritage and Auto Parts Recyclers Association of Australia (APRAA) has produced guide booklets on waste oil recycling, which were sent to recyclers and dismantlers throughout Australia during 2003. They are also encouraging recyclers to prepare their own environmental action plan, highlighting the efficiency benefits and improved reputation amongst councils, environmental protection agencies, customers and staff, of any operators taking actions to protect the environment. There is also a current project being undertaken by the Plastics and Chemicals Industries Association (PACIA) looking at the potential for recycling automotive plastics [11].

3.0 END-OF-LIFE VEHICLE PROCESS

From end-of-life vehicles, dismantling companies first remove the oil, engine, transmission, tire, battery, catalytic converter, and other parts, which are commonly recycled or reused. Dismantling process is the process or procedure of

breaking down and end-of-life vehicle into its individual components and material-specific elements [12]. Shredding companies then sort out the ferrous and non-ferrous metals and resin from the remaining vehicle bodies. At shredder facilities, hulks are inspected prior to shredding to ensure that potentially hazardous components such as batteries, gas tanks, and fluids have been removed. Hulks (and other collected materials) are then shredded into fist-sized pieces using large hammer mills. The post shredder process separates the stream of materials into the basic streams, ferrous material and non ferrous material. By using air separation the non-ferrous materials are separated into the metal (containing aluminum, brass, bronze, copper, lead, magnesium, nickel, stainless steel, and zinc) and non-metal known as ASR (containing plastic, glass, rubber, carpet, foam, textile, etc.) fraction. The ferrous metal fraction is sent to the steel smelters for recycling. The metal fraction is typically sent to another, specialized facility to separate the stream into its individual metals by a variety of means. The ASR is disposed into landfill [8]. ASR often contains hazardous substances such as lead, cadmium, and printed circuit board (PCB). Therefore, some countries have classified ASR as hazardous waste and have established legislative controls. ASR represents about 20–25% of the end-of-life vehicle weight [1].

4.0 THE EVALUATION METHOD OF DISASSEMBLABILITY

The disassemblability concept evolved from the life cycle engineering concept where the design for disassembly is one of the strategies in reducing the impact of the product to the environment.

According to Alting and Legarth [13] life cycle engineering/design is the discipline which incorporates environmental issues and parameters across the life cycle of a product into product development, and life cycle assessment (LCA) is the tool that visualizes the environmental and resource consequences of these choices [14, 15].

Pre Consultant Netherlands [16] designed a tool in list form that provides 100 indicators measuring the effect of commonly used materials and processes for ecosystem named as eco-indicator. Perrson [17] presented an approach for structuring the concepts of eco-indicators. A software for environmental assessment known as Simapro was designed by Pre Consultant [18]. Hesselbach and Küln [19] designed assessment software named as ASTROID. Lenau and Bey [20] presented the Oil Point Method (OPM) in order to fulfill the requirement of product designers on method for environment evaluation. Huisman et al. [21] proposed the Environmentally Weighted Recycling Quotes (EWRQ) in calculating the recyclability of products. Industries also developed their assessment system for internal use. Volvo developed the evaluation system based on a single figure Environmental Load Unit (ELU) and named it as Environmental Priority System (EPS) [22], Motorola designed product life cycle matrix to compare the life cycle stages project against sustainability [23].

The strategies for increasing the environmental performances of products were proposed by Wenzel et. al. [14] and by Alting and Legarth [13]. The two design strategies that get more attention in life cycle engineering is Design for Disassembly (DfD) and Design for Energy Savings (DfS) because of their

widespread implementation, and because they take action on some of the most important environmental issues [13].

