AUTOMOTIVE EVALUATION COMPLEMENTARY TOOL FOR RECOVERABILITY AND REUSABILITY

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ABSTRACT

Keywords: Recoverability; Reusability; Complementary; Evaluation; Fuzzy

The automotive industry manufactured products is increasing due to the incremental size of the global population. This will definitely lead to an increasing amount of automotive waste during the end of life of vehicles. The solution lies at the designing stage where the materials are chosen and multiple designs are drawn on the drawing board before mass production of vehicles. A complementary evaluation tool is needed at the designing stage for engineers and designers to determine the recovery and reusability value of the designs made by engineers and designers of respective automotive companies. It is crucial to calculate the possibility of having to recover, recycle and reuse components and parts of vehicles to reduce the waste generated at the end of life. A fuzzy based approach is proposed to evaluate the recovery and reusability value. The factors used in the evaluation of end of life vehicle include presence of hazardous substances, accessibility index, difficulties of cleaning automotive components, type of fasteners index, material compatibility and type of tools needed for disassembly. Three case studies are conducted to verify and to prove the usefulness of the evaluation complementary tool showing the different values of recover and reusability based on the factors that affect the value of the vehicle at the end of life thus affecting the amount of waste produced. The proposed complementary tool has the potential to allow automotive companies to determine the recovery and reusability value of their designs at the onset of development to comply with certain standards.

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LIST OF SYMBOLS AND ABBREVIATIONS

For examples:

ELV	:	End of Life Vehicle
EOL	:	End of Life
EU	:	European Union
GUI	:	Graphical User Interface
ISO	:	International Standard Organization
PID	:	Proportional Integrative Derivative

CHAPTER 1: INTRODUCTION

1.1 Overview

End-of-Life-Vehicles has been producing 7-8 mil waste in EU (Kanari, Pineau, & Shallari, 2003). The amount of end of life vehicle is increasing due to manufacturing of newer cars on the road. There is a need to integrate this waste into a correct waste management system so that the waste could be transformed into useful secondary raw materials (Eurostat, 2014) since end-of-life vehicles are still valuable in resources if taken care properly. The decision made by the designer in the automotive designers plays a huge role in implementing sustainable materials and efficient recovery of a new vehicle at the end of life. End-of-life of products are often neglected during the design process. This will lead to a difficult time for disassembly which would most likely reduces the profitability (Jeandin & Mascle, 2016).

A research was done by the Organization for Economic Cooperation and Development (OECD). The statistics collected by the organization has shown that the total no of vehicles in OECD countries were expected to grow by 32% from 1997 to 2020 (United Nations, 2007). The value shown in figure 1.1.1 is worrying since the number of vehicles manufactured for the last 20 years has increased from 38 million close to 60 million. There is a need of a complementary support tool to be implemented in the automotive sector for designers to evaluate their design so as to ease the recycling and remanufacturing industries of end-of-life vehicles.

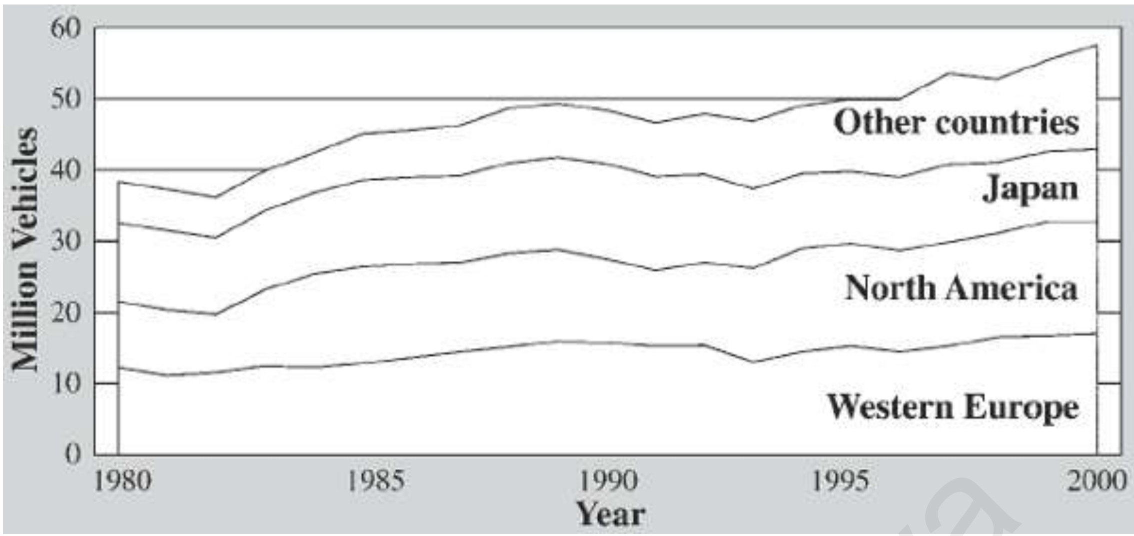


Figure 1:1: Figure above shows the number of vehicles manufactured for the last 20 years (United Nations, 2007).

ELV policy has never taken place in the Malaysia's automotive ecosystem so it is deemed as incomplete or unhealthy. A proper End of Live Vehicles plan can contribute to sustainable environmental control (Jawi, Isa, Solah, & Ariffin, 2017). The amount of vehicles produced and registered has been no doubt increasing. The data collected in table 1 by Malaysian Automotive Institute (Malaysian Automotive Institution, 2017) shows a worrying figure for the amount of registered vehicles on Malaysian roads. This paper applies to other similar developing countries as well.

Table 1:1: Table below shows the summary of new passenger and commercial vehicles registered in Malaysia (Malaysian Automotive Institution, 2017).

Year	Passenger Cars	Commercial Vehicles	4 x 4 Vehicles	Total Vehicles
1980	80,420	16,842	-	97,262
1985	63,857	26,742	4,400	94,999
1990	106,454	51,420	7,987	165,861
1995	224,991	47,235	13,566	285,792
2000	282,103	33,732	27,338	343,173
2005	416,692	97,820	37,804	552,316
2006	366,738	90,471	33,559	490,768
2007	442,885	44,291	-	487,176
2008	497,459	50,656	-	548,115
2009	486,342	50,563	-	536,905
2010	543,594	61,562	-	605,156
2011	535,113	65,010	-	600,123
2012	552,189	75,564	-	627,753
2013	576,657	79,136	-	655,793
2014	588,341	78,124	-	666,465
2015	591,298	75,376	-	666,674
2016	514,545	65,579	-	580,124
March 2017	127,530	13,309	-	140,839

1.1.1 Problem Statement

There is an increasing amount of automotive waste during the end of life of vehicles based on statistics globally and locally shown by United Nations and Malaysian Automotive Association. The solution lies at the designing stage where the materials are chosen and multiple designs are drawn on the drawing board before mass production of vehicles. There is a need for a complementary evaluation tool at the designing stage to assist engineers and designers to determine the recovery and reusability value of the components/part for respective automotive companies. This is to reduce the expected amount of waste produced by vehicles at the end of life. The untreated waste from end of life vehicles could cause detrimental effects to the environment. There is potential to salvaging secondary resources and remanufacture different parts and components of end of life vehicles. The potential to salvage these parts and components are based on the materials used and other factors involved.

1.1.2 Objective of Study

The main objective is to develop an automotive evaluation complementary tool for recoverability and reusability based on fuzzy logic inference system.

The specific objectives are as follows:

1. To investigate the different factors involved in recoverability and reusability of the different components involved at the end of life of vehicles.
2. To develop a complementary evaluation tool based on Fuzzy Logic Inference System to determine the recoverability and reusability value of end of life vehicle components.
3. To evaluate case studies using the complementary evaluation tool to check the effectiveness and feasibility of the tool.

1.1.3 Scope and Limitation of Study

The scope of this study is to find the factors involved in the recoverability and reusability of vehicle components and parts. The scope is further extended where the GUI complementary evaluation tool is made and applied into the field to check its effectiveness on evaluating the recoverability and reusability of end of life vehicles. A vehicle car door is used due to the limitation of resources and time.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents related survey pertaining to recoverability and reusability of end of life vehicles specifically theoretical recovery hierarchy, different evaluation methods and factors determining the recoverability and reusability of end of life vehicles are presented.

2.1.1 Theoretical Recovery Hierarchy

The recovery of a product is based on the ability of a product, its components and all the other parts in the product to be either reused, recycled or recovered as energy (Mathieux, Froelich, & Moszkowicz, 2008). There are a lot of factors that affect the end of life vehicle recovery. (Mat Saman & Blount, 2008) stated that there are four main End-of-Life requirements that automotive designers have to consider which are design consideration, materials used, economic aspect and directive requirements.

(Gerrard & Kandlikar, 2007) came up with a theoretical recovery hierarchy with the inclusion of the waste hierarchy pyramid. This involves Re-use, Remanufacturing, Recycling, Energy Recovery and Landfill stages. Each stages have different hierarchy comparatively to each other as shown in the figure below.

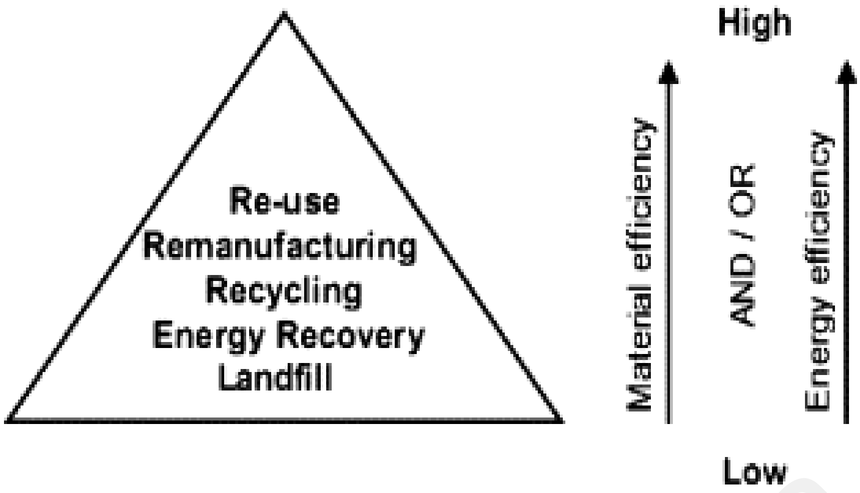


Figure 2:1: Figure above shows the theoretical waste hierarchy pyramid that has different stages of recovery with the top being most desired to the bottom being the least desired (Gerrard & Kandlikar, 2007).

The theoretical recovery hierarchy from (Gerrard & Kandlikar, 2007) also shows the material and energy efficiency in the pyramid. It shows the reuse stage having the highest efficiency for materials and energy whereas the landfill has the lowest among all the stages. The Principles of Environmental Assurance at Canon also stated that the impact of waste products on the environment is clearly less if a part is reused in its original form rather than converting into raw materials. If the product is unable to be reuse, there might be a need of additional work on the product.

The next stage in the hierarchy is the remanufacturing or reconditioning stage. This involves the processing or upgrading of the product in an industrial manner (Östlin, Sundin, & Björkman, 2009).The remanufacturing stage aims to extend the life of products or making it into a second life product instead of being obsolete (Zwolinski, Lopez-Ontiveros, & Brissaud, 2006). The remanufacturing of either products or parts have the most significant impact on resource conservation and economic. This includes primarily on aftermarket supply (Subramoniam, Huisingh, & Chinnam, 2009). Recycling stage is where the material is processed out of one form to be made into a new product ((Fred)

Lambert & Gupta, 2004). Recovery stage is the use of waste for useful purposes such as energy recovery, road surfacing and many more. The last consideration is a waste material that is sent for disposal in landfill.

2.1.2 Design Considerations: Design for Disassembly

A design approach that incorporates disassembly considerations into the product during the research and development phase is known as design for disassembly. Disassembly is an important activity since this activity greatly affects the salvaging of components.

Design for Disassembly prioritizes minimizing the complexity of the product structure, improving the reusability of the product. This involves the systematic removal of the desired parts from an assembly with condition that the disassembly process does not damage the desired parts ((Fred) Lambert & Gupta, 2004). Design for Disassembly involves many factors and design concepts to produce a product to be easily disassemble (Boothroyd & Alting, 1992)for remanufacturing or recycling purposes, recycling of materials, components and sub-assemblies (Bogue, 2007). Design for Disassembly has to be considered in product recovery as many factors affect the cost and difficulties in disassembly of a product such as a vehicle during end-of-life. There are two types of disassembly according to (Güngör, 2006)which are destructive and non-destructive. The purpose of non-destructive disassembly is to retrieved components undamaged to be remanufactured. Destructive disassembly is used for the purpose of when non-destructive disassembly is too costly.

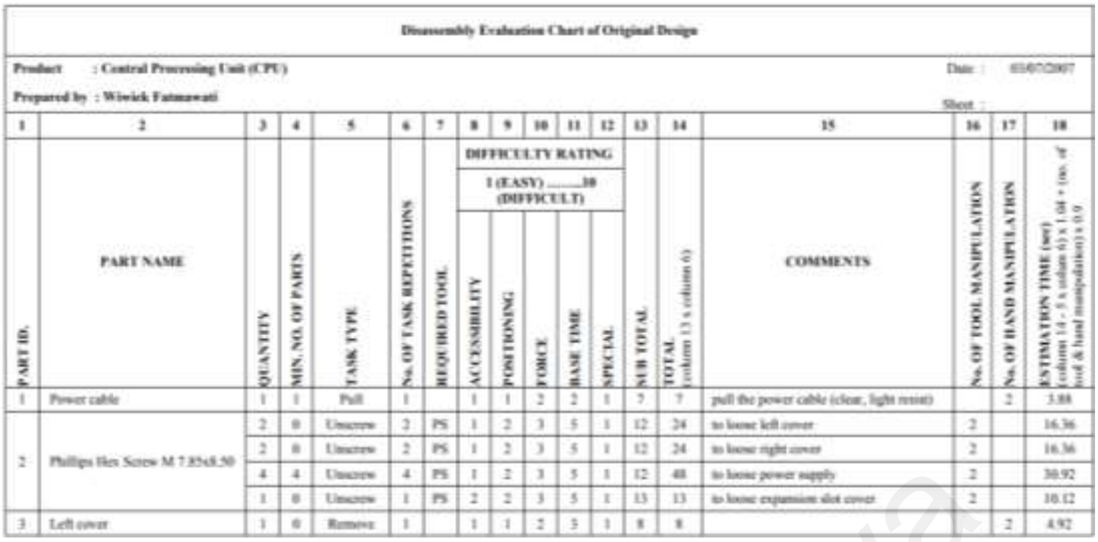
2.2 Different Evaluation Methods

2.2.1 Disassemblability Evaluation Chart Method (DECM)

Disassemblability Evaluation chart Method (DECM) by (Fatmawati, 2007) is an upgraded version of Disassemblability Evaluation Method by (Kroll & Hanft, 1998) and Spread Sheet-like chart(Go, Wahab, Rahman, Ramli, & Azhari, 2011).

The Disassemblability Evaluation Method is a qualitative evaluation on difficulty of disassembly operation and quantitative evaluation on disassembly time. It was developed in 1993 by Hitachi Limited as a quantitative measurement on the level of difficulty where the product could be disassembled (Go et al., 2011). It serves as an effective tool to determine disassembly difficulty without using the prototype or experimentation of the product. The method is done using quantitative evaluation of the level of difficulty during disassembly of the product.

The method was further enhanced by (Fatmawati, 2007) with the use of spreadsheet like chart which then became Disassemblability Evaluation Chart Method (DECM). This is one of the various method in design for disassembly that is able to be used alongside with the spreadsheet-like-chart to evaluate the disassembly difficulty. This is done for each task of the disassembly operation with the equations derived from the Maynard Operation Sequence Technique (MOST) system. The evaluation results are as such: disassembly cost estimation, disassembly time and disassembly efficiency. These results are calculated and evaluated to identify which areas can be improved. A product case study was done on a Central Processing Unit (CPU) by (Fatmawati, 2007)



Disassembly Evaluation Chart of Original Design

Product : Central Processing Unit (CPU) Date : [illegible]

Prepared by : Wiwiek Fatmawati Sheet :

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
							DIFFICULTY RATING 1 (EASY) ....10 (DIFFICULT)										
PART ID.	PART NAME	QUANTITY	MIN. NO. OF PARTS	TASK TYPE	No. OF TASK REPETITIONS	REQUIRED TOOL	ACCESSIBILITY	POSITIONING	FORCE	BASE TIME	SPECIAL	SUB TOTAL	TOTAL (column 13 x column 6)	COMMENTS	No. OF TOOL MANIPULATION	No. OF HAND MANIPULATION	ESTIMATION TIME (sec)
1	Power cable	1	1	Pull	1		1	1	2	2	1	7	7	pull the power cable (clear, light resist)		2	3.88
2	Phillips Hex Screw M 7.85x8.50	2	0	Unscrew	2	PS	1	2	3	5	1	12	24	to loose left cover	2		16.36
		2	0	Unscrew	2	PS	1	2	3	5	1	12	24	to loose right cover	2		16.36
		4	4	Unscrew	4	PS	1	2	3	5	1	12	48	to loose power supply	2		30.92
		1	0	Unscrew	1	PS	2	2	3	5	1	13	13	to loose expansion slot cover	2		10.12
3	Left cover	1	0	Remove	1		1	1	2	3	1	8	8			2	4.92

Figure 2:2: Disassemblability Evaluation Chart Method by(Fatmawati, 2007)

Table 2:1: Table below shows the advantages and limitations of Disassemblability Evaluation Chart Method based on literatures (Go et al., 2011)

Advantages	Limitations
"weakness" in the design at the earliest possible stage is identified using disassembly evaluation score and disassembly cost index.	The evaluation is based on technicians' expertise in disassembling vehicles. Results may vary when used by new technicians or personnel on the job
Design improvements is achieved by reviewing and interpreting evaluation results for further disassemblability evaluation to determine the effect of the improvement on disassembly time.	The method used is time consuming when there are more parts and components involved in the system
It is more recent compared to Disassembly Evaluation Method and Spread Sheet-like chart	

2.2.2 Disassembly Time

There are a few methods proposed by the academic community using time as a factor for disassembly. This include Total Time for Disassembly (TTD)by (Gungor & Gupta, 1997), disassembly time evaluation using Work Factor by (Hwa-Cho Yi, Young-Chan Park, & Kun-Sang Lee, 2003) and Total Time for Disassembly sequence by (Kongar & Gupta, 2006).

The method proposed by (Gungor & Gupta, 1997) is based on disassembly evaluation that uses Total Time for Disassembly (TTD). This serves as a parameter to provide a measure of the efficiency of a given disassembly sequence of a product. The parameters taken into account are disassembly sequence of the product, disassembly time of each component of the product disassembly directions and joint types of the components of the product.

Another method proposed by (Hwa-Cho Yi et al., 2003) is based on using the work factor method. The main purpose of this particular method is to obtain the approximated disassembly time for the product to be disassembled using a particular formula derived from the information of the connecting parts and working environment of the particular product without disassembling the product directly. Investigations are done by (Hwa-Cho Yi et al., 2003) to determine various factors that impacted the disassembly time. The factors found were time required for preparing tool, time required for moving between join elements, time required for disassembling joint elements with the use of a tool and post processing time required for moving disassembled parts to proper locations. The results of this particular analysis obtained by (Hwa-Cho Yi et al., 2003) considers on moving body part, moving distance, weight and artificial regulation factors.

(Kongar & Gupta, 2006) presented a method known as genetic algorithm for disassembly sequencing of End-Of-Life (EOL) products using a fitness function. This function is dependent on the increment in disassembly time. The three factors involved in the adding up of the disassembly time of a component are basic disassembly time for component in sequence, penalty for each direction change for component in sequence and the penalty for change in disassembly method.