DFD is one of the aspects of product development which focus on the recovery of resources at the end of the product lifecycle [24]. Manufacturers who fail to practice DFD now risk squandering future revenues when their current products are due for disposal. Desai and Mital [25] defined the disassembly, in the engineering context, as the organized process of taking apart a systematically assembled product (assembly of components). Disassembly process may be clearly distinguished into two categories based on the method of disassembly, destructive and non-destructive. Non-destructive disassembly can be divided into total disassembly and selective disassembly [25]. Based on Luttrup [26], design for disassembly means design efforts in order to improve the performance of a product with a focus on separation and sorting of waste. Design for Disassembly (DfD) is a class of design method and guidelines to enhance the ease of disassembly for product maintenance and/or end-of-life treatments [27]. Jovane et al. [28] proposed the generally accepted the design rules in design for disassembly. Leagrth [29] modeled the disassembly time (disassembly depth) against cost. Lee et al. [30] proposed a guideline in considering the end-of-life disassembly of a product.

Based on the Mok et al. [31], disassemblability is defined as the degree of easiness of disassembly. Desai and Mital [25] stated that the use of force, mechanism of disassembly, use of tools, repetition of parts, recognizability of disassembly points, product structure, and use of toxic materials affect the disassemblability.

Various methodologies have been developed to evaluate the disassemblability of a product. The methodologies vary from the methodologies that use the spread sheet-like chart, energy use, entropy for disassembly, time, to the end-of-life value of a product. There are also several computerized tools that have developed been to help designers in measuring the disassemblability of the product at the design stage. The methodologies can not only be applied for mechanical products such as automotive components but also for electrical products.

4.1 Spread Sheet-Like Chart

Early disassemblability methodologies used the spread sheet-like chart to measure the disassemblability [24, 32]. McGlothin and Kroll [32] designed the spread sheet-like chart to measure the ease of disassembly of a product.

The authors categorized the disassembly difficulties into 5 subjective categories, accessibility: a measure of the ease with which a part can be accessed, positioning: a measure of how precisely the tool or hand needs to be positioned and oriented in order to perform the task, force: a measure of the amount of force required performing the task, additional time: while each of the previous difficulty sources is related to time, this category has to do with additional time penalties, special: this is a provision to note special problems encountered that do not fit in any of the other categories.

| DISASSEMBLY EVALUATION CHART | | | | | | | | | | | | | |
|------------------------------|----------|--------------------|-----------|-------------------------|---------------|---------------|-------------|-------|-----------|-----------------|----------|-------|----------|
| PRODUCT : Hand Drill | | | | | | | | | | DATE : 7/5/1995 | | | |
| PREPARED BY : | | | | | | | | | | SHEET : 1 of 1 | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Part No. | Quantity | Min. N.o. of Parts | Task Type | No. of Task Repetitions | Required Tool | Accessibility | Positioning | Force | Base Time | Special | Subtotal | Total | Comments |
| 1 | 0 | 0 | Un | 0 | PS | 1 | 2 | 1 | 3 | 1 | 0 | 0 | |
| 2 | 2 | 0 | Un | 2 | PS | 2 | 2 | 1 | 3 | 1 | 9 | 18 | |
| 3 | 1 | 1 | We | 3 | PB | 2 | 1 | 1 | 2 | 1 | 7 | 21 | |
| | | | FI | 1 | | 1 | 1 | 1 | 2 | 1 | 0 | 0 | |
| | | | CI | 1 | RG | 2 | 1 | 1 | 2 | 1 | 7 | 7 | |
| 4(sub) | 0 | 0 | We | 2 | PB | 1 | 1 | 1 | 2 | 1 | 0 | 12 | |
| | | | Re | 1 | | 2 | 1 | 1 | 1 | 1 | 0 | 0 | |
| 5 | 2 | 2 | Re | 2 | | 1 | 1 | 1 | 1 | 1 | 0 | 10 | |
| 6 | 1 | 1 | Ho | 1 | | 1 | 1 | 1 | 2 | 1 | 0 | 0 | |

Figure 1: Disassembly evaluation chart [32]

$$Overall\ efficiency = \frac{5 \times \sum col . 2}{\sum col .13} \tag{1}$$

$$Disassembl\ y\ time\ (sec) = (\sum col .13 - 5 \times \sum col .5) \times 1.04 + (Numb .of\ tool\ and\ hand\ manipulat\ ion) \times 0.9 \tag{2}$$

The authors use the scoring system (1: easy to 4: difficult) to measure the above categories. By using the chart, shown in Figure 1, the disassembly overall efficiency can be calculated by using the equation (1).

Kroll and Hanft [24] extended the Mcglothin and Kroll work. They derived the disassembly scores from the work-measurement analyses of standard disassembly tasks. The scores used in this method are 1 to 10. The authors analyzed the disassembly task by using the Maynard Operation Sequence Technique (MOST) time measurement system and comparing their estimated performance times. The authors also introduced the standard disassembly tasks and the standard disassembly tools with their letter code. By using the chart disassembly time is calculated, equation (2). Kroll and Hanft [24] did not use the term of design efficiency but the effectiveness of the design because in the engineering context efficiency means as the comparison between output and input.

Kroll and Carver [7] presented a method for estimating disassembly time to allow the designer to identify weakness in the design and improve it accordingly. Kroll and Carver stated that the disassembly efficiency or effectiveness is an unrealistic metric because it was derived from the assembly efficiency and there are the fundamentals different between assembly and disassembly operations.

Desai and Mital [33] presented a methodology in spread sheet-like chart to design products for disassembly. This would facilitate end-of-life product disassembly with a view to maximizing material usage in the supply chain at a low

cost to the environment. The numeric evaluation is made based on Methods Time Measurement (MTM) system. The authors also considered the posture allowance for the need of specialized postural requirements and designed a table which is fully equipped with scores for unnatural postural requirements.

4.2 Energy and Entropy for Disassembly

Suga et al. [34] presented the quantitative method to evaluate the disassembly evaluation by introducing two parameters, energy for disassembly and entropy for disassembly. Energy for disassembly is energy required to disconnect of an interconnection. Entropy for disassembly is used to calculate the degree of disassembly difficulty. It measures the randomness of the total number of connection in subassembly, type of interconnection methods, and the interconnection made by each method for the direction +x, -x, +y, -y, +z or -z. The equations (3) and (4) are used to calculate the energy for disassembly of a screw and equation (5) is used for snap-fit.

$$E_n = T_f 0.8 \theta \tag{3}$$

$$T_f = 0.2 F_f d \tag{4}$$

$$E_s = \frac{1}{8} E w t^3 \frac{h_2^3}{h_1^3} \tag{5}$$

where

- F_f = clamping force
- D = diameter of screw
- θ = rotational angle producing the axial tension
- E_s = modulus elasticity of the material

T_f , θ , F_f , d , h_1 , h_2 , w and t are defined in Figure 2 and 3.

To calculate the disassembly entropy, the following equation is used.

$$S_i = \sum_k \left[\ln \left(\frac{N_{ik}!}{\prod_j n_{ij}!} \right) + \sum_i \ln \left(\frac{n_i!}{\prod_j n_{ij}!} \right) \right] \tag{6}$$

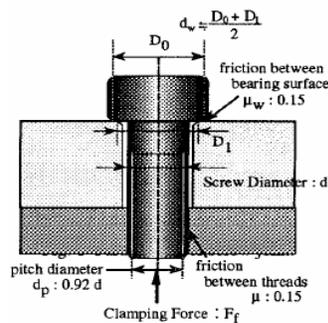


Figure 2: Parameter of a screw joint [34]

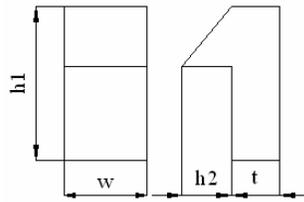


Figure 3: Parameter of a simple model of snap-fit [34]

Where N_{ik} is the total number of interconnections belongs to assembly k , n_i is the number of interconnections made by method i (for instance, $i = 1$ is the screw, and $i = 2$ is snap fit). n_{ij} is the number of interconnection for the direction j (+x, -x, +y, -y, +z and -z). In analyzing the correlation between energy for disassembly and time for disassembly the authors used the linear regression method. To analyze the relationship among entropy for disassembly, connection types, and disassembly paths, the authors used a bar chart.