Table 2:2: Table below show the advantages and limitations of Disassembly Time based on literatures (Gungor & Gupta, 1997), (Hwa-Cho Yi et al., 2003), (Kongar & Gupta, 2006)&(Kannan, Sasikumar, & Devika, 2010).

Advantages	Limitations
Various parameters are considered resulting in a more detailed analyzation to determine the optimum sequence for disassembly.	Multiple equations needed to be developed to determine optimum sequence for disassembly of the products when more components and parts involved.
Instant and reliable input to the disassembly scheduling environments which involves mathematics equations which are simple to understand and apply.	Different components will have different information to be considered, often resulting in lots of information to be considered for one particular component. More component = time needed

2.2.3 End-of-Life Value

End-of-Life Value method uses goal programming in order to identify certain trade-off between technological, economic feasibility and the degree of environmental damage. This value analysis tool made by (Gupta & Isaacs, 1997) is an evaluation methodology also known as physical programming enables automotive designer or engineer to measure disassembly and recycling prospects. (Lee, Lye, & Khoo, 2001) managed to enhanced this method by having these few objectives.

Table 2:3: Table below shows the methods used to achieve certain objectives by using this evaluation method(Lee et al., 2001)(Go et al., 2011).

Objectives	Methods
Minimize environmental impact	Extract as many reusable, recyclable and toxic components from the product.
Minimize deficit or maximizing surplus	Disassembly is stopped when greatest positive net cost or lowest negative net cost is reached.
Minimize time for disassembly and deficit or maximize surplus	Disassembly is stopped when the highest rate of return is achieved by dividing the net cost recovered by the total time elapsed.

(Coates & Rahimifard, 2006) contributed to this evaluation method by presenting an end-of-life cost model for automotive recovery sector by having these few parameters involved. The parameters involved are End-of-Life-Vehicles (ELV) costing database, indirect ELV processing costs, pre-shredder dismantling costs, post fragmentation costs. The ELV costing database consists of capital equipment costs, average material pricing, material property data etc.

(Coates & Rahimifard, 2006) have also found that these few areas are not analyzed sufficiently enough. One of the areas involved is that the entire vehicle needs to be analyzed at an initial stage in the design. This is done so as to isolate the problematic materials as early as possible. Another area involved is that the assemblies are not efficient in material and part should be identified much earlier in the design process where redesigning can reduce potential disassembly time while increasing reuse and recycling value. The third area involved is that redesign methods should consider also the functional value of the assembly being removed alongside with disassembly time. This is to focus on improving the functional connections of other assemblies.

(Afrinaldi, Zameri, Saman, & Shaharoun, 2008) recommended another methodology that includes the implementation of computer based disassemblability evaluation tool. The methodology includes end of life options determination and numerical evaluation of disassemblability. The authors use the equations proposed by (Lee et al., 2001) with use of disassemblability evaluation method by (Desai & Mital, 2003).

Table 2:4: Table below show the advantages and limitations of End-of-Life Value based on literatures by (Coates & Rahimifard, 2006), (Afrinaldi et al., 2008), (Lee et al., 2001), (Desai & Mital, 2003)&(Go et al., 2011).

Advantages	Limitations
Automotive designer or engineer has the capability to calculate and measure the disassembly and recycling potential for different automotive designs.	Information on cost and other variables are required to proceed with this particular method. The information required to implement this evaluation method could be missing or vague.
Specific objectives can be evaluated provided that certain information is available to be applied to the equation. Detailed evaluation can be achieved for specific objectives.	There are different objectives that require different methods to evaluate which can be confusing for inexperienced users. Human error can easily occur when an inexperienced personnel handles the multitude of equations and required information for evaluation.

2.2.4 Life Cycle Assessment (LCA)

Life Cycle Assessment has the ability to estimate the environmental aspects and potential impacts throughout the products' lifetime which is also known as cradle-to-grave. The scope of the life cycle assessment includes from raw materials to the final disposal of either the product or sub-assemblies. This means the scope includes, material extraction, processing, manufacturing, transport , used, reuse, maintenance and its end-of-life which is through recycling or landfilling the product (Mayyas, Qattawi, Mayyas, & Omar, 2012). The organization for Standardization ISO classified LCA framework into 4 phases which are goa and scope definition phase, inventory analysis phase, impact assessment and interpretation phase("ISO 14000 family - Environmental management," n.d.).

(Soo, Compston, & Doolan, 2016) managed to run a Life Cycle Assessment case study on four different models of car door where the material composition of the four doors of different years from the scrapyard were compared to highlight the presence of contaminants during the recycling phase. (Soo et al., 2016) found that the impurities present in the different valuable recovered streams need to be included in the life cycle analysis. This is for a more informed decision to improve recyclability of high quality materials. The method used for the assessment takes into account of the mass of the material that is being recycled, incinerated, landfill and quality of material loss.

Table 2:5: Table below show the advantages and limitations of Life Cycle Assessment based on literatures (Soo et al., 2016), (Castro, Remmerswaal, Brezet, & Reuter, 2007) & (Tian & Chen, 2014).

Advantages	Limitations
Detailed account of different designs from different models of vehicles	Limited by the time delays and inability to account for material degradation in a closed-loop system
Takes into account of the mass of different materials of vehicle components	Does not include impurities present in the life cycle analysis
Highlights the presence of contaminants during recycling phase	Difficult to apply in practice due to data limitations
Assess the sensitivity of the vehicle doors' life cycle impact under different end-of-life scenarios	
Able to asses numerous aspects including raw materials refining ore recycling, material handling and processing, automotive parts production , vehicle assembly, and vehicle scrapping and recycling process that produce energy consumption and emissions.	

2.2.5 Grey Modelling based Forecasting System

The grey modelling based forecasting system was designed for end-of-life vehicle return flow prediction where it was applied in Turkey. (Ene & Öztürk, 2017) developed a forecasting system for discarded end-of-life vehicles. The forecasting system uses a small amount of the most recent data with improvement by applying parameter optimization, Fourier series and Markov chain correction.

(Ene & Öztürk, 2017) managed to achieve high accuracy in predicting the return of End-of-Life-Vehicles for all regions in Turkey using their Grey Modelling based forecasting system approach. The model handles data sets characterized by uncertainty and sizes with other sub models involved.

Table 2:6: Table below shows the Advantages and Limitations of Grey Modelling based forecasting system based on literatures (Ene & Öztürk, 2017)

Advantages	Limitations
High accuracy in forecasting return flow of end-of-life-vehicles	Complicated problems including a number of known and unknown parameters that affect the return of products
Forecasting models can be integrated into recovery network decisions	The return flow of end-of-life vehicles has rarely been studied since it is a new concept.
Decision support systems can be established for the management of EOV returns	There is a lack of study in the area of combining parameter optimization, Fourier series and Markov chain
Model can work with limited amount of information available.	

Table 2:7: Table below shows different evaluation methods used by different authors.

Evaluation Methods	References	Units used for Evaluation Method	Factors Used for Evaluation
Spread sheet-like Chart (DECM) Disassemblability Evaluation Chart Method	(McGlothlin & Kroll, 1995) (Kroll & Hanft, 1998) (Fatmawati, 2007)	Quantitative evaluation using score method based on 100 point scale with disassembly time estimation Score based system using Maynard Operation Sequence Technique (MOST) Equations are used to calculate the factors based on the scores	- Ease of disassembly of a product - Disassembly time estimation - Disassembly evaluation score - Disassembly cost index - Ease of disassembly of a product - Accessibility - Positioning - Force - Additional time - Special problems - No of tools & hand manipulations

Evaluation Methods	References	Units used for Evaluation Method	Factors Used for Evaluation
Disassembly Time	(Gungor & Gupta, 1997) –Total Time for Disassembly (TTD)	Time required for each factors and parameters. Substitution of the time into each of the equations	- Disassembly sequence - Disassembly time of each component - Disassembly directions - Joint types - Number of subassemblies in the product
	(Kongar & Gupta, 2006) – Genetic Algorithm	Total Time for Disassembly Sequence Genetic algorithm	- Basic disassembly time for different components in sequence - Penalty for each direction change for different components in sequence - Penalty for change in disassembly method
	(Hwa-Cho Yi et al., 2003)	Using the work factor method that considers moving body parts, moving distances, weight and artificial regulation factors	- Preparation time - Movement time - Operation time / disassembly time - Post- processing time

Evaluation Methods	References	Units used for Evaluation Method	Factors Used for Evaluation
End of Life Value	(Lee et al., 2001)	Using equations to determine optimal level for disassembly by - Minimising environmental impact - Minimizing associated costs - Maximising the rate of return	- Number of components disassembled and processed - Total Number of components in the product - Cost Gained, Disassembled Cost, Processing Cost, Land cost of Component - Rate of Return - Net cost Recovered
	(Coates & Rahimifard, 2006)	Activity Based Costing	- Indirect ELV processing costs - Pre-shredder dismantling costs - Post-fragmentation costs - Manual dismantling of parts and assemblies - Separation of post shredder plastics - Recycling value of post shredder material streams
	(Desai & Mital, 2003)	Disassembly Score Disassembly Time Disassembly Cost	- Degree of accessibility of components and fasteners - Amount of force or torque required for disengaging components - Positioning - Requirement of tools - Design factors such as weight , shape & size of components being disassembled
	(Afrinaldi et al., 2008)	End-of-Life options determination Numerical evaluation of disassemblability	A combination of factors proposed by (Lee et al., 2001) and (Desai & Mital, 2003)

Evaluation Methods	References	Units used for Evaluation Method	Factors Used for Evaluation
Life Cycle Assessment	(Soo et al., 2016)	Mass of the materials % composition of materials Green House Gasses Emissions (g CO2-eq/km)	- Material Composition - Presence of contaminants - Mass of material being recycled, incinerated, landfill and quality of material loss - Human Toxicity - Freshwater eco-toxicity & eutrophication - Metal depletion impacts - Electricity source
Grey Modelling Forecasting System	(Ene & Öztürk, 2017)	Using data sets characterized by uncertainty and sizes with other sub models involved - Fourier Series - Markov Chain Number of discarded cars used in different regions. Population density Economic Strength Mean Absolute Percentage Error	- Data Series of end of life vehicles for different regions. - Basic Grey Model - Optimized Grey Model - Grey Model with parameter optimization - Fourier Series Modification

Based on the different evaluation methods used by different authors, there is a need to evaluate an entire vehicle at the initial stage of the design. This is to isolate problematic materials as early as possible (Coates & Rahimifard, 2006).

2.3 Factors Determining the Recovery and Reusability of end-of-life-vehicle

A few factors are chosen to determine the recovery value of the end-of-life-vehicle. These factors can be evaluated by viewing the components or part of the vehicle to justify the recovery value using fuzzy inference system. The factors are found through literature review.

2.3.1 Presence of Hazardous Substances

ELVs consist of complex contents with some of them affects the recovery process due to the presence of pollutants and hazardous substances (Zhang & Chen, 2018).

(Mat Saman & Blount, 2008) stated that the presence of hazardous substances affects the level of difficulty for dismantle-ability where it affects the components to be remanufactured. There are occasions during the disassembling of the whole product into smaller components is impractical due to the presence of hazardous materials (Desai & Mital, 2003). Not to mention, the presence of hazardous substances will tend to generate higher recycling costs since treatment is needed for the disposal of these materials (Shih, Chang, & Lin, 2006). Furthermore, China has implemented a policy to reduce the amount of lead and other environmentally hazardous substances for an easy and cost effective ELV recycling(Tian & Chen, 2014).

Therefore, it is noted that the design decisions on the part of vehicle designers will be able to make a safer and more efficient process by eliminating the presence of hazardous substances. (de Aguiar et al., 2017) used the Brazilian standard (NBR, 2004) for the classification of end-of-life materials which involves three material classes. The indexes of 1 to 3 are directly related to the Brazilian Standard 10004's Classes III, II and I (NBR, 2004) whereas index 4 is related to the existence of materials where the use is controlled by Montreal Protocol or any existing restriction (de Aguiar et al., 2017).

Table 2:8: Table below shows the Brazilian standard classification of end of life materials (NBR, 2004)

Classes	Description
I	Hazardous materials where risk is present to human health and environment. This includes inflammable, corrosive, reactive, toxic and pathogenic materials
II	Non-inert Materials where there is a possibility posing a risk unto human health or the environment. This includes combustible, biodegradable and soluble materials.
III	Inert Materials where the materials do not post any risk to human health or the environment.

Table 2:9: Table below shows the description of different classes of materials, index and desired states provided by (de Aguiar et al., 2017).

Description	Index	Desired States
Inert Materials	1	Desired
Non-inert Materials	2	
Hazardous Materials	3	
Controlled use of Materials	4	Undesired

Components with inert materials do not post any risk to human health or the environment, this makes the recoverability of the components relatively easier.

Table 2:10: Table below shows an example of different classes of materials.

Description	Example
Inert Materials	Metal, glass etc (Pg, 2013)
Non-inert Materials	Fuel etc
Hazardous Materials	All waste oil except edible oil (Environment Agency, 2007), etc
Controlled use of Materials	Explosives (such as used in airbags), etc

2.3.2 Accessibility Index (AI)

(de Aguiar et al., 2017) came up with an indicator to measure the level of difficulty to reach a component or a part in the assembly (Kroll & Carver, 1999). (Desai & Mital,

2003) also stated that an easy access to the specific part or component is a first step to a process that is fast and efficient. The indicator proposed by (de Aguiar et al., 2017) considered the fastener accessibility is directly proportional to the obstructed area with the surface used for fastener removal. This also includes 4 levels of accessibility which are free access, 50% or more accessible, 50% or more inaccessible and inaccessible.

Table 2:11: Table below shows the description for the accessibility index and desired states provided by (de Aguiar et al., 2017)

Description	Index	Desired States
Free Access	1	Desired
50% or more accessible	2	
50% or more inaccessible	3	
Inaccessible	4	**Undesired**

2.3.3 Difficulties of Cleaning Automotive Components (Eg corrosion, dirt, sludge, etc)

Components that are remanufacture-able provides vehicle owners with an alternative to new replacement parts. This alternative not only saves the customer money but also addresses the concerns of different constituencies such as environmentalist (Hormozi, 1997).

The process for remanufacturing used components requires the components to be cleaned. Cleaning of automotive components is identified as one of the highest cost contributors to remanufacturing right after replacement of parts. This is due to the Environmental Protection Agency and other environmentally oriented legislation (Hammond, Amezquita, & Bras, 1998) in certain countries.

High costs sometimes prohibits the remanufacturing of a component since it could be cheaper to buy a replacement part instead of cleaning it due to difficulties in cleaning.

Some of the difficulties of cleaning the components are related to the presence of dirt, corrosion, sludge or other foreign substances on the components with variant amounts.

Corrosion leads to multiple problems according to (Hammond et al., 1998). It was ranked the highest in complicating the disassembly process. The presence of corrosion causes adjacent parts to be bonded together. It also leads to difficulties in cleaning during the recovery process. A ranking of easy to hard difficulty can be formed to estimate the probability of recovery and reusability based on the difficulties of cleaning of the components.

Table 2:12: Table below shows the basic ranking for difficulties of cleaning of automotive components.

Description	Index	Desired States
Easy	1	Ideal
Medium	2	
Hard	3	Undesired

2.3.4 Type of Fasteners Index

The product recovery and preserving of product life are highly dependent on the ease of disassembly. One of the factors that affects the ease of disassembly is the type of fasteners used. During design for disassembly, there are many fastener related factors that needs to be considered such as structural, disassembly process and the pre-disassembly process (Ghazilla, Taha, Yusoff, Rashid, & Sakundarini, 2014).

(Jeandin & Mascle, 2016) managed to provide two different scenario of disassembly. The first situation focuses on materials recycling whereas the second situation is focused on part reusing. The following tables shows a correlation between each different fasteners that is used has varying degree of disassembly and equal importance.

Table 2:13: Table below shows the results for situation one that focuses on material recycling.

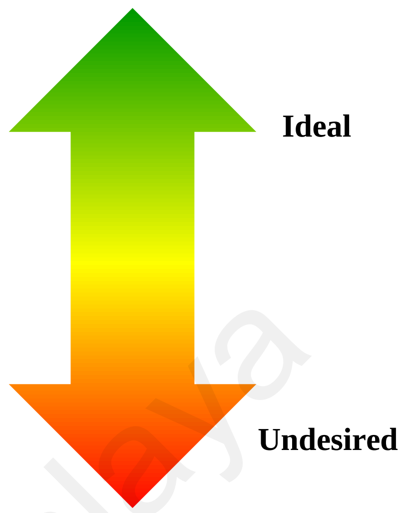
Example	Equal importance	Disassembly
Nut and bolt	49,41 %	77,49 %
Screw	62,38 %	93,95 %
Rivet	53,19 %	61,23 %
Cantilever	100 %	100 %
Welded	77,55 %	76,50 %
Glue	64,09 %	63,64 %

Table 2:14: Table below shows the results for situation two that focuses on part reusing.

Example	Equal importance	Disassembly
Nut and bolt	50,78 %	82,16 %
Screw	64,06 %	99,85 %
Rivet	54,71 %	66,05 %
Cantilever	100 %	100 %
Welded	76,93 %	74,32 %
Glue	63,36 %	61,12 %

(de Aguiar et al., 2017) proposed a type of fastener index where there is an undesired state to an ideal state for a fastener used in the component. The desired states of each of all the fasteners are compared and calculated using different factors such as mean time for disassembly, quantity of tools for disassembly, mean strength for disassembly and destructive disassembly with the use of percentage of fasteners index and the type of fastener index.

Table 2:15: Table below shows the evaluated type fasteners index by (de Aguiar et al., 2017).

Type of Fasteners Index (TFI)	Index	Desired States
Snap-fit	1.07	
Scotch Tape	1.33	
Clasp	1.33	
Retaining Ring	1.33	
Screw	1.60	
Nut and Bolt	1.60	
Magnetic Attachment	1.60	
Pin	1.60	
Velcro	1.87	
Wire	1.87	
Nylon Tag Fastener	1.87	
Nail	2.67	
Glue	*2.93*	
*Rivet *	*4.00*	

2.3.5 Material compatibility

The combination of materials has a direct effect on materials recycling during the sorting phase according to (van Schaik & Reuter, 2007). The lower the variety of materials in the components will lead to better recycling possibilities since the recycling process becomes easier. Compatibility materials usually means a mixture of materials that reach a desired property such as having good impact resistance and or high impact strength. Different materials could be defined as compatible when material properties are not lost when processed simultaneously. Sorting process is needed for non-compatible materials which may lower the recoverability value since effort is needed for separation to avoid contamination of different materials.

The compatibility of materials is important especially polymers since most polymers are not compatible with each other. This means the separation from each other can be challenging and costly. Disassembly is easy if the material of a part from the same module of product, assembly or component have high compatibility. High compatibility enables different materials to be processed via the same processing technology at the end-of-life of the vehicle (de Aguiar et al., 2017).

Table 2:16: Table below shows the evaluated material compatibility index by (de Aguiar et al., 2017)

Description	Index	Desired States
Same Materials	1	**Ideal**
Compatible Materials	2	
Low Compatibility Materials	3	
Non-Compatible Materials	4	**Undesired**

Non - compatible materials can be recoverable or not recoverable depending on how the design was made according to (Sopher, 2009). An example is when there is an encapsulated steel frame molded over by a thermoset (PU foam) with adhesive which is not recoverable.