4.3 Time for Disassembly

Mok et al. [31] published a paper that defined the parameters of disassemblability and propose design rules for easy disassembly. The authors divided the disassembly process into 3 categories: pre-process, in process and after process. For each process the authors defined the determining factors for disassembly. For each factor, the authors defined the influence parameters, such as material, weight, shape, work fixture, product structure, contact condition, disassembly direction, surface roughness and gripping point.

Gungor and Gupta [35] proposed the evaluation method for different disassembly strategies, so that the best one could be chosen. The authors use Total Time for Disassembly (TTD) as the parameter to measure a given disassembly sequence of a product, shown in equation (7) and (8). But, the information about the disassembly sequence, disassembly time for each component, disassembly direction and joint types have to be known earlier.

$$TTD = \sum_{i=1}^n (T_{x_{i-1}, x_i}) \quad (7)$$

$$T_{x_{i-1}, x_i} = t_{x_i} (1 + \alpha + \beta) \quad (8)$$

$$i=1, \dots, n \quad T_{x_{i-1}, x_i} = t_{x_i} (1 + \alpha + \beta) \quad i=1, \dots, n$$

T_{x_{i-1}, x_i} = adjusted time for disassembly of X_i being disassembled after X_{i-1} ,

when $i = 1$ then $T_{x_{i-1}, x_i} = t_{x_i}$

α = Direction factors

α = 0.1 – 1.0 if the direction changes from X_i to X_{i-1}

α = 0, other wise

$$\beta = 0.1 - 1.0 \text{ if the joint type of } X_i \text{ is different with the joint type of } X_{i-1}$$

$$\beta = 0, \text{ other wise}$$

Yi et al. [36] proposed the method for evaluating the disassembly time. The aim of the study is to obtain approximate disassembly time for the product to be disassembled by using the formula derived from the information on the product's connecting parts and working environment without disassembling the product directly. The authors divide the disassembly time into 4 base times, preparation time (Tp), moving time (Tm), disassembly time (Td), and post processing time (Tpr). Each base time has the influenced factors time. As an example, the disassembly time is affected by time for aligning between tool and joint element (Tdb), time for tool operation area (Tda), time for basic separation of joint element (Tdb) and time for intensity of work (Iw).

4.4 End-of-Life Value

Lee et al. [30] proposed a guideline for determining feasible end-of-life options for manufactured products, set against the conflicting objectives of minimizing environmental impact and minimizing deficit and how to determine the end-of-life value of a product. The guidelines and equation to calculate the end-of-life value are as followed.

1. If component is made of metal without any other alloy, primary recycling is recommended. If alloys are present, they alter the mechanical properties of the parent metal, so secondary recycling or landfill is more appropriate.
2. If component is polymeric, primary recycling is recommended; otherwise, consider secondary recycling or incineration to recover its energy content.
3. If component is made of ceramic, secondary recycling or landfill is recommended.
4. If component is made of an elastomer or is a composite material, secondary recycling or incineration is recommended, otherwise landfill.
5. If component contains toxic or hazardous material, special handling is required. To calculate the end-of-life value equations (9) until (17) were proposed by the authors.

$$\text{Reuse value} = \text{Cost of component (\$)} - \text{Miscellaneous cost (\$)} \quad (9)$$

$$\begin{aligned} \text{Remanufacture value} &= \text{Cost of component (\$)} - \text{Remanufacture cost (\$)} \\ &- \text{Miscellaneous cost (\$)} \end{aligned} \quad (10)$$

$$\begin{aligned} \text{Primary recycle value} &= \text{Weight of component (kg)} \times \\ &\text{Market value of material (\$/kg)} - \text{Miscellaneous cost (\$)} \end{aligned} \quad (11)$$

$$\begin{aligned} \text{Secondary recycle value} &= \text{Weight of component (kg)} \times \\ &\text{Scrap value of material (\$/kg)} - \text{Miscellaneous cost (\$)} \end{aligned} \quad (12)$$

$$\begin{aligned} \text{Incinerate value} &= \text{Energy produced (Watt)} \times \\ &\text{Unit cost of energy (\$/Watt)} - \text{Miscellaneous cost (\$)} \end{aligned} \quad (13)$$