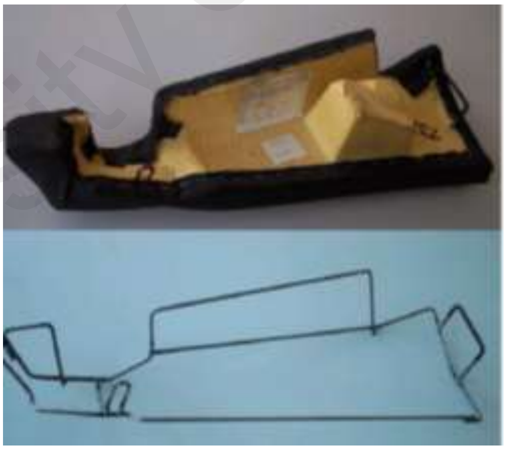


Figure 2.3: Figure above shows the encapsulated steel frame with thermoset by (Sopher, 2009)

An example of compatible materials in a design is the presence of solid EPP foam part with installed plastic inserts without any metal in it. This design incorporates a TPO cover that is press-fit into the EPP foam. The primary component part, EPP which is a readily recyclable thermoplastic.

Figure 2.4: Figure above shows the compatible materials with readily recyclable thermoplastics.

2.3.6 Type of Tools needed for Disassembly

The type of tools needed affect the disassembly rate and difficulty of the fasteners on the components. If the fasteners can be released or loosened without the need of special tools, the accessibility of the fasteners will not be an issue (Soh, Ong, & Nee, 2014).

An ideal disassembly is taken place without the use of tools but if the need of tools arises, the job should be doable using simple tools (Desai, 2002). Complex tools are most of the time not preferred since there might be complications involved using complex tools.

Table 2:17: Table below shows the grading of the need of tools required by (Desai, 2002).

Requirement of tools for disassembly	Exertion of force		1	No tools required
			2	Common tools required
			3	Specialized tools required
	Exertion of torque		1	No tools required
			2	Common tools required
			3	Specialized tools required

Table 2:18: Table below shows the proposition for evaluated tools needed for disassembly of fasteners.

Description	Index	Desired States
No Tools Needed	1	Ideal
Tools Needed	2	
Special Tools Needed	3	Undesired

2.4 Summary

In this chapter, the different evaluation methods and factors determining the recoverability and reusability of end of life vehicles were discussed. The survey shows that most of the methods are still based on manual inputting of factors into table in order to predict recoverability and reusability of end of life vehicles. This procedure is slow and largely inefficient, suggesting the formulation of more efficient models. There were other evaluation methods involved that uses algorithms to estimate the recovery of end of life vehicles. These methods are efficient but it takes a year or so for the estimation to be complete.

CHAPTER 3: METHODOLOGY

3.1 Introduction

There are multiple factors that affect the recoverability and reusability of the automotive end of life components. Different input in the factors that yield different desirability of outputs has the potential to assist automotive engineers and designers to evaluate the end of life recovery and reusability of each components during the end of life at the design stage. An appropriate model is most desirable when it is capable of being implemented on the field. This is true, especially in different countries or areas where there are different distinguishable facilities and resources capable of recovering and reusing end of life vehicles. The difference in facilities and resources determines different outcomes for recoverability and reusability of the end of life vehicle components.

The Mamdani Fuzzy Logic Inference System has been one of the most robust modelling techniques used for many years. The simplicity of this system enables it to be interpretable when the user uses linguistic terms to set the different rules capable of delivering different outputs. The user has the capability to adjust different outputs based on the situation that varies from time to time. This makes the Mamdani Fuzzy Logic Inference System suitable for the ever-changing automotive industry since the rules can be adjusted based on the current reality of recoverability and reusability of automotive components.

3.2 Fuzzy Inference System

Fuzzy inference which also known as fuzzy reasoning is a process of plotting from a given input to an output using fuzzy logic. A fuzzy analytical hierarchical process using Matlab can be implemented using human judgments and underlying information (Saaty, 2008) to evaluate and determine the recycling parameters and value of the different components and materials found in the vehicle. A method used so called ranking by having a set of alternatives in order from most desirable to least desirable options (Forman & Gass, 2001) is also done to build the model.

There are two types of fuzzy inference which are mamdani and sugeno. Mamdani fuzzy inference is the most universal seen method used worldwide. It was also among the first control systems build using fuzzy set theory proposed by Ebrahim Mamdani in 1975 (Mamdani & Assilian, 1975) based on Lofti Zadeh's 1973 paper on fuzzy algorithms from decision processes and complex systems (Zadeh, 1973). It was an attempt by Ebrahim Mamdani to take control a boiler combination and steam engine with the use of synthesized set of linguistic control rules gathered by experienced technicians on the job. The output membership functions of Mamdani fuzzy inference is expected to be fuzzy sets. There is a fuzzy set for each output variable that needs to be defuzzified after the aggregation process.

Sugeno fuzzy inference was introduced in 1985 by (Sugeno, 1985) where the methods are similar to Mamdani in many aspects. The fuzzyfying and applying fuzzy operators are similar whereas the main difference will be the output membership function are either linear or constant. The advantages of having Sugeno systems is that it is computationally efficient, works well with linear techniques like PID controls, works well with optimization and adaptive techniques, guarantees continuity of output surface and well suited to mathematical analysis.

Mamdani Fuzzy Inference System is chosen for this project since it is more intuitive, has widespread acceptance by other parties and also well suited to human input especially for experience automotive design engineers that are required to have their professional inputs.

The factors such as Presence of Hazardous Substances, Accessibility Index, Number of fasteners, type of fasteners and material compatibility can be used in the fuzzy inference system. The factors with different hierarchy of index value can be used to predict the recovery and reusability value of the components during the end-of-life-vehicle. The factors can be diversified into two categories which are components and fasteners.

Table 3:1: Table below shows the factors that are going to be used as inputs in the fuzzy inference system.

Factors for Recoverability and Reusability for	
Components	Fasteners
Presence of Hazardous Substances	Accessibility Index
Accessibility Index	Type of Fasteners
Cleaning Difficulty	Material Compatibility with Components
Material Compatibility with other Components	Type of Tools Needed
Material Compatibility with other Fasteners	

3.2.1 Fuzzy Inference System for Components

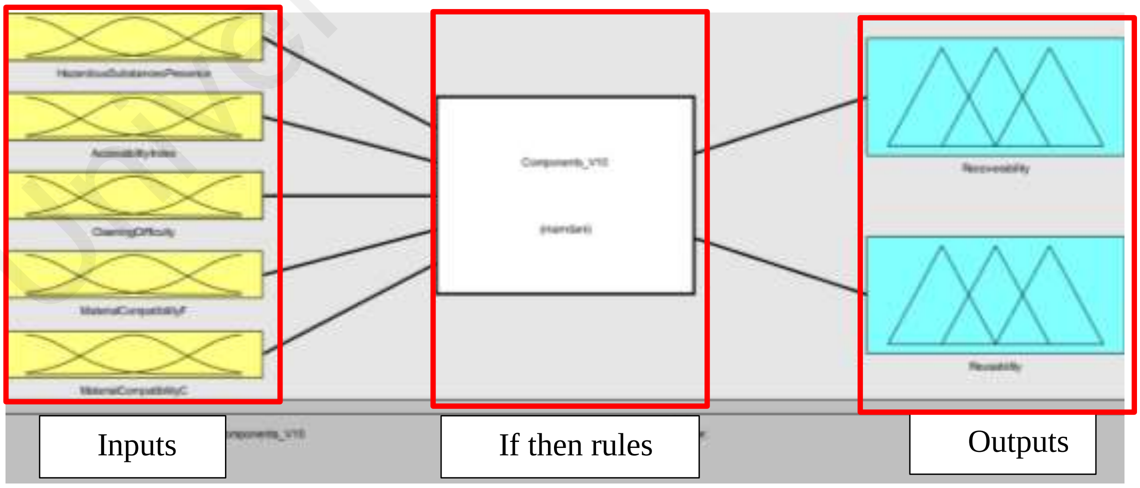


Figure 3:1: Figure above shows the Fuzzy Inference System for Components

The above figure shows the 5 inputs for the 5 factors involved which are Presence of Hazardous Substances, Accessibility Index, Cleaning Difficulty, Material Compatibility with other components and Material Compatibility with other Fasteners.

The above fuzzy inference also includes the fuzzy if then rules and two outputs: recoverability and reusability. Each inputs on the left side of the figure consists of a hierarchy of material efficiency or energy efficiency in terms of output for recovery. The stages of hierarchy in each factor is recorded in membership functions. Each membership functions will have a different output due to the recovery efficiency hierarchy. The if-then rules determine the hierarchy of outputs for each membership functions from the least to the most desired in each different factors.

3.2.1.1 Inputs Membership Function for Components

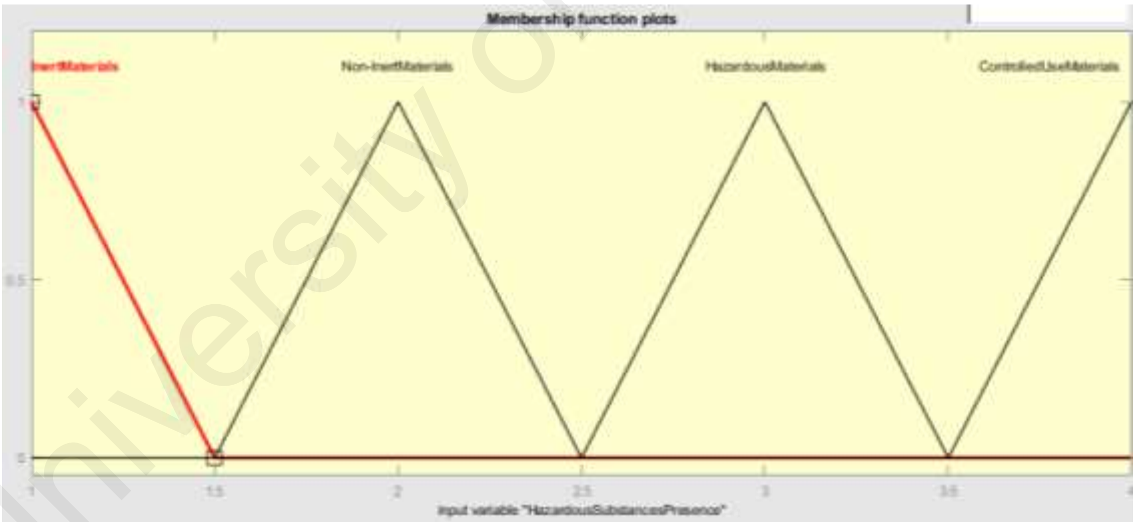


Figure 3:2: Figure above shows the membership function for Presence of Hazardous Substances.

Figure previously shows 4 membership functions for Presence of Hazardous Substances. The inputs are from 1 to 4 which depicts 1=Inert Materials, 2=Non-Inert Materials, 3=Hazardous Materials and 4=Controlled Use of Materials. Each membership function in this input will have a different output based on the configuration of if then rules.

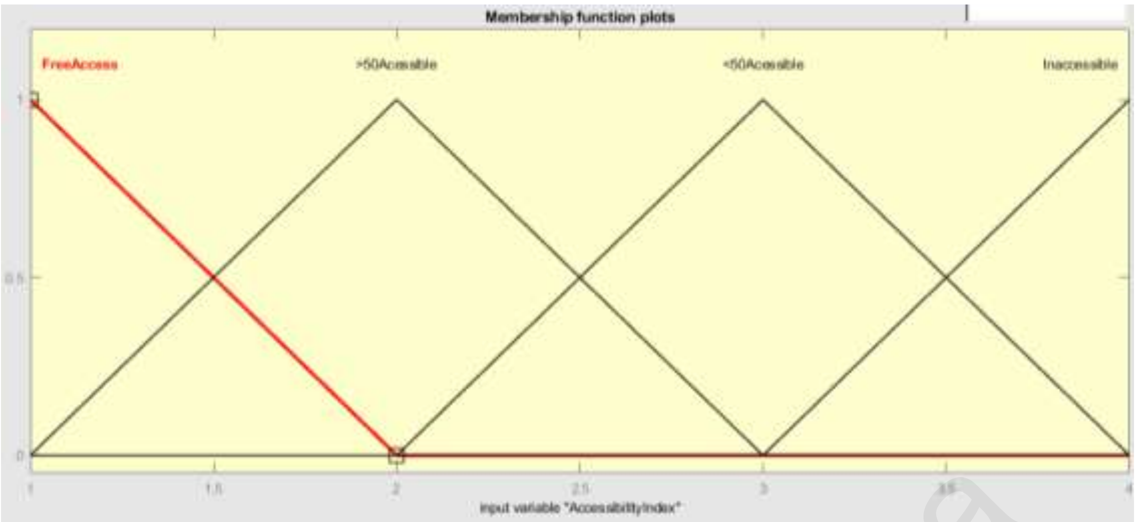


Figure 3:3 Figure above shows the membership function Accessibility Index.

Figure previously shows 4 membership functions for Accessibility Index. The inputs are from 1 to 4 which depicts 1=Free Access, 2=>50% Accessible, 3=<50%Accessible and 4=Inaccessible. Each membership function in this input will have a different output based on the configuration of if then rules.

Figure 3:4: Figure above shows the membership function Cleaning Difficulty of Automotive Components.

Figure previously shows 3 membership functions for Cleaning Difficulty of Automotive Components. The inputs are from 1 to 3 which depicts 1=Easy, 2=Medium and 3=Hard. Each membership function in this input will have a different output based on the configuration of if then rules.

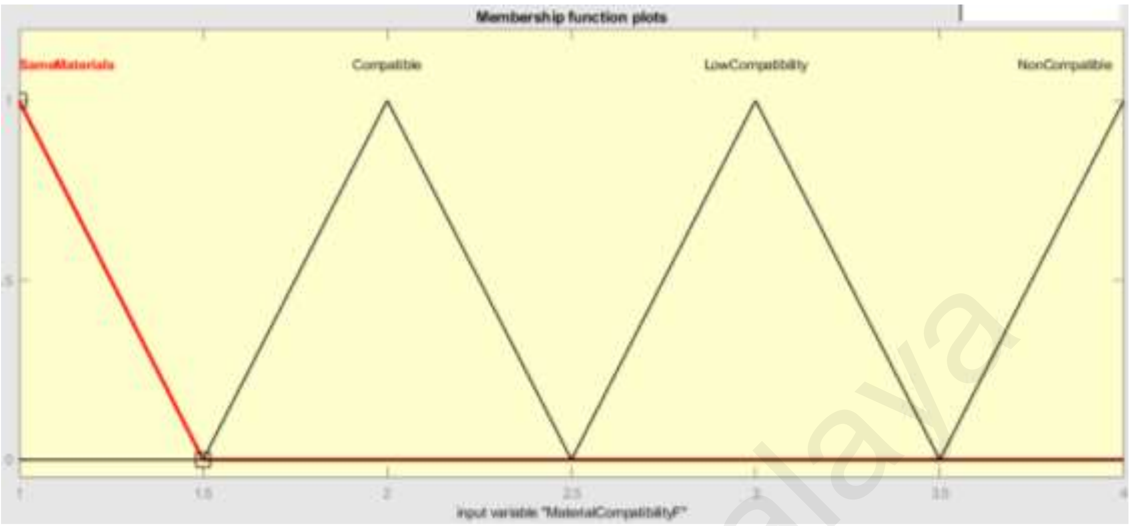


Figure 3:5: Figure above shows the membership function Material Compatibility with Fasteners.

Figure previously shows 4 membership functions for Material Compatibility of fasteners with current component. The inputs are from 1 to 4 which depicts 1=Same Materials, 2=Compatible, 3=Low Compatibility and 4=Not Compatible. Each membership function in this input will have a different output based on the configuration of if then rules.

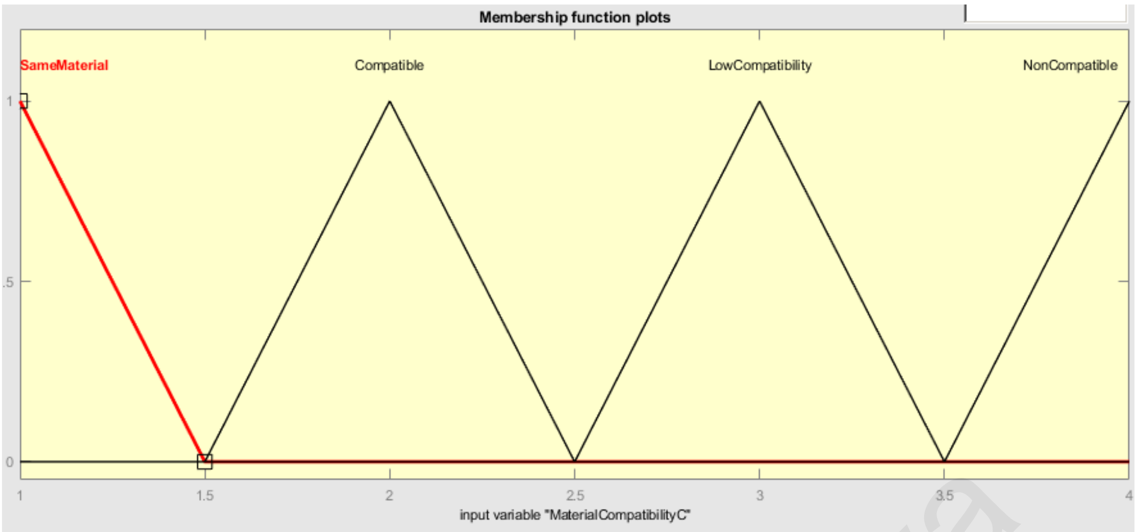


Figure 3:6: Figure above shows the membership function Material Compatibility with Components.

Figure previously shows 4 membership functions for Material Compatibility of component with other component in a sub-assembly. The inputs are from 1 to 4 which depicts 1=Same Materials, 2=Compatible, 3=Low Compatibility and 4=Not Compatible. Each membership function in this input will have a different output based on the configuration of if then rules.

3.2.1.2 If Then Rules for Components

1. If (HazardousSubstancesPresence is InertMaterials) then (Recoverability is VeryHigh)(Reusability is VeryHigh) (1)
2. If (HazardousSubstancesPresence is Non-InertMaterials) then (Recoverability is Recoverable)(Reusability is Low) (1)
3. If (HazardousSubstancesPresence is HazardousMaterials) then (Recoverability is Low)(Reusability is VeryLow) (1)
4. If (HazardousSubstancesPresence is ControlledUseMaterials) then (Recoverability is VeryLow)(Reusability is NotReusable) (1)
5. If (AccessibilityIndex is FreeAccess) then (Recoverability is VeryHigh)(Reusability is Reusable) (1)
6. If (AccessibilityIndex is >50Acessible) then (Recoverability is Recoverable)(Reusability is Reusable) (1)
7. If (AccessibilityIndex is <50Acessible) then (Recoverability is Medium)(Reusability is Medium) (1)
8. If (AccessibilityIndex is Inaccessible) then (Recoverability is VeryLow)(Reusability is Low) (1)
9. If (CleaningDifficulty is Easy) then (Recoverability is VeryHigh) (1)
10. If (CleaningDifficulty is Medium) then (Recoverability is Recoverable) (1)
11. If (CleaningDifficulty is Hard) then (Recoverability is Low) (1)
12. If (MaterialCompatibilityF is SameMaterials) then (Recoverability is VeryHigh) (1)
13. If (MaterialCompatibilityF is Compatible) then (Recoverability is Recoverable) (1)
14. If (MaterialCompatibilityF is LowCompatibility) then (Recoverability is Low) (1)
15. If (MaterialCompatibilityF is NonCompatible) then (Recoverability is VeryLow) (1)
16. If (MaterialCompatibilityC is SameMaterial) then (Recoverability is VeryHigh) (1)
17. If (MaterialCompatibilityC is Compatible) then (Recoverability is Recoverable) (1)
18. If (MaterialCompatibilityC is LowCompatibility) then (Recoverability is Low) (1)
19. If (MaterialCompatibilityC is NonCompatible) then (Recoverability is VeryLow) (1)
20. If (AccessibilityIndex is Inaccessible) and (MaterialCompatibilityC is NonCompatible) then (Recoverability is NotRecoverable) (1)

Figure 3:7: Figure above shows the edited rules for fuzzy inference system for components.

Figure previously is edited rules for the fuzzy if then rules that depicts the outcome of the outputs for each selection. The selection of rules is based on the hierarchy of material efficiency and energy efficiency based on (Gerrard & Kandlikar, 2007) by using the hierarchy pyramid discussed in literature review. The weightage of each rules are set to 1 to make all the rules to be equal since there is not enough comprehensive data to validate each rule. The weightage for each if-then rules can be adjusted accordingly to each comprehensive data found.

3.2.2 Fuzzy Inference System for Fasteners

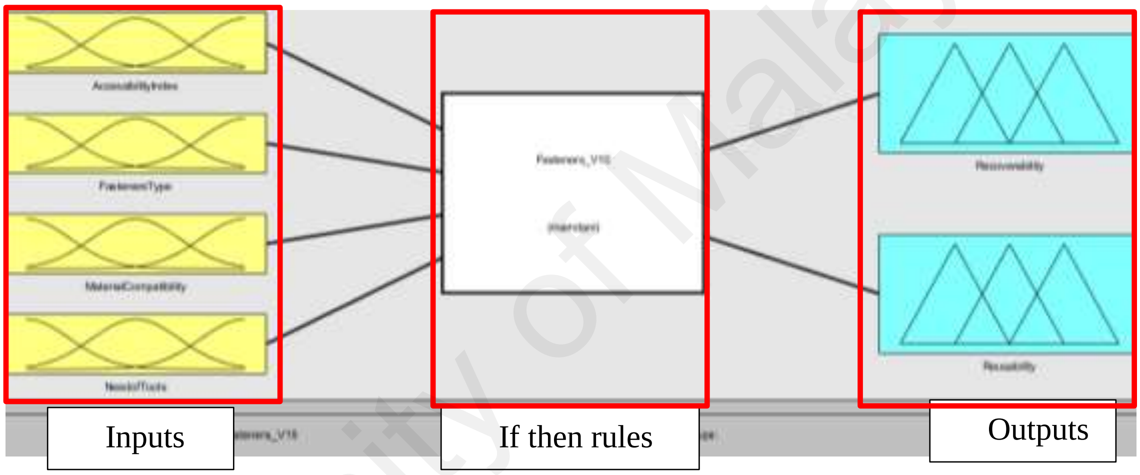


Figure 3:8: Figure above shows the Fuzzy Inference System for Fasteners.

The above figure shows the 4 inputs for the 4 factors involved which are Accessibility Index, Type of Fasteners, Material Compatibility with Components and Type of tools needed.

The above fuzzy inference also includes the fuzzy if then rules and two outputs: recoverability and reusability. Each inputs on the left side of the figure consists of a hierarchy of material efficiency or energy efficiency in terms of output for recovery. The stages of hierarchy in each factor is recorded in membership functions. Each membership functions will have a different output due to the recovery efficiency hierarchy. The if-then rules determine the hierarchy of outputs for each membership functions from the least to the most desired in each different factors.

3.2.2.1 Inputs Membership Function for Fasteners

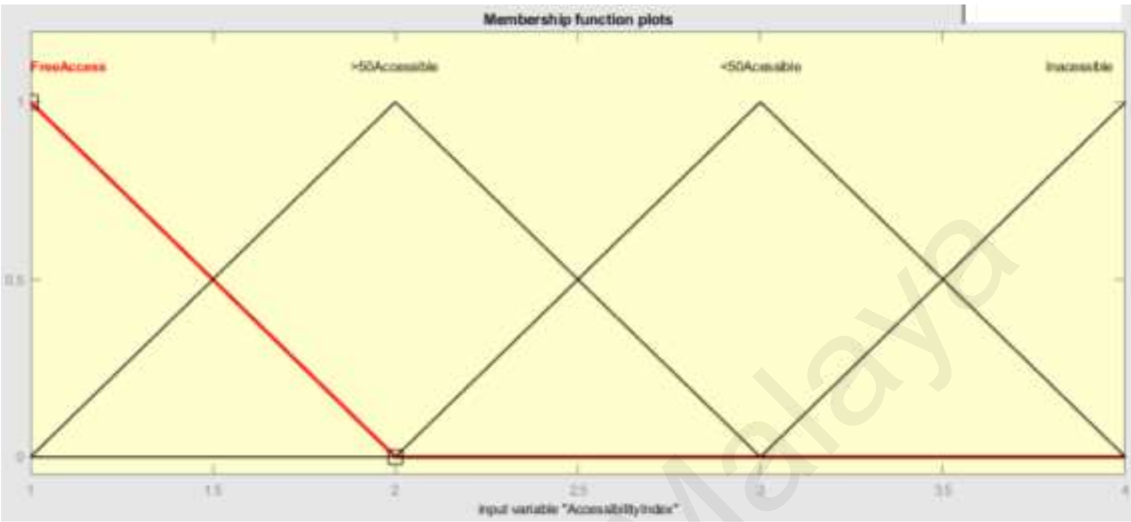


Figure 3:9: Figure above shows the membership function for Accessibility Index for Fasteners.

Figure previously shows 4 membership functions for Accessibility Index of Fastener. The inputs are from 1 to 4 which depicts 1=Free Access, 2=>50% Accessible, 3=<50% Accessible and 4=Inaccessible. Each membership function in this input will have a different output based on the configuration of if then rules.

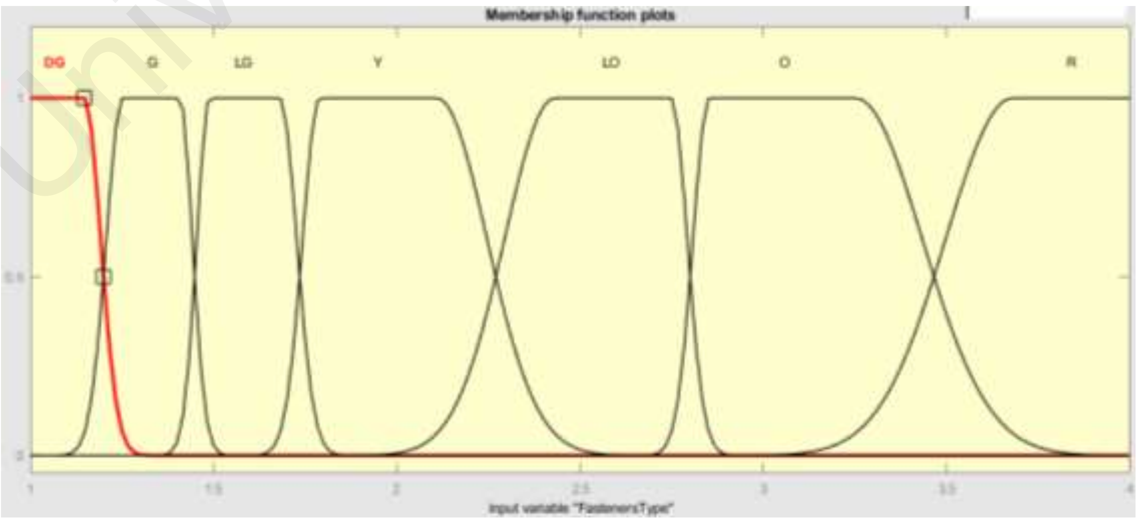


Figure 3:10: Figure above shows the membership function of Type of Fasteners' index for fasteners.

Figure previously shows 7 membership functions for Type of Fasteners index. The inputs are from 1 to 4 which depicts different fasteners used for each membership function used. The shape of the membership function follows the color code based on (de Aguiar et al., 2017) discussed in type of fasteners' index in table 8. Each membership function in this input will have a different output based on the configuration for if then rules.

Table 3:2: Table below describes the color codes used by different fasteners.

Index	Color	Color Code	Description of Fasteners used by the color code and index
1.07	Dark Green	DG	Snap-Fit
1.33	Green	G	Scotch Tape, Clasp, Retaining Ring
1.60	Light Green	LG	Screw, Nut & Bolt, Magnetic Attachment, Pin
1.87	Yellow	Y	Velcro, Wire, Nylon Tag Fastener
2.67	Light Orange	LO	Nail
2.93	Orange	O	Glue
4.0	Red	R	Rivet

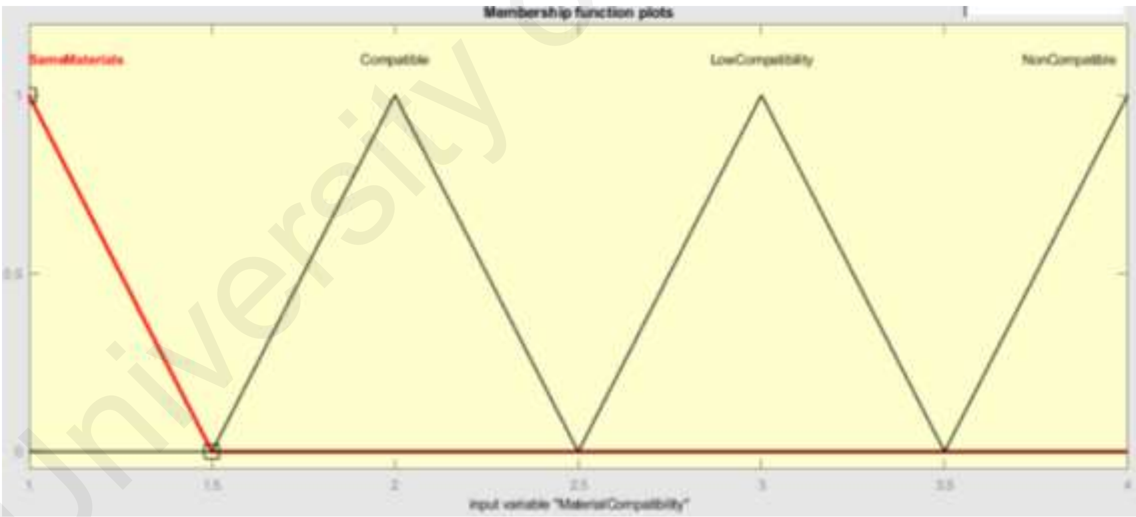


Figure 3:11: Figure above shows the membership function of Material Compatibility of Fastener with Component.

Figure previously shows 4 membership functions for Material Compatibility of Fastener with component. The inputs are from 1 to 4 which depicts 1=Same Material, 2=Compatible, 3=Low Compatibility and 4=Non Compatible. Each membership function in this input will have a different output based on the configuration for if then rules.

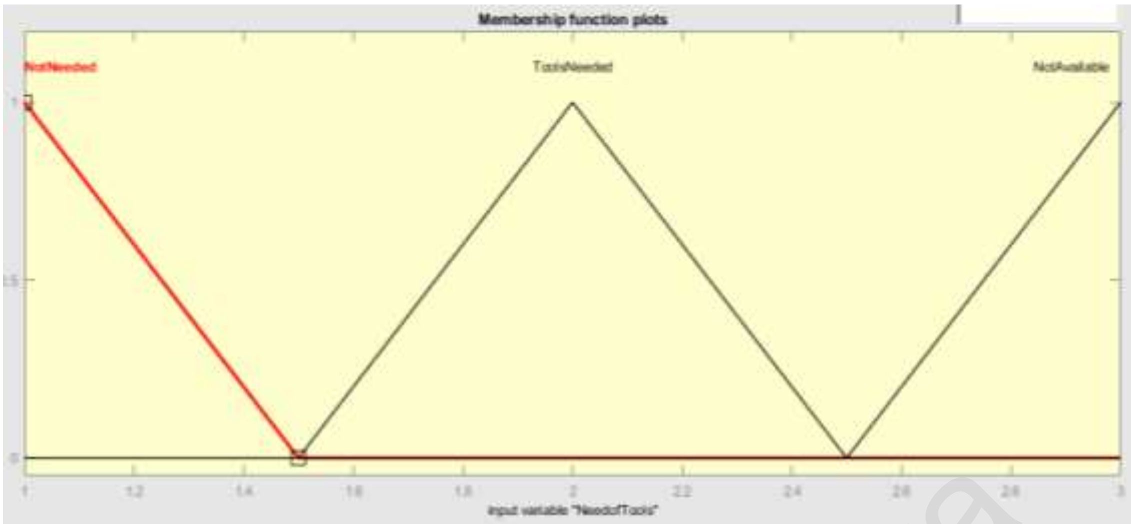


Figure 3:12: Figure above shows the membership function of Type of tools needed for fastener.

Figure previously shows 3 membership functions for type of tools needed for fastener. The inputs are from 1 to 3 which depicts 1=Not Needed, 2=Tools Needed and 3=Not Available. Each membership function in this input will have a different output based on the configuration for if then rules.

3.2.2.2 If Then Rules

1. If (AccessibilityIndex is FreeAccess) then (Recoverability is VeryHigh)(Reusability is VeryHigh) (1)
2. If (AccessibilityIndex is >50Accessible) then (Recoverability is Recoverable)(Reusability is Reusable) (1)
3. If (AccessibilityIndex is <50Acessible) then (Recoverability is Medium)(Reusability is Reusable) (1)
4. If (AccessibilityIndex is Inacessible) then (Recoverability is VeryLow)(Reusability is Medium) (1)
5. If (AccessibilityIndex is Inacessible) and (MaterialCompatibility is NonCompatible) then (Recoverability is NotRecoverable)(Reusability is Medium) (1)
6. If (FastenersType is DG) then (Recoverability is VeryHigh)(Reusability is VeryHigh) (1)
7. If (FastenersType is G) then (Recoverability is VeryHigh) (1)
8. If (FastenersType is LG) then (Recoverability is High)(Reusability is Reusable) (1)
9. If (FastenersType is Y) then (Recoverability is Recoverable)(Reusability is Reusable) (1)
10. If (FastenersType is LO) then (Recoverability is Medium)(Reusability is Low) (1)
11. If (FastenersType is O) then (Recoverability is NotRecoverable)(Reusability is NotReusable) (1)
12. If (FastenersType is R) then (Recoverability is VeryLow)(Reusability is NotReusable) (1)
13. If (MaterialCompatibility is SameMaterials) then (Recoverability is VeryHigh)(Reusability is NotReusable) (1)
14. If (MaterialCompatibility is Compatible) then (Recoverability is Recoverable)(Reusability is NotReusable) (1)
15. If (MaterialCompatibility is LowCompatibility) then (Recoverability is Low)(Reusability is NotReusable) (1)
16. If (MaterialCompatibility is NonCompatible) then (Recoverability is VeryLow)(Reusability is NotReusable) (1)
17. If (NeedofTools is NotNeeded) then (Recoverability is VeryHigh)(Reusability is Reusable) (1)
18. If (NeedofTools is ToolsNeeded) then (Recoverability is High)(Reusability is Reusable) (1)
19. If (NeedofTools is NotAvailable) then (Recoverability is VeryLow)(Reusability is VeryLow) (1)
20. If (NeedofTools is NotAvailable) then (Recoverability is NotRecoverable)(Reusability is NotReusable) (1)

Figure 3:13: Figure above shows the edited rules for fuzzy inference system for fasteners.

Figure previously is edited rules for the fuzzy if then rules that depicts the outcome of the outputs for each selection. The selection of rules is based on the hierarchy of material efficiency and energy efficiency based on (Gerrard & Kandlikar, 2007) by using the hierarchy pyramid discussed in literature review previously. The weightage of each rules are set to 1 to make all the rules to be equal since there is not enough comprehensive data to validate each rule. The weightage for each if-then rules can be adjusted accordingly to each comprehensive data found.

3.2.3 Output Membership Functions for Components and Fasteners.

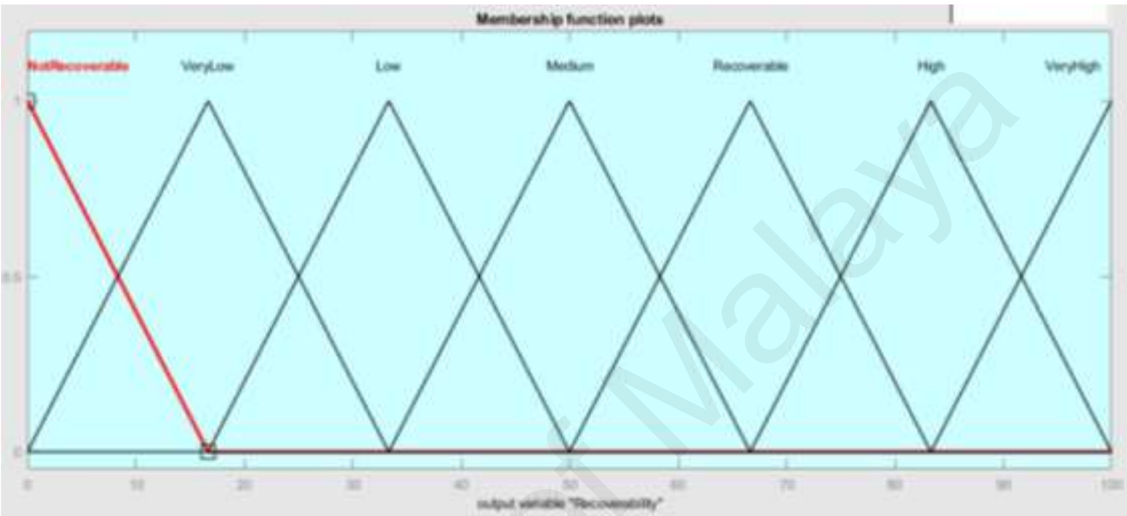


Figure 3:14: Figure above shows the membership functions for the Recoverability outputs

Figure previously shows 7 membership functions for recoverability output. The outputs are from 0 to 100 which each membership functions spaced equally from Not Recoverable as the lowest to Very High as the highest with Very Low, Low, Medium, Recoverable and High in between. The output result for each input is dependent on the configuration of if-then rules set by the user. The output for each input is determined with the consideration of material efficiency and energy efficiency (Gerrard & Kandlikar, 2007) by using the hierarchy pyramid.

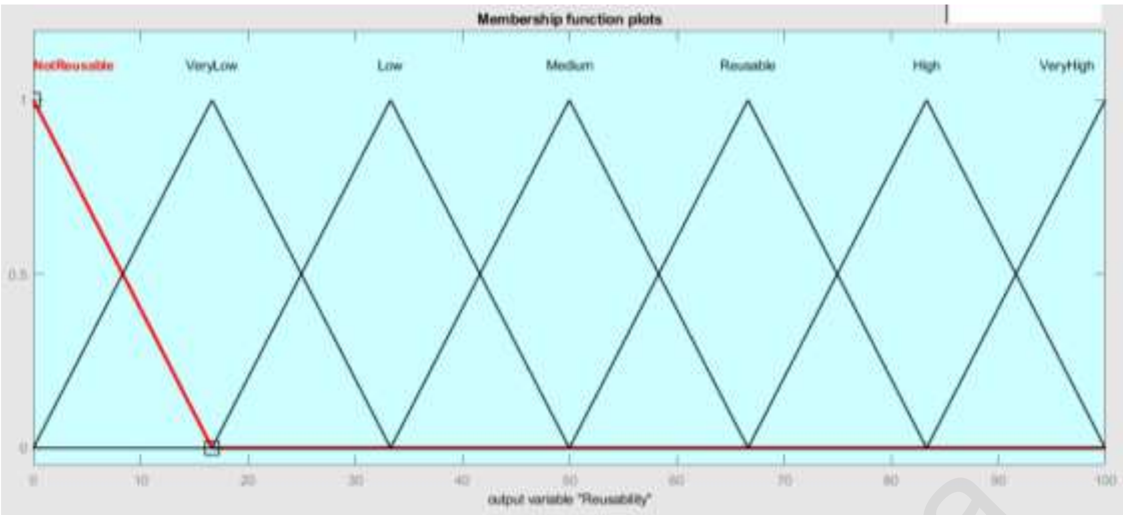


Figure 3:15: Figure above shows the membership functions for the Reusability outputs

Figure previously shows 7 membership functions for reusability output. The outputs are from 0 to 100 which each membership functions spaced equally from Not Recoverable as the lowest to Very High as the highest with Very Low, Low, Medium, Recoverable and High in between. The output result for each input is dependent on the configuration of if-then rules set by the user. The output for each input is determined with the consideration of material efficiency and energy efficiency (Gerrard & Kandlikar, 2007) by using the hierarchy pyramid.