$$\begin{aligned} \text{Landfill cost} &= -(\text{Weight of component (kg)} \times \text{Cost of landfill (\$/kg)}) \\ &- \text{Miscellaneous cost (\$)} \end{aligned} \quad (14)$$

$$\begin{aligned} \text{Special handling cost} &= -(\text{Weight of component (kg)} \times \text{Cost of special} \\ &\text{handling (\$/kg)}) - \text{Miscellaneous cost (\$)} \end{aligned} \quad (15)$$

$$\text{Miscellaneous cost} = \text{Collection cost (\$)} + \text{Processing cost (\$)} \quad (16)$$

$$\text{Collection cost} = \text{Handling} + \text{transportation} + \text{storage} \quad (17)$$

For product redesign Lee et al. [30] proposed the following guideline.

1. Positioning the component which generate the greatest surplus at the top of the product structure, so as to realize this surplus as soon as possible
2. Positioning the component which generate the greatest deficit at the bottom of the product structure, so they can be disposed into landfill without the need for disassembly
3. Reducing the disassembly time by simplifying the joining technique.
4. Avoid the using of toxic materials, as they have to be disassembled for special handling.

Gupta and Isaac [37] also proposed a value analysis tool of disposal strategies for automobile but it used a goal programming to identify the trade off between technological, economic feasibility and degree of environment detriment. Coates and Rahimifard [38] presented the holistic end-of-life cost model for vehicle recovery sector and focus on the potential applications of this model to support both high and low level decisions, in terms of a process economic merits and it's influenced on the end-of-life vehicle direction recycling recovery targets. Authors used the activity based costing (ABC) method to attribute the indirect cost to the end-of-life vehicle's processing cost, used the data from 300 ATFs (Authorized Treatment Facilities) in UK to determine the standard subassembly removal times, and used the an end-of-life vehicle costing database. The information in the database is capital equipment costs, material price, material prototype data, machine efficiency value, vehicle information, and rate (labor and fuel). Mat Saman [39] proposed a framework for end-of-life vehicle value analysis for automotive design assessment to fulfill the requirements of the end-of-life vehicle directive.

4.5 Computerized Disassembly Evaluation Tools

Srinivasan et al. [40] developed the disassembly tool that consists of a geometric software program that gives recommendations to product design based on disassembly analysis. Hesselbach and Kln [19] presented the disassembly evaluation of electronic and electrical products. The evaluation tool was translated

to the computer software that was developed by Institute of Production Automation and Handling Technology, Germany. Feldman et al. [41] presented a computer based methodology for a product structure analysis regarding the determination of economically optimal end-of-life strategies for technical goods. Herrmann et al. [42] proposed a planning approach to support the planning process of efficient disassembly systems.

5.0 AUTOMOTIVE MANUFACTURER REQUIREMENTS

In general, the designers do not have the experience in disassembly and recycling to determine the impact of various design aspects on the disassemblability at the disassembly stage. It is therefore important that support system for disassemblability is available that encourages designers to incorporate disassemblability issue in order to fulfill the legislation that will fully be implemented in 2015. The system should provide feedback regarding possible improvement to the designer.

The system should provide assistance in making decisions at the early stage of the vehicle design and development process in order to avoid the cost and time consumed through later design. There needs to be fast and correct decision making in order to remain competitive in the world market.

6.0 CONCLUSION

Based on the study on the several papers published in the field of end-of-life vehicle, integrating the constraints from end-of-life strategies into the early design is one of the important aspects that need to be considered. Current situation shows that there is a need for a system in determining the impact of various design aspects on the disassemblability at the disassembly stage in order to fulfill the legislation that will fully be implemented in 2015. Several researchers have proposed the evaluation methodology of disassemblability. The metrics used in the proposed methodology can be generally divided into two categories, absolute metric such as time and cost, energy for disassembly and entropy for disassembly, and relative metrics such as design effectiveness. Based on the Kroll and Craver [7] the absolute metric only can be used in relative manner, if it is used for evaluating single design, the result may be not tell how good the design is but the relative metrics are normalized respect to the ideal situation. The main research challenge in developing the relative disassemblability metrics is defining the reference designs, or in other words, deciding what should be considered a 100% effective design.