3.3 Matlab Graphical User Interface (GUI)

The following fuzzy inference system is implemented into a graphical user interface using Matlab software to ensure user is capable to evaluate the components with ease.

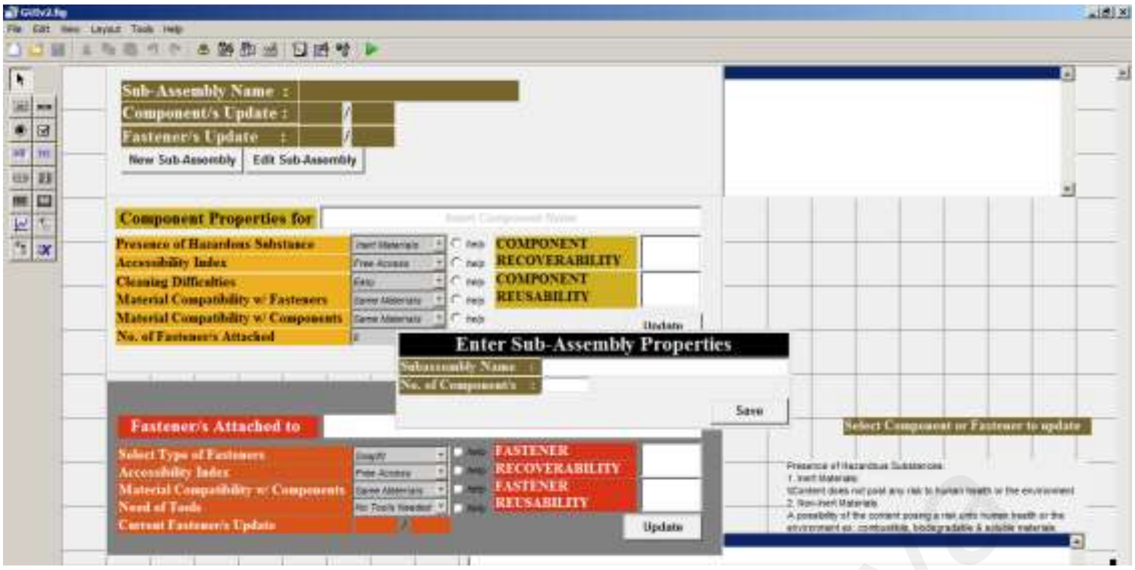


Figure 3:16: Figure above shows the Graphical User Interface where the panels and list-box are edited.

The figure previously shows the User Interface Panel where the coding and all the User Interface Panel is situated at a position where it is easy to use for the user.

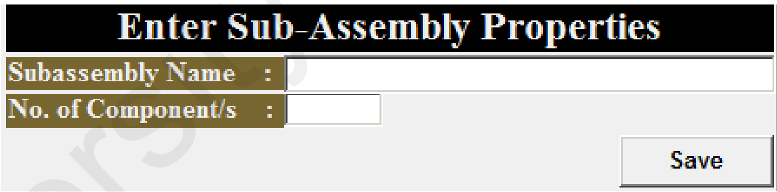


Figure 3:17: Figure above shows the Sub-assembly name and number of components in the sub-assembly.

The figure previously shows the User Interface Panel where the user has to key in the sub-assembly name and number of components in the sub-assembly into the white box prepared. The save button is then clicked to proceed to the next stage.

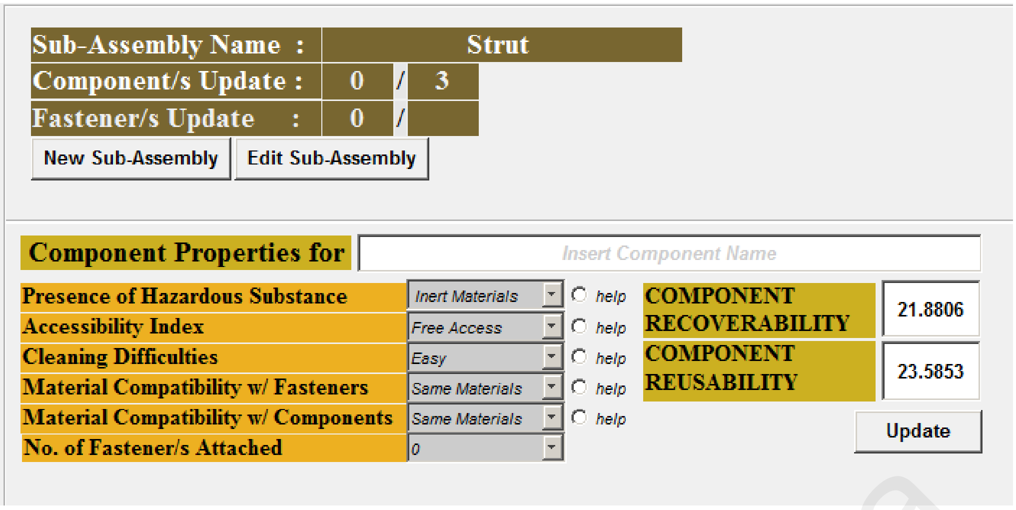


Figure 3:18: Figure above shows the inputs for the fuzzy inference system to calculate the recoverability and reusability value of Components.

The figure previously shows the inputs for each component. Each component will have different characteristics based on the factors discussed in the literature review. The user will select each input for the factors based on the component characteristics. The update button is selected by the user to proceed to the next stage once all the inputs for this particular component is completed.

Figure 3:19: Figure above shows the inputs for the fuzzy inference system to calculate the recoverability and reusability value of Fasteners for the particular component.

The figure previously shows the inputs for each fastener on the component that is attached to. Each fastener has different characteristics based on the factors discussed in the literature review. The user will select each input for the factors based on the fastener characteristics. The update button is selected by the user to proceed to the next stage once all the inputs for the fastener is completed. The user will then have to click on the select button to proceed to key in more inputs of other components or click New Sub-Assembly to calculate the overall sub-assembly recoverability and reusability once the user is done.

Sub-Assembly Description Recoverability Reusability

1. Strut (component) Absorber Mounting [21.8806] [23.5853]
2. Strut (Fastener) Screw / Nut&Bolt / Magnetic Attachment / Pin 44.1451 39.4168
3. Strut (Fastener) Screw / Nut&Bolt / Magnetic Attachment / Pin 44.1451 39.4168
4. Strut (component) Shock Absorber [21.8806] [23.5853]
5. Strut (Fastener) Screw / Nut&Bolt / Magnetic Attachment / Pin 44.1451 39.4168
6. Strut (component) Spring [21.8806] [23.5853]
Average value for Sub-Assembly (Strut) Recoverability=[2.475964e+01] Reusability=[2.362579e+01]

Figure 3:20: Figure above shows the list-box of components and fasteners for this particular sub-assembly

The figure above shows a list-box containing information of the components and fasteners. The information of the sub-assembly name, description, recoverability and reusability value of each individual component and fastener in the sub-assembly. The average recoverability and reusability of the entire sub-assembly is also included in the list box.

3.4 Summary

In this chapter, the design and modelling of the automotive evaluation complementary tool has been presented. The design embeds the fuzzy inference system in a GUI developed using Matlab development environment. Two fuzzy inference system were modelled mainly for components and fasteners that makes up each sub-assembly with some factors overlapping.

CHAPTER 4: CASE STUDY

4.1 Introduction

This chapter presents the experimental procedure and three case studies conducted to validate the developed model of automotive evaluation for end of life vehicles. The first case study evaluates the effectiveness of the proposed model. The second and third case study validates the proposed model against previous work done by other researches. s

4.2 Experimental Procedure

The first step of procedure to conduct the case study is to disassemble each sub-assembly of the car door. The car door assembly is disassembled at one sub-assembly at a time to reduce confusion. The second step will be having the disassembled sub-assembly identified based on the functionality of the sub-assembly in the assembly of the car door. The third step is to tighten the fastener on the current sub-assembly. These first three steps are conducted simultaneously to avoid mismanagement of sub-assemblies, components and fasteners.

The fourth step of the procedure requires the user to determine the inputs required by different models used to determine the recoverability & reusability of each component, fasteners and sub-assemblies. The fifth step of the procedure is to record the data output of each components and fasteners in each sub-assembly. The sixth step is to record the average value of the output of recoverability and reusability of each sub-assembly into a table where the highest recoverability and lowest reusability value of each sub-assembly are stated clearly.

The inputs of each factors are laid out in the Graphical User Interface for the user to input the data for each components and fasteners for each sub-assembly. This provides a more detailed data for different factors for each components and fasteners displayed in the Graphical User Interface.

4.3 Automotive Evaluation Complementary Tool for Recoverability and Reusability

A case study was done on a real car door with missing parts involved. The case study is focused on different sub-assemblies with different components.

Figure 4:1: Figure above shows a sub-assembly of an Interior Door Handle sub-assembly.

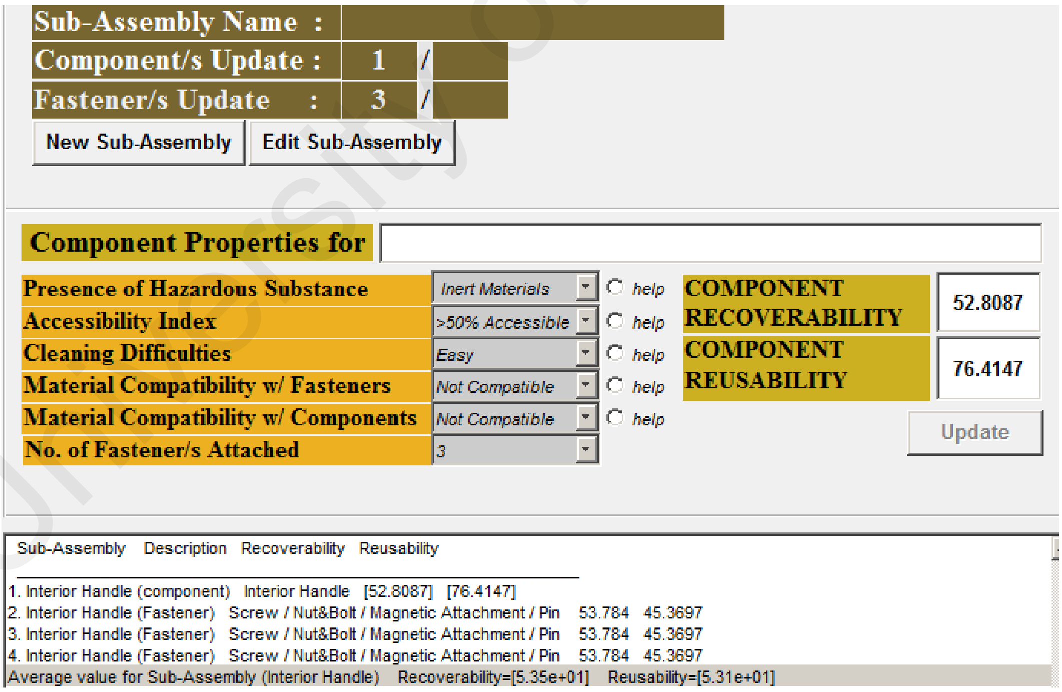


Figure 4:2: Figure above shows the recoverability and reusability value of the sub-assembly of interior door handle.

Figure 4:3: Figure above shows the Interior Plastic Trim subassembly.

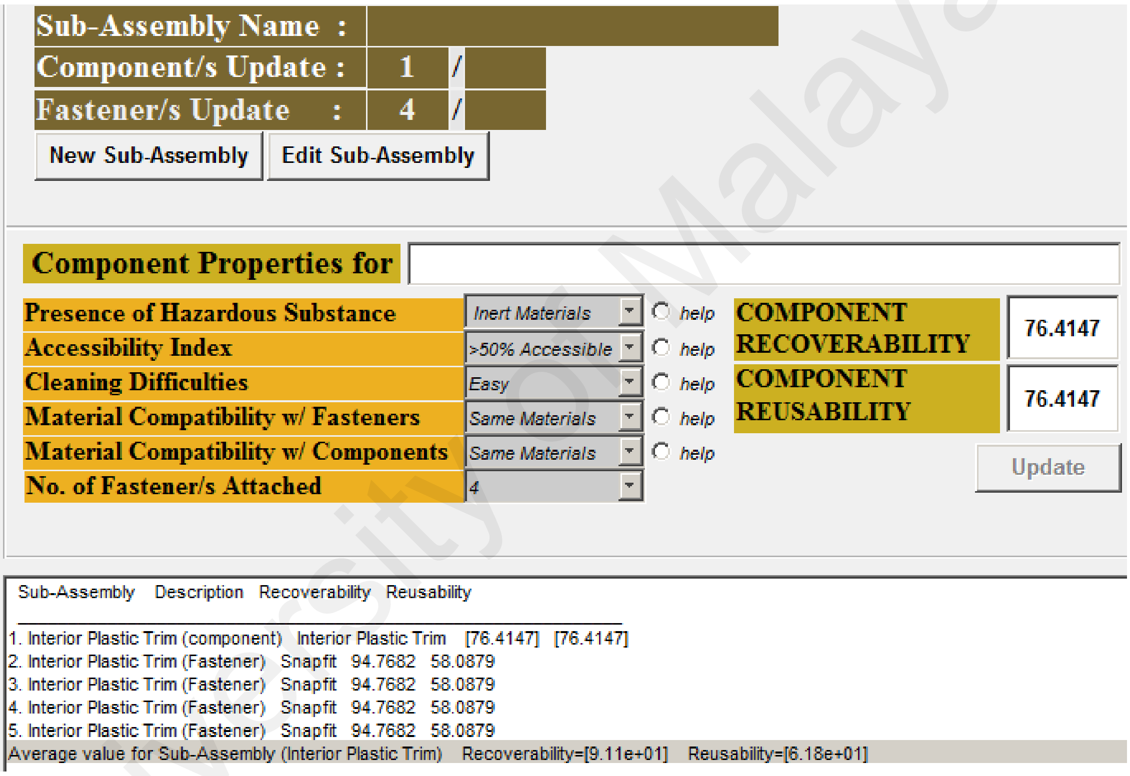


Figure 4:4: Figure above shows the recoverability and reusability value of the sub-assembly of Interior Plastic Trim.

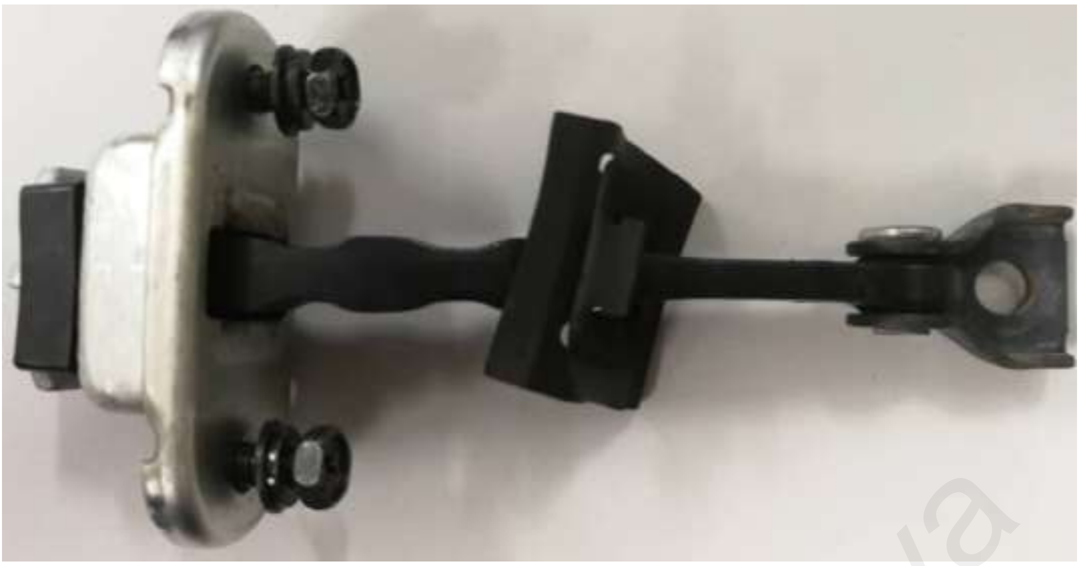


Figure 4:5: Figure above shows the Sliding Door Hinge subassembly.

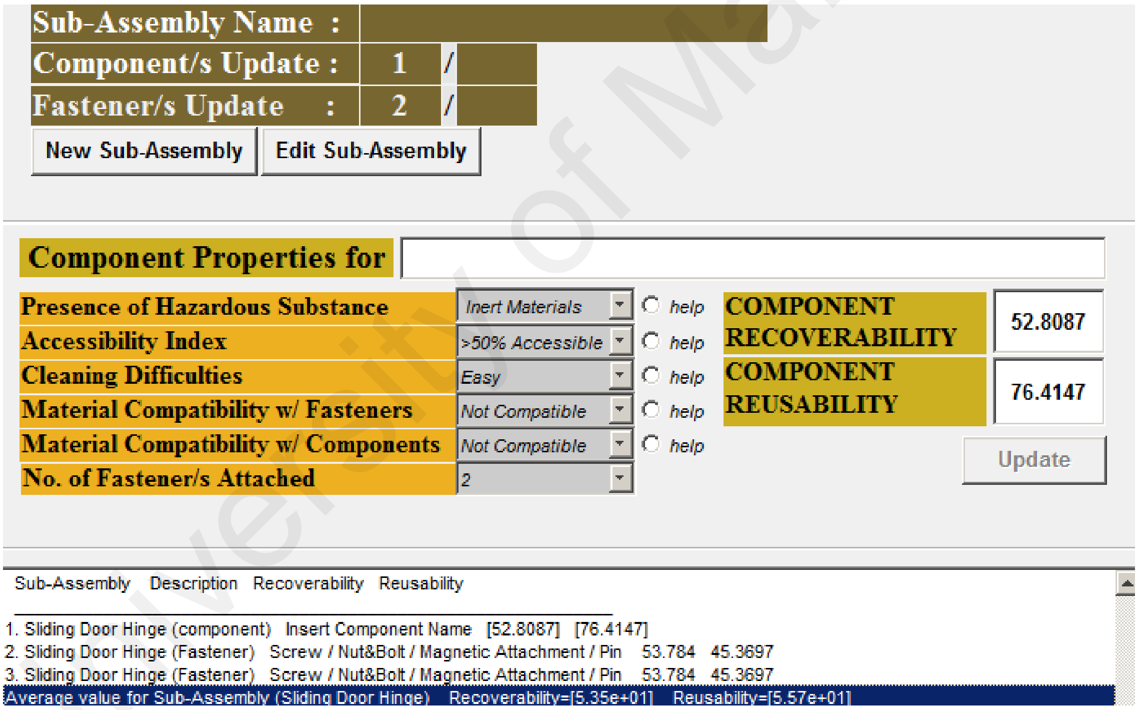


Figure 4:6: Figure above shows the recoverability and reusability value of the sub-assembly for Sliding Door Hinge.

Figure 4:7: Figure above shows the Side Mirror Wiring subassembly.

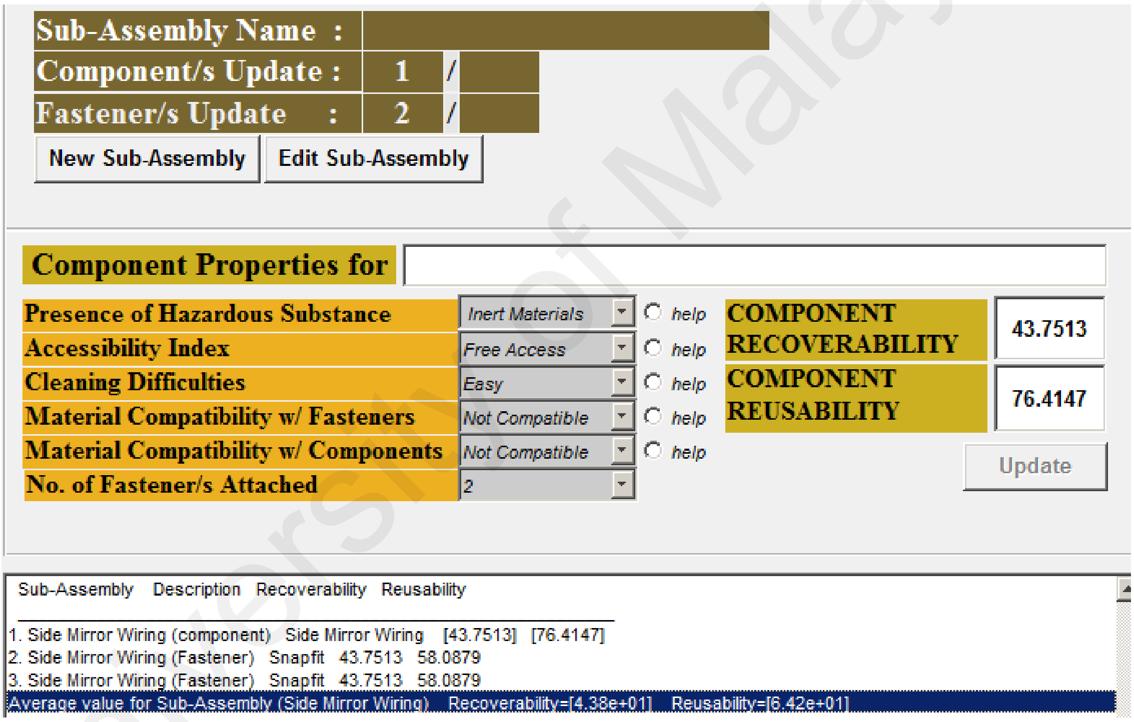


Figure 4:8: Figure above shows the recoverability and reusability value of the sub-assembly of Side Window Wiring.

Figure 4:9: Figure above shows the Car Door Side Foam subassembly.

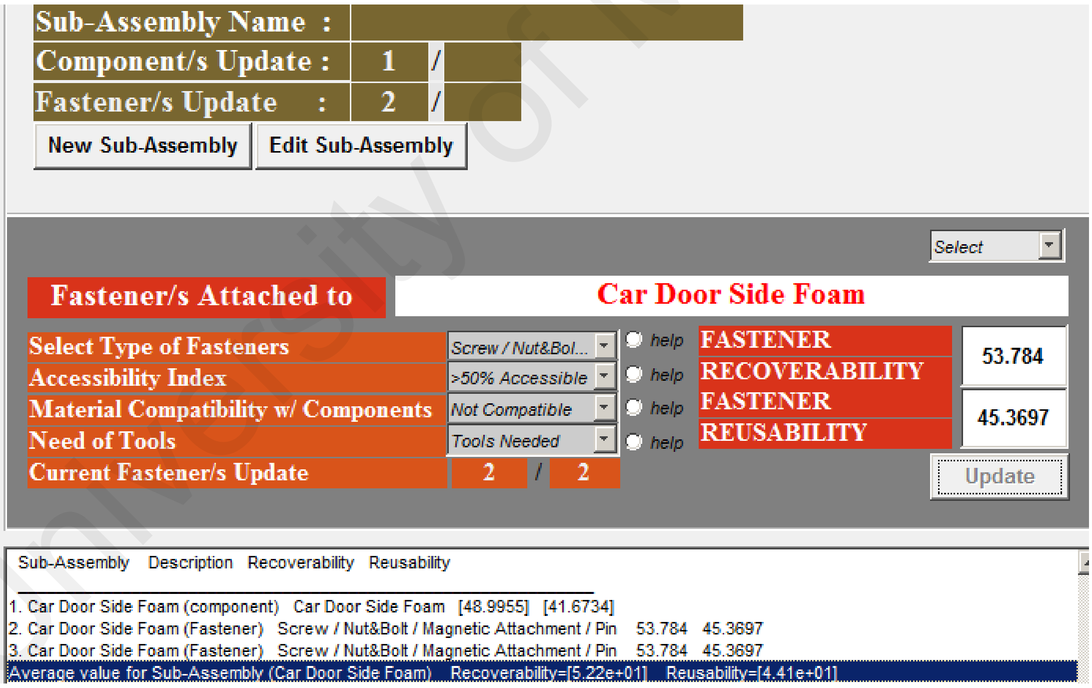


Figure 4:10: Figure above shows the recoverability and reusability value of the sub-assembly for Car Side Door Foam.

Figure 4:11: Figure above shows the Window Outer Door Trim subassembly.

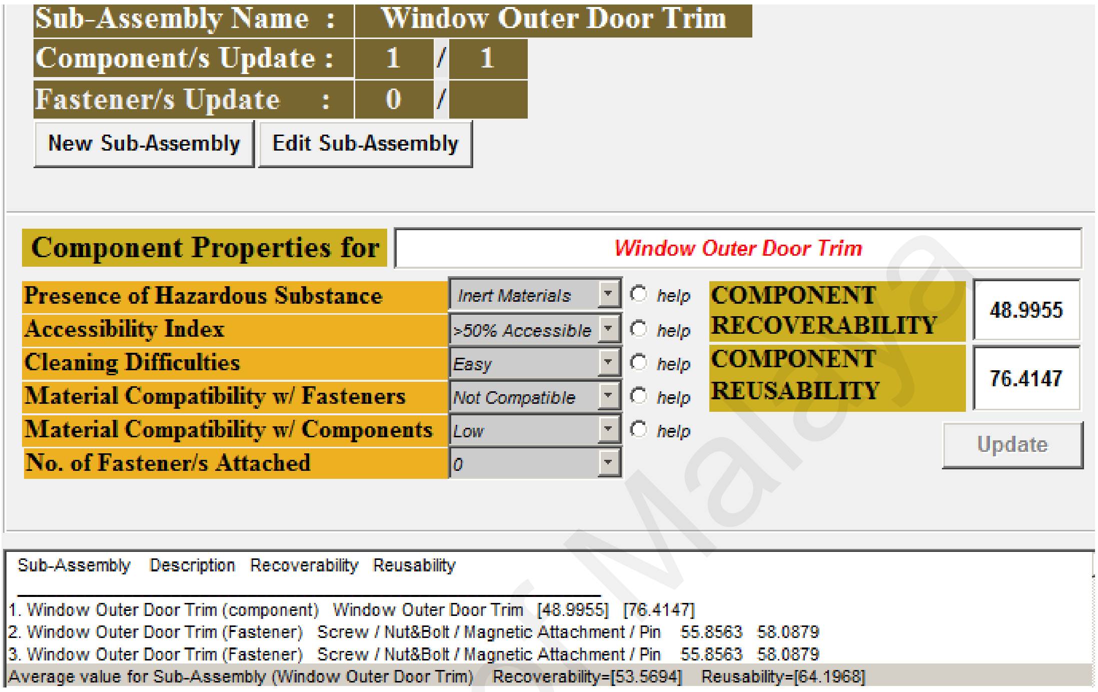


Figure 4:12: Figure above shows the recoverability and reusability value of the sub-assembly of Window Outer Door Trim.

Figure 4:13: Figure above shows the Window Inner Door Trim subassembly.

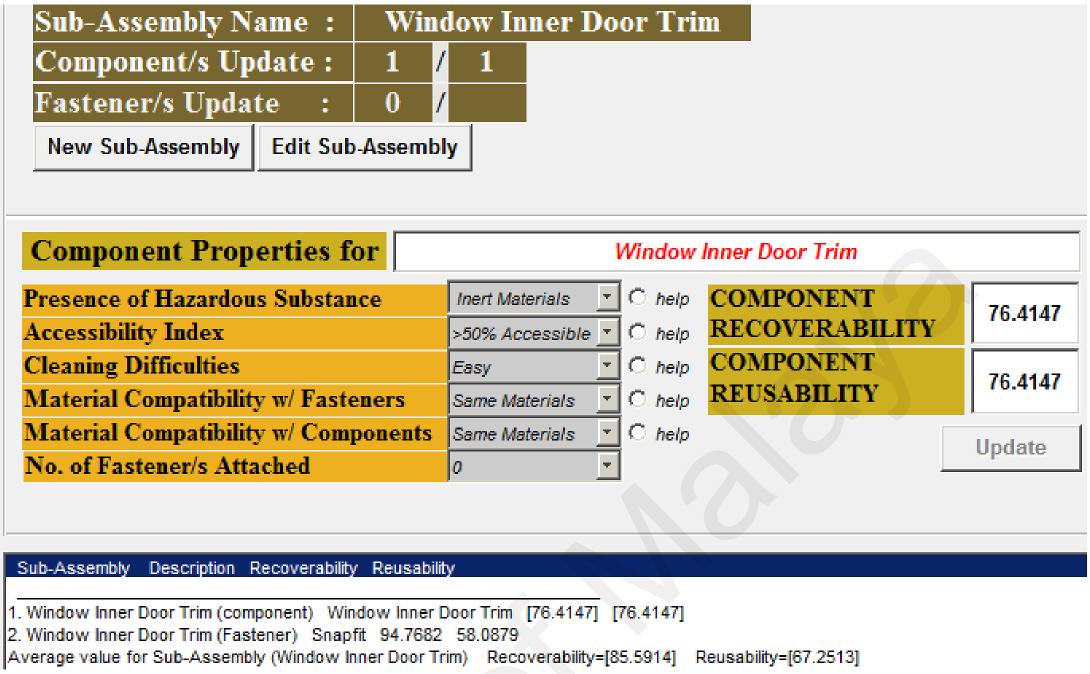


Figure 4:14: Figure above shows the recoverability and reusability value of the sub-assembly of Window Inner Door Trim.

Figure 4:15: Figure above shows the Interior Main Panel subassembly.

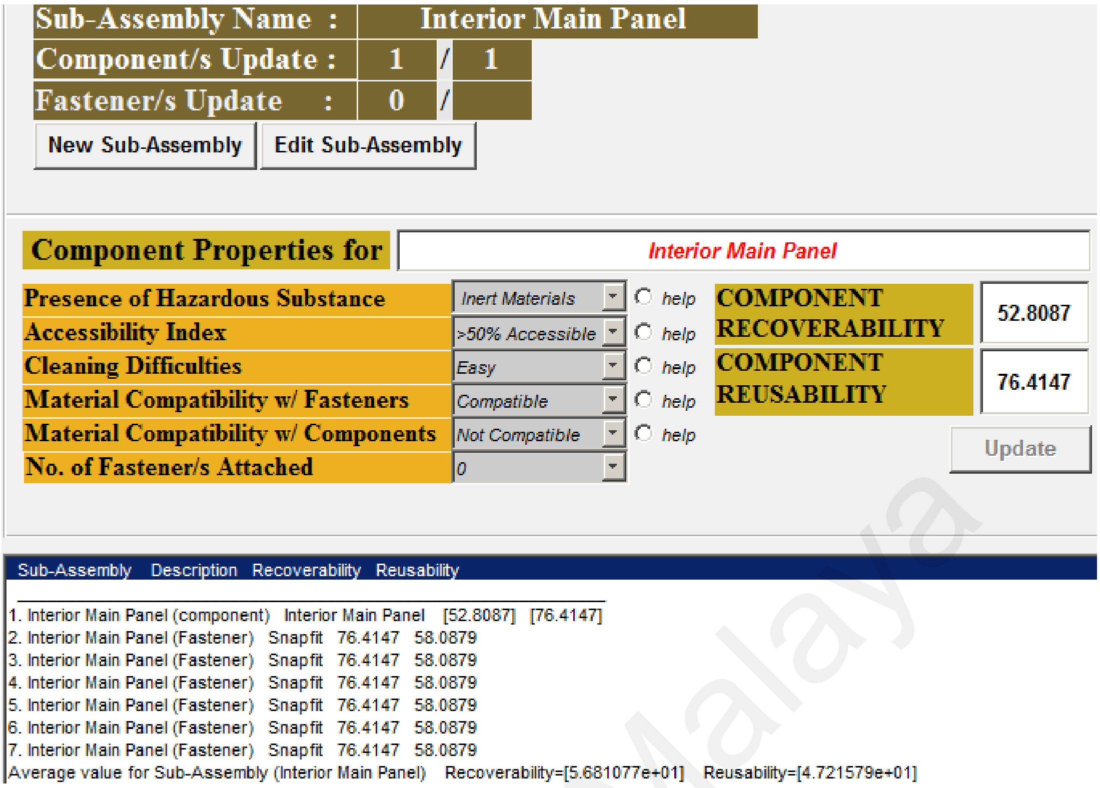


Figure 4:16: Figure above shows the recoverability and reusability value of the sub-assembly of Interior Main Panel.

Figure 4:17: Figure above shows the Main Door Wiring subassembly.

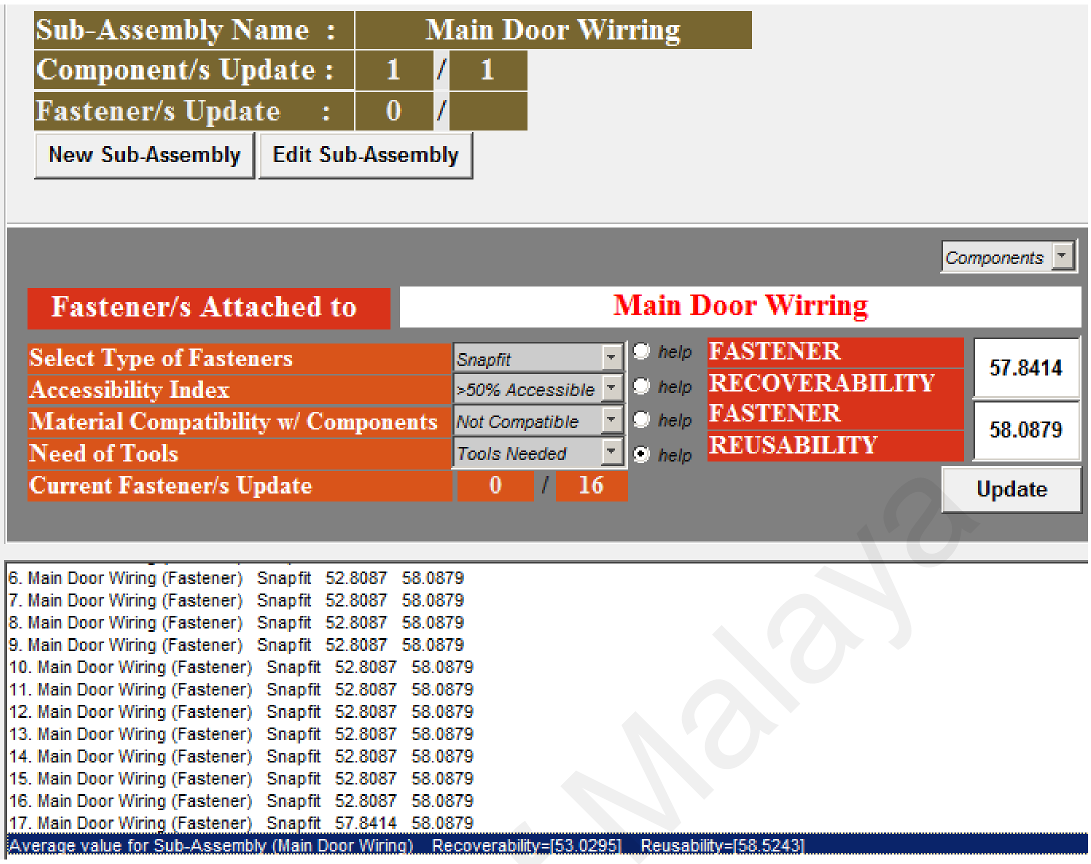


Figure 4:18: Figure above shows the recoverability and reusability value of the sub-assembly of Main Door Wiring.

Figure 4:19: Figure above shows the Window Motor Mechanism subassembly.

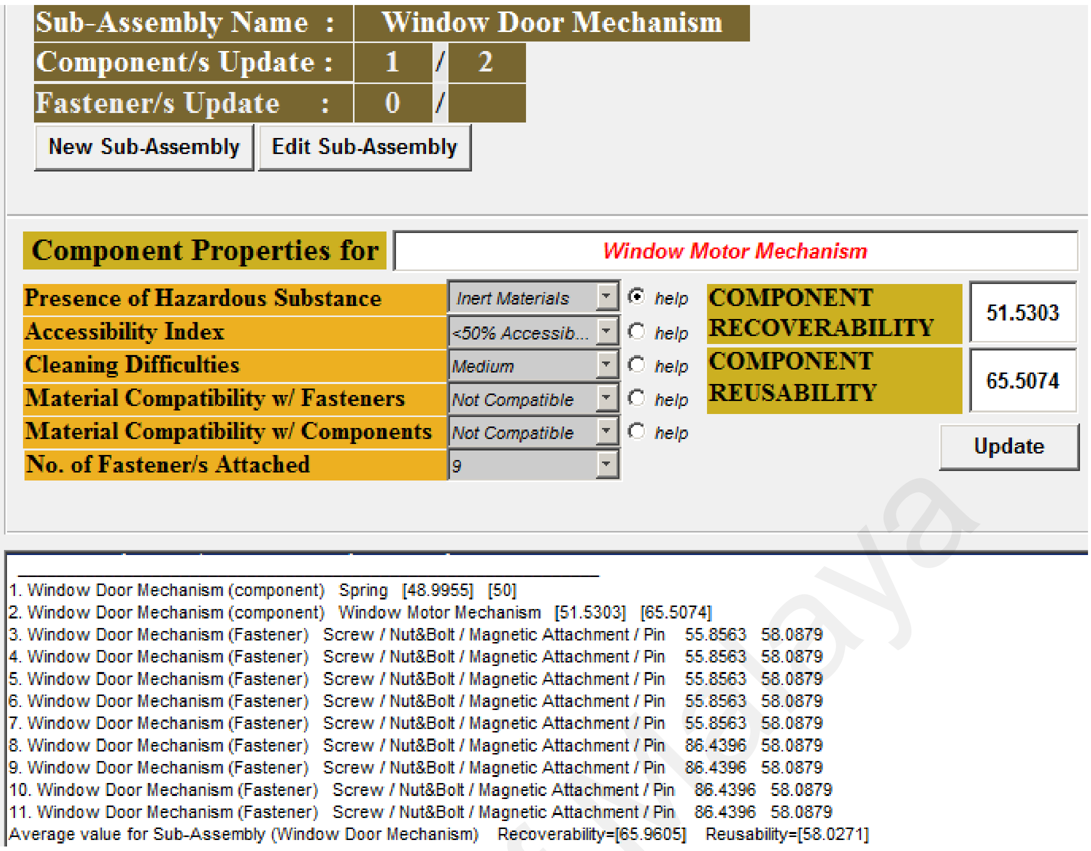


Figure 4:20: Figure above shows the recoverability and reusability value of the sub-assembly of Window Motor Mechanism.

Figure 4:21: Figure above shows the Window Motor subassembly.