7.0 AGENDA FOR FUTURE RESEARCH

It is generally accepted that the main fundamental use of the tool and metrics of disassemblability is to tell how much feedback regarding possible improvement should the metrics provide to the designer. Clearly, single metric does not tell much about the design weakness. Only combining the individual metrics into a single number allows monitoring the overall improvement [7]. So, the further

system that going to developed should combine the single metrics in order to give feedback for possible improvements.

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REFERENCES

1. Kanari, N., Pineau, J.L. and Shallari, S., 2002. *End-of-life vehicle recycling in the European Union*, [Website] URL: <http://www.tms.org/>.
2. Toyota Motor Company, 2005. *Responses to automobile recycling laws in Japan*, [Website] URL: <http://www.toyota.co.jp/>.
3. European Commission, 2000. *Directive 2000/53/EC of the European Parliament and of the Council on End-of-Life Vehicles*, EU.
4. PricewaterhouseCoopers LLP., 2002. *The European Union end-of-life vehicle directive is a sensitive issue for the global automotive industry*, [Website] URL: PricewaterhouseCoopers LLP. <http://www.pwc.com/>.
5. Mat Saman, M.Z., Zakuan, N., 2006. *End-of-life vehicle directive: a key element to the vehicle design process*. Proceedings of the Regional Conference on Vehicle Engineering and Technology (RIVET 2006), Malaysia.
6. Kuo, Tsai C., 2000. Disassembly sequence and cost analysis for electromechanical products, *Robotics and Computer-Integrated Manufacturing*, Vol. 16, 43-54.
7. Kroll, E., Carver, B.S., 1999. Disassembly analysis through time estimation and other metrics, *Robotics and Computer-Integrated Manufacturing*, Vol. 15, 191-200.
8. Staudinger, J. and Keoleian, A., 2001. *Management of end-of-life vehicles (ELVs) in the US*. Centre for Sustainable Systems – University of Michigan, Report No. CSS01-01, March 2001.
9. The United State Environmental Protection Agency (EPA), 2007. [Website] URL: <http://www.epa.gov/>.
10. Australian Department of the Environment and Heritage, 2002. *Environmental impact of end-of-life vehicles: an information paper*.
11. Gilmore Hankey Limited Company, 2006. *A Study to examine the benefits of the end-of-life vehicles directive and the costs and benefits of a revision of the 2015 targets for recycling, re-use and recovery under the ELV directive*, [Website] URL: www.ghkint.com.
12. BMW Group, 2002. Manual for recycling-optimized product development.
13. Alting, L., Legarth, B.L., 1995. Life cycle engineering and design, *Annals of the CIRP*, Vol. 44, 569-580.
14. Wenzel, H., Hauschild, M., Jørgensen, J., Alting, L., 1994. Environmental tools in product development, *Proceedings of the 1994 IEEE International Symposium on Electronics & the Environment*, San Francisco. 100-108.