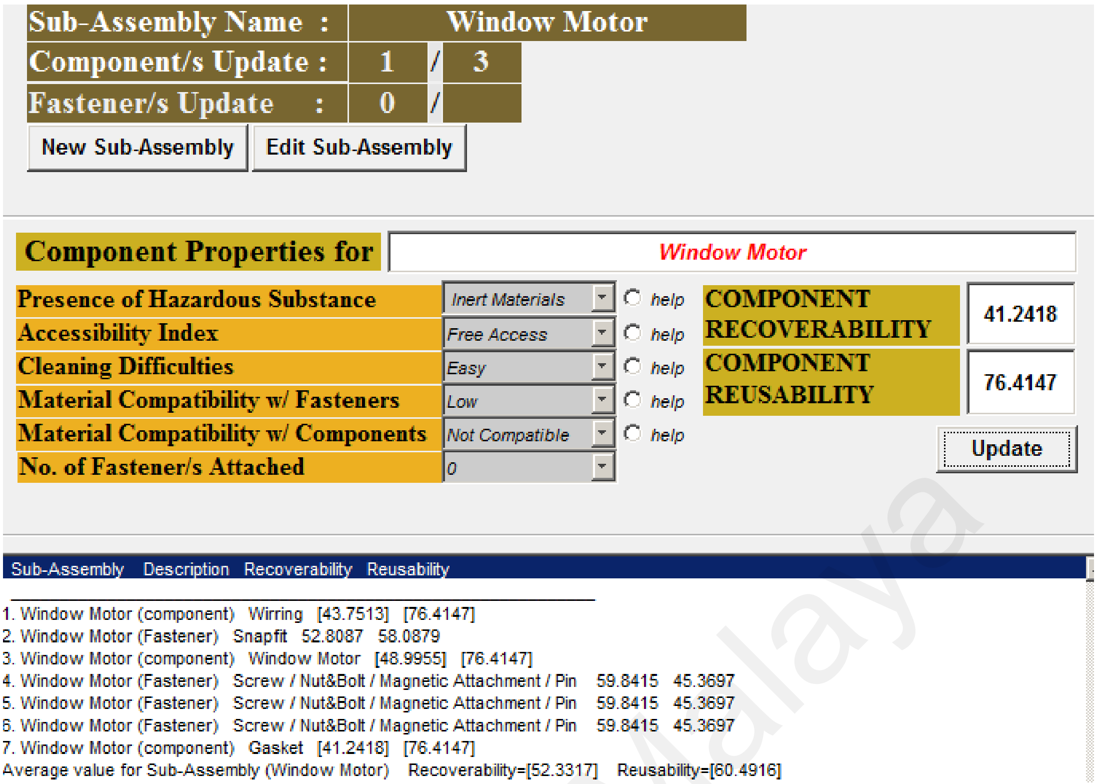


Figure 4:22: Figure above shows the recoverability and reusability value of the sub-assembly of Window Motor.

Figure 4:23: Figure above shows the Door Lock Mechanism subassembly.

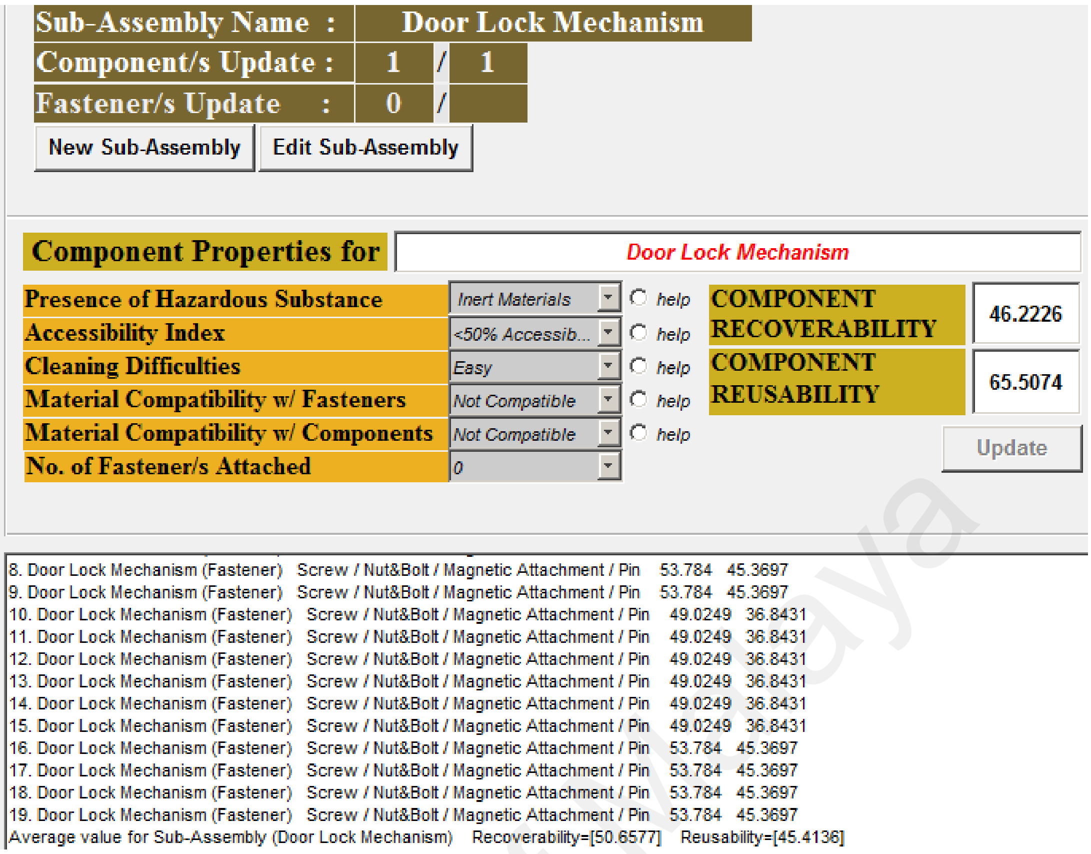


Figure 4:24: Figure above shows the recoverability and reusability value of the sub-assembly of Door Lock Mechanism.

Figure 4:25: Figure above shows the Outer Door Handle Mechanism subassembly.

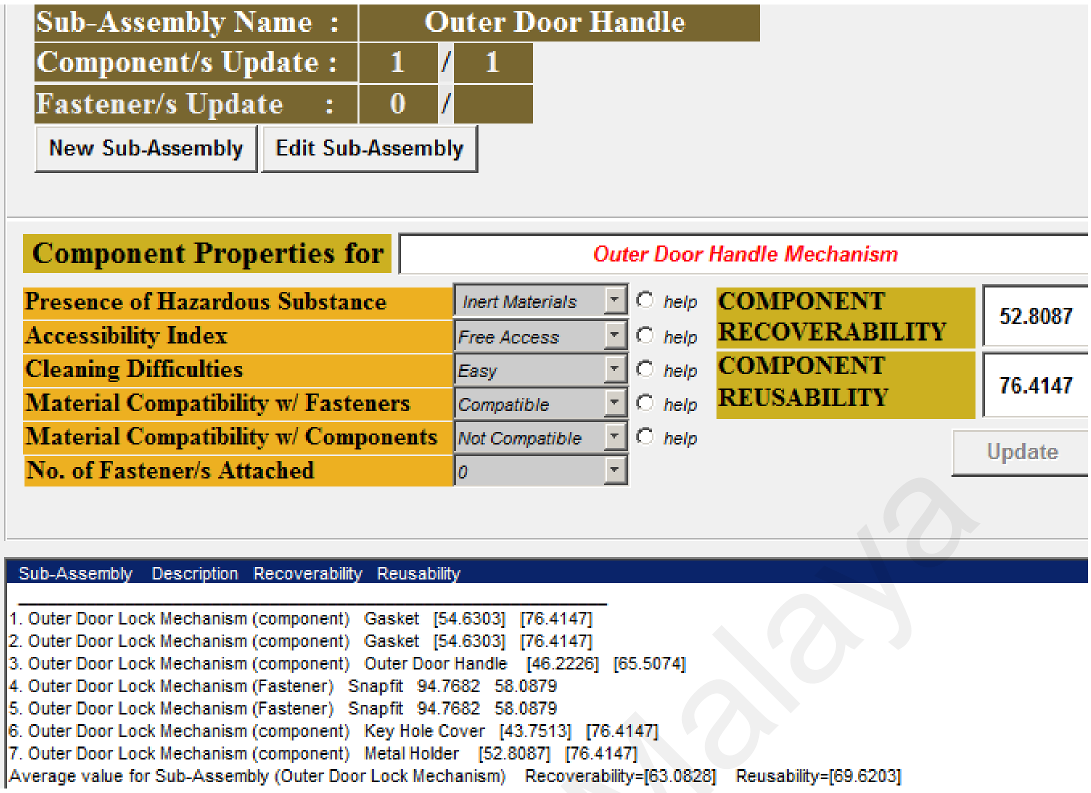


Figure 4:26: Figure above shows the recoverability and reusability value of the sub-assembly of Outer Door Handle Mechanism.

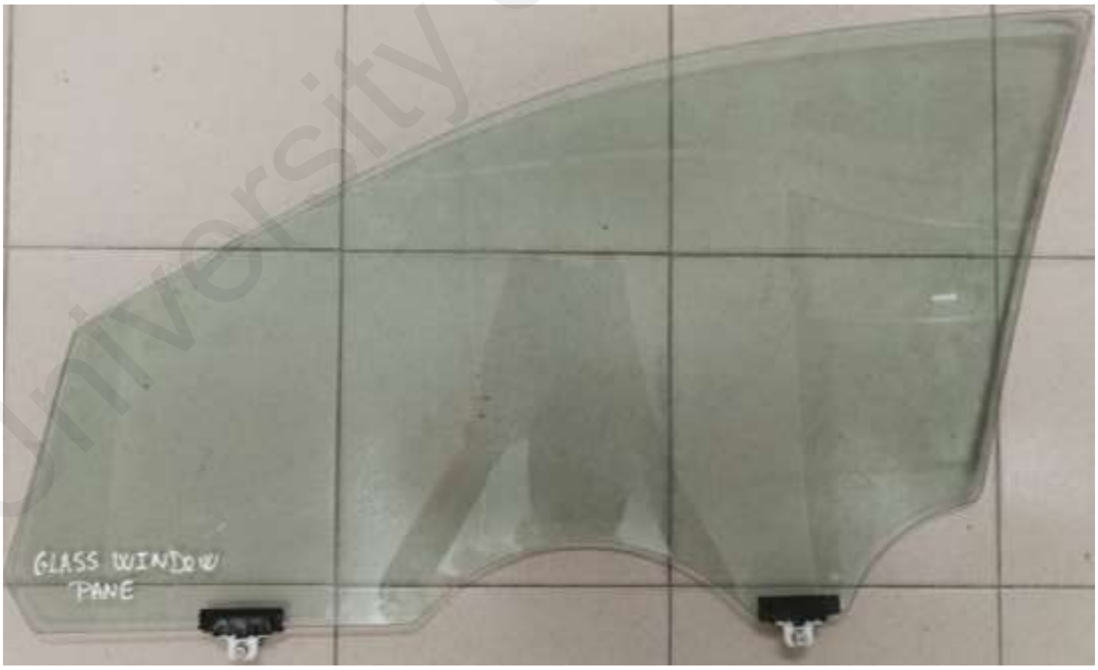


Figure 4:27: Figure above shows the Glass Window Pane subassembly.

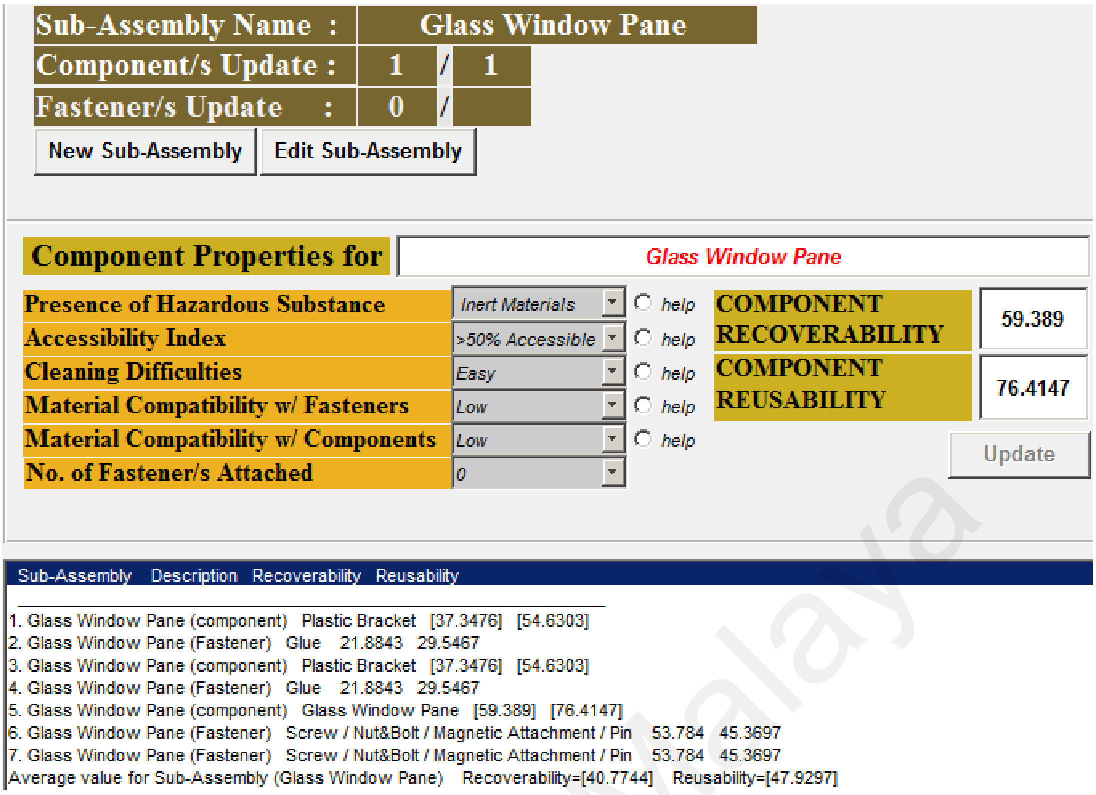


Figure 4:28: Figure above shows the recoverability and reusability value of the sub-assembly of Glass Window Pane.

Figure 4:29: Figure above shows the Glass Window Slider subassembly.

Figure 4:30: Figure above shows the recoverability and reusability value of the sub-assembly of Glass Window Slider.

Figure 4:31: Figure above shows the Glass Window Rubber Seal component.

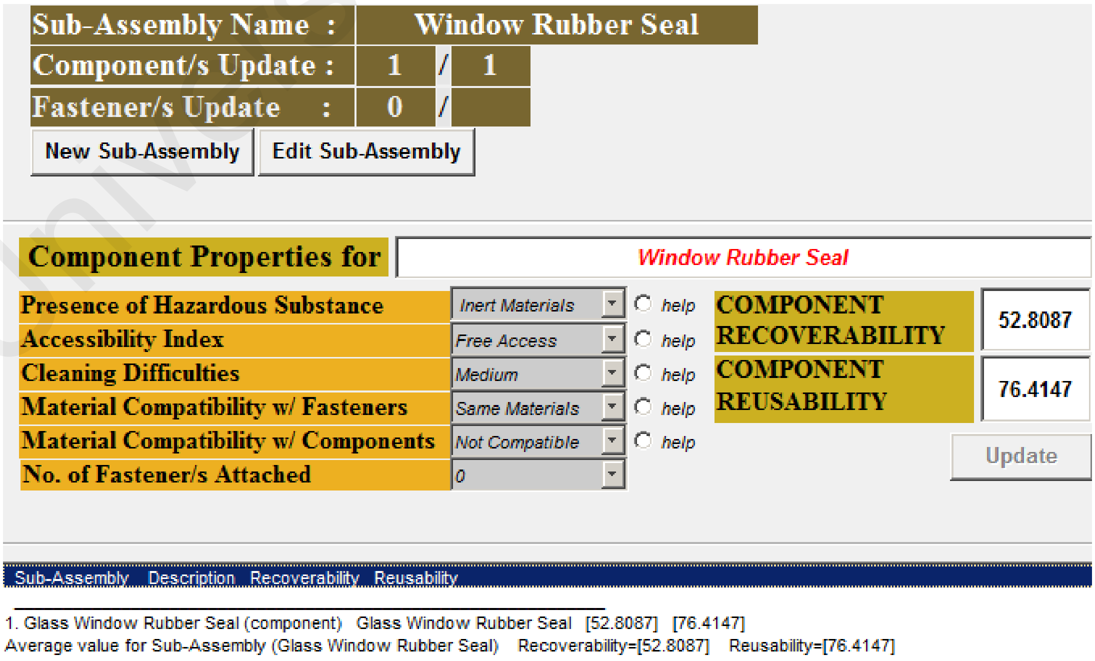


Figure 4:32: Figure above shows the recoverability and reusability value of the sub-assembly of Glass Window Rubber Seal.

Figure 4:33: Figure above shows the Door Rubber Seal component.

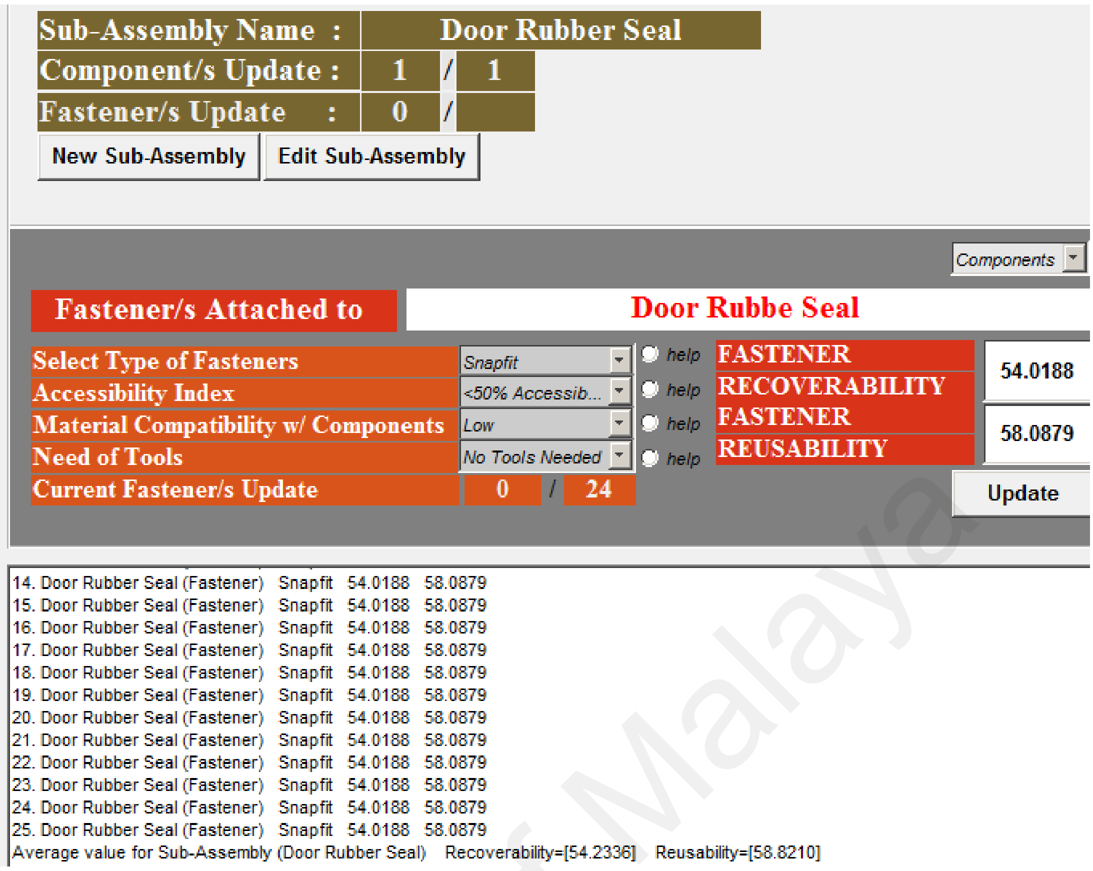


Figure 4:34: Figure above shows the recoverability and reusability value of the sub-assembly of Door Rubber Seal.

Figure 4:35: Figure above shows the Interior Plastic Seal component.