15. Legarth, J.B., Alting, L., Erichsen, H., Gregersen, J., Jørgensen, J., 1994. Development of environmental guidelines for electronic appliances, *IEEE International Symposium on Electronics & the Environment*, 69-74.
16. Pre-Consultant, 2000. *Eco-indicator 99: Manual for designers*. [Website] URL : <http://www.pre.nl/>.
17. Persson, J.G., 2001. Eco-indicators in product development, *Proceeding of the Institution of Mechanical Engineers*. Vol. 215, 627-636.
18. Pre-Consultant, 2008. *Simapro 7.1 LCA software*, [Website] URL: <http://www.pre.nl/>.
19. Hesselbach, J., Kuln, M., 1998. Disassembly evaluation of electronic & electrical products, *Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment*, ISEE, 79-81.
20. Lenau, T., Bey, N., 2001. Design of environmentally friendly products using indicators, *Journal of Engineering Manufacture*, Vol. 215, 637-646.
21. Huisman, J., Boks, C., Stevels, Ab., 2000. Environmentally weighted recycling quotes - better justifiable and environmentally more correct, *IEEE Conference on Electronics and Environment*, San Fransisco, California.
22. Volvo Group, 1998. Volvo Environmental Report.
23. Graedel, T.E., 1998. *Streamlined Life-Cycle Assessment*, Prentice-Hall, Inc. Englewood Cliffs, New Jersey.
24. Kroll, E., Hanft, T.A., 1998. Quantitative evaluation of product disassembly for recycling, *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, Vol. 10, 1-14.
25. Desai, A., Mital, A., 2003. Evaluation of disassemblability to enable design for disassembly in mass production, *International Journal of Industrial Ergonomics*, Vol. 32, 265-281.
26. Luttrupp, C., 1998. Design for disassembly: a new element in product development, *The Journal of Sustainable Product Design*, Vol. 6, 30-40.
27. Takeuchi, S., Saitou, K., 2005. Design for product embedded disassembly sequence, *Proceedings of the 2005 IEEE International Symposium on Assembly and Task Planning*, 41-46.
28. Jovane, F., Alting, L., Armillotta, A., Eversheim, W., Feldmann, K., Seliger, G., Roth, N., 1993. A key issue in product life cycle: disassembly, *Annals of the CIRP*, Vol. 42, No. 2, 651-658.
29. Legarth, J.B., 1993. *New strategies in the disposal of complex products*, Paper presented at the biannual EDIP Meetings, Denmark.
30. Lee, S.G., Lye, S.W., Khoo, M.K., 2001. A multi-objective methodology for evaluating product end-of-life options and disassembly, *International Journal of Advanced Manufacturing Technology*, Vol. 18, 148-156.
31. Mok, H.S., Kim, H.J., Moon, K.S., 1997. Disassemblability of mechanical parts in automobile for recycling, *Computers & Industrial Engineering*, Vol. 33, No. 3-4, 621-624.
32. McGlothlin, S., Kroll, E., 1995. Systematic estimation of disassembly difficulties: application to computer monitors, *IEEE International Symposium on Electronics & the Environment*, 83-88.

33. Desai, A., Mital, A., 2005. Incorporating Work Factors in Design for Disassembly in Product Design, *Journal of Manufacturing Technology Management*, Vol. 16, 712-732.
34. Suga, T., Saneshige, K., Fujimoto, J., 1996. Quantitative disassembly evaluation, *Proceedings of the 1996 IEEE International Symposium on Electronics & the Environment*, 19-24.
35. Gungor, A., Gupta, S M., 1997. Evaluation methodology for disassembly processes, *Computers & Industrial Engineering*, Vol. 33, No. 1-2, 329-332.
36. Yi, H-C., Park, Y-C., Lee, K-S., 2003. A study on the method of disassembly time evaluation of a product using work factor method, *Proceedings of the 2003 IEEE International Conference on Systems, Man and Cybernetics*, 1753-1759.
37. Gupta, S.M., Isaacs, J, A., 1997. Value analysis of disposal strategies for automobiles, *Computers & Industrial Engineering*, Vol. 33, No. 1-2, 325-328.
38. Coates, G., Rahimifard, S., 2006. *Cost models for increased value recovery from end-of-life vehicle.*
39. Mat Saman, M.Z., 2005. *Methodology of design for end-of-life value in automotive engineering*, Phd Thesis, Coventry University.
40. Srinivasan, H., Shyamsundar, N., Gadh, R., 1997. Virtual disassembly tool to support environmentally conscious product design, *Proceedings of the 1997 5th IEEE International Symposium on Electronics and the Environment*, ISEE, 7-12.
41. Feldmann, K., Trautner, S., Lohrman, H., Melzer, K., 2001. Computer-based product structure analysis for technical goods regarding optimal end-of-life strategies, *Journal of Engineering Manufacture*, Vol. 215, 683-693.
42. Herrmann, C., Luger, T., Ohlendorf, M., 2005. SiDDatAS - Analysis and economic evaluation of alternative disassembly system configurations, *4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Eco Design*, 210-215.