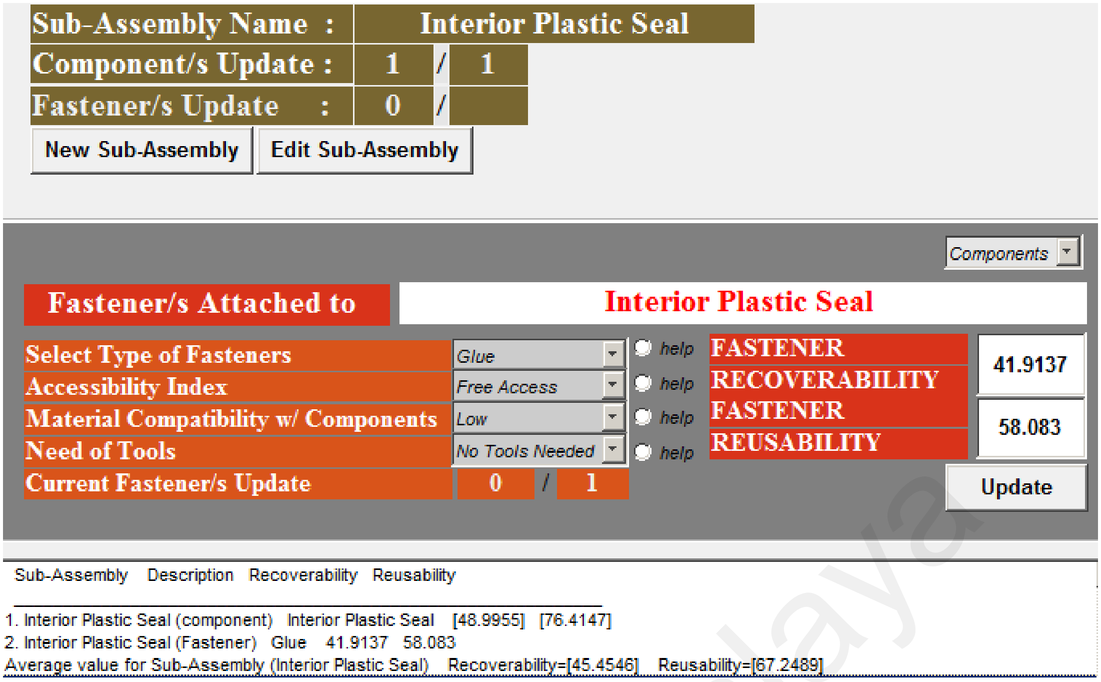


Figure 4:36: Figure above shows the recoverability and reusability value of the sub-assembly of Interior Plastic Seal.

Figure 4:37: Figure above shows the Car Door sub-assembly.

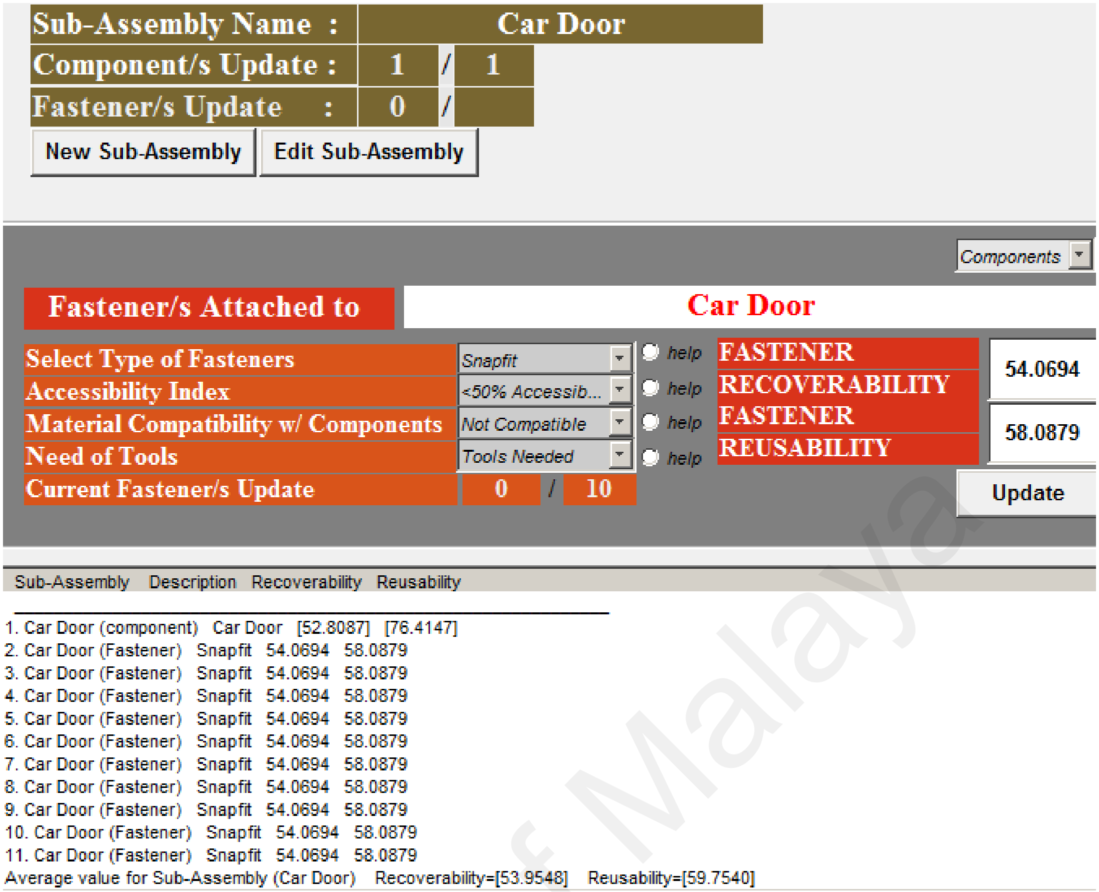


Figure 4:38: Figure above shows the recoverability and reusability value of the sub-assembly of Car Door.

Table 4:1: Table below summarizes the recoverability and reusability of each sub-assembly taken previously.

Sub-Assemblies	Recoverability Value	Reusability Value
Interior Handle	53.5	53.1
Interior Plastic Trim	91.1	61.8
Sliding Door Hinge	53.5	55.7
Side Mirror Wiring	43.8	64.2
Car Door Side Foam	52.2	44.1
Window Outer Door Trim	53.6	64.2
Window Inner Door Trim	85.6	67.3
Interior Main Panel	56.8	47.2
Main Door Wiring	53.0	58.5
Window Motor Mechanism	66.0	58.0
Window Motor	52.3	60.5
Door Lock Mechanism	50.6	45.4
Outer Door Handle Mechanism	63.1	69.6
Glass Window Pane	40.8	47.9
Glass Window Slider	83.1	64.2
Window Rubber Seal	52.8	76.4
Door Rubber Seal	54.2	58.8
Interior Plastic Seal	45.5	67.2
Car Door	54.0	59.8
Average Value	**56.4**	**57.8**

4.4 A design tool to diagnose product recyclability during product design phase by (de Aguiar et al., 2017)

A case study was done on the same car door with the same components and fasteners using a different technique by the authors (de Aguiar et al., 2017). Abbreviations were used by the author to simplify the findings into an organized table

.

Table 4:2: Table below shows the abbreviation to understand the work of (de Aguiar et al., 2017).

Abbreviations	**Full Form**
QFI	Quantity of Fastener's Index
%FI	Percentage of Fasteners' Index
QFTI	Quantity of Types of Fasteners Index
TFI	Type of Fastener index
AI	Accessibility Index
II	Infrastructure Index
MCI	Material Compatibility Index
MGI	Material Group Index
Eol CI	End-of-Life Contamination Index

The total number of fasteners in the entire assembly of the car door was counted to be 112 in total. This value is needed for the %FI = % of fastener index where %FI=$\frac{number\ of\ fasteners\ attached\ to\ part}{total\ of\ fasteners\ in\ the\ product}$. The numbers and colors represent the different hierarchy of value for each factors involved. The hierarchy is as follows from 1 being the most desired to 4 being the least desired which corresponds to the color as well from dark green being the most desired to dark red being the least desired.

Table 4:3: Table below shows the analyses of data for each sub-assembly using the design tool by (de Aguiar et al., 2017).

Sub-assembly	Fasteners			Disassembly Indexes				Material Indexes			
	Access	Type	QFI	%FI	QFTI	TFI	AI	II	MCI	MGI	EoI CI
Interior Handle	100%	Screw	3	2.68%	1	1.60	2	3	4	1	4
Interior Plastic Trim	90%	Snap Fit	4	3.57%	1	1.07	1	3	1	1	4
Sliding Door Hinge	100%	Screw	2	1.79%	1	1.60	2	3	4	1	1
Side Mirror Wiring	80%	Snap Fit	3	2.68%	1	1.07	3	3	4	1	1
Car Door Side Foam	100%	Screw	2	1.79%	1	1.60	2	1	4	2	4
Window Outer Door Trim	100%	Screw	2	1.79%	1	1.60	1	3	4	2	1
Window Inner Door Trim	100%	Snap Fit	1	0.89%	1	1.07	1	2	3	2	1
Interior Main Panel	50%	Snap Fit	6	5.36%	1	1.07	2	3	3	2	1
Main Door Wiring	80%	Snap Fit	16	14.29%	1	1.07	3	3	4	1	1
Window Motor Mech.	80%	Screw	9	8.04%	1	1.60	3	3	4	2	1
Window Motor	100%	Screw	3	2.68%	1	1.60	2	3	4	1	1
Door Lock Mechanism	60%	Screw	17	15.18%	2	1.60	3	3	4	1	1
		Snap Fit	1	0.89%		1.07					
Outer Door Handle Mech.	70%	Snap Fit	1	0.89%	1	1.07	2	3	4	2	4
Glass Window Pane	70%	Screw	2	1.79%	2	1.60	3	3	4	1	4
	0%	Glue	2	1.79%		2.93	4				
Glass Window Slider	100%	Screw	2	1.79%	1	1.60	2	1	1	2	4
Window Rubber Seal	70%	Snap Fit	1	0.89%	1	1.07	2	1	4	2	1
Door Rubber Seal	60%	Snap Fit	24	21.43%	1	1.07	2	2	3	2	1
Interior Plastic Seal	90%	Glue	1	0.89%	1	2.93	2	1	3	2	4
Car Door	80%	Snap Fit	10	8.93%	1	1.07	1	1	4	2	4

Table 4:4: Table below shows the average value of each component summarized from the table previously.

Sub-Assembly	Average Value
Interior Handle	44.4880
Interior Plastic Trim	43.0899
Sliding Door Hinge	24.3440
Side Mirror Wiring	37.7076
Car Door Side Foam	27.9240
Window Outer Door Trim	24.3440
Window Inner Door Trim	9.8523
Interior Main Panel	70.0552
Main Door Wiring	201.0603
Window Motor Mech.	125.4240
Window Motor	36.4480
Door Lock Mechanism	267.8869
Outer Door Handle Mech.	15.1923
Glass Window Pane	78.8674
Glass Window Slider	22.5540
Window Rubber Seal	10.7423
Door Rubber Seal	237.2301
Interior Plastic Seal	14.1777
Car Door	125.6451

4.5 Analysis of Product Disassemblability Using The Disassembly Evaluation Chart Methodology by (Fatmawati, 2007).

A case study was done on the same car door with the same components and fasteners using another technique by the authors (Fatmawati, 2007). The method used is quantitative method where all the factors involving the difficulty of disassembling each sub-assembly of the product. The factors used are quantified into the estimation time for disassembly.

Table 4:5: Table below shows the Disassembly Evaluation Chart Method to evaluate the existing car door assembly.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
					Difficulty Rating 1(EASY) to 10(HARD)										
Part Name/ sub-assemblies	Quantity	Task Type	No. of Task Repetitions	Required Tool	Accessibility	Positioning	Force	Base Time	Special	Sub Total	Total (column 11 x column 4)	No. of Tools Manipulation	No. of Hand Manipulation	Estimation Time (Sec) (C12 – 5 x C4) x 1.04 + (no. Of tools & hand manipulation) x 0.9	Total Estimation Time for Sub-Assembly
Interior Handle	1	Pull	1		2	1	1	4	1	9	9		2	5.96	22.56
Screw 10mm	3	Unscrew	3	Screw driver	1	1	2	5	1	10	30	1		16.6	
Interior Plastic Trim	1	Pull	1		3	1	4	5	1	14	14		1	10.26	107.94
Snap Fit Fastener	4	Pry	4	Screw Driver	6	3	3	13	3	28	112	2		97.68	
Sliding Door Hinge	1	Pull	1		3	3	1	5	1	13	13		1	8.7	35.3
Screw 10 mm	2	Unscrew	2	Screw Driver	3	3	2	9	1	18	36	1		26.6	

Side Mirror Wiring	1	Push & Pull	1		2	2	2	2	1	9	9		2	5.6	5.6
Car Door Side Foam	1	Pull	1		1	1	1	2	1	6	6		1	1.7	14.3
Screw Fastener	2	Unscrew	2	Screw Driver	1	2	2	5	1	11	22	1		12.6	
Window Outer DoorTrim	1	Pull	1		1	1	2	4	1	9	9		1	4.7	39.3
Screw Fastener	2	Unscrew	2	Screw Driver	1	3	2	15	1	22	44	1		34.6	
Window Inner Door Trim	1	Pull	1		1	1	1	3	1	7	7		1	2.7	2.7
Interior Main Panel	1	Pull	1		2	3	3	10	1	19	19		1	14.7	20.4
Snap Fit Fastener	6	Slide & Pull	6		1	1	1	2	1	6	36		1	5.7	
Main Door Wiring	1	Push & Pull	1		3	2	7	58	2	72	72		2	68.6	161.3
Snap Fit	10	Press & Push	10		1	1	2	5	1	10	100		1	48.9	
Electrical Connector	4	Push and Pull	4		1	2	3	3	1	10	40		1	20.1	
Electrical Connector	1	Pry & Pull	1	Screw Driver	4	5	2	13	3	27	27	1	1	23.7	

Window Motor Mech.	1	Lower & Pull	1		5	3	3	20	1	32	32		1	27.7	90.1
Screw	6	Unscrew	6	Socket	1	2	2	5	1	11	66	1		35.8	
Nut	2	Unscrew	2	Socket	3	3	3	8	1	18	36	1		26.6	
Window Motor	1				1	1	1	3	1	7	7		1	7.9	30.3
Screws	3	Unscrew	3	Impact Drill	1	1	1	8	1	12	36	2		22.4	
Door Lock Mechanism	1	Lower & Pull	1		2	3	1	6	1	13	13			7.8	38.8
Screws	3	Unscrew	3	Impact Drill	1	1	1	5	1	9	27			11.4	
Screws	2	Unscrew	2	Screw Driver	1	2	2	9	1	15	30			19.6	
Outer Door Handle Mechanism	1	Slide & Pull	1		5	4	5	17	1	32	32		2	28.6	28.6
Glass Window Pane	1	Push & Pull	1		1	2	2	5	1	11	11		2	7.6	7.6
Glass Window Slider	1	Pry, Lower & Pull			5	3	3	18	2	31	31		3	33.7	72.3
Screws	2	Unscrew	2	Socket	1	2	4	16	1	24	48	1		38.6	

Window Rubber Seal	1	Pry & Pull	1		1	3	3	13	1	21	21		2	17.6	17.6
Door Rubber Seal	1	Pull Left & Right	24		5	5	2	5	1	18	432		3	309.9	1026.1
Snap Fit Fastener	24	Pull	24	Pliers	3	1	6	24	1	35	840	1		716.2	
Interior Plastic Seal	1	Pull	1		1	1	3	2	1	8	8		1	3.7	3.7

The shortest estimation time to disassemble the sub-assembly is the Window Inner Door Trim whereas the longest estimation time to disassemble the sub-assembly is the Door Rubber Seal along with the 24 snap fit fasteners involved.

CHAPTER 5: DISCUSSION

5.1 Results obtained from Automotive Evaluation Complementary Tool for Recoverability and Reusability

The Graphical User Interface used in this model helped to speed up the process for evaluating different components and sub-assemblies in the product. The Graphical User Interface connected to the Fuzzy Inference System proved to be user friendly and straight forward when evaluating the components involved.

5.1.1 Highest Recoverability: Interior Plastic Trim sub-assembly

The Interior Plastic Trim sub-assembly shows the highest recoverability value of 91.1/100. This is due to the certain factors found from the fasteners and the component sub-assembly of the Interior Plastic Trim sub-assembly.

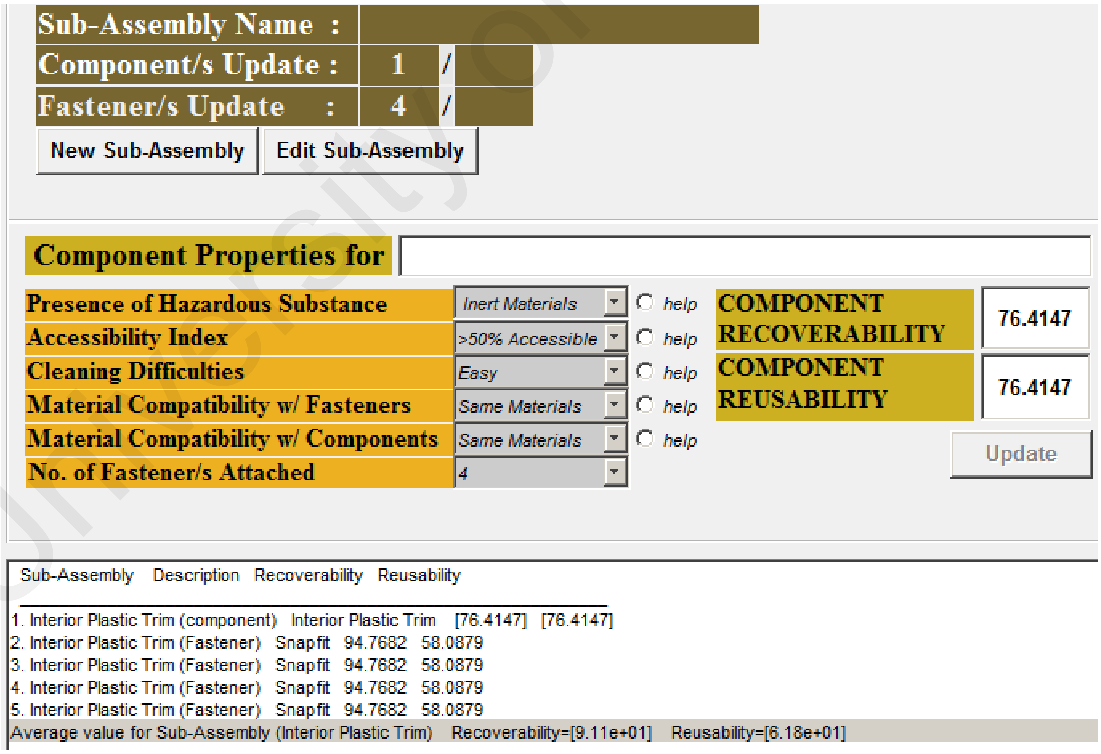


Figure 5:1: Figure above shows the input for different factors in the sub-assembly for Interior Plastic Trim.

The figure above shows the different input for each factors involved for the Interior Plastic Trim component. The plastic trim is an inert material where the materials do not post any risk to human health or the environment. This will lead to safer handling during the recoverability or recycling of components hence lessens the cost and time needed to disassembled this particular component. The Accessibility Index is rated >50% accessible instead of Free Access since some force was needed to pry open the interior plastic panel component with ease. The fasteners of this component has the same material with the component leading to ease of sorting during disassembly for recovery, recycling or reuse. The material compatibility with other components is set to same material since this sub-assembly only consist of the Interior Plastic Trim itself and all the other fasteners involved. The Interior Plastic Trim component scored a recoverability and reusability value of 76.41.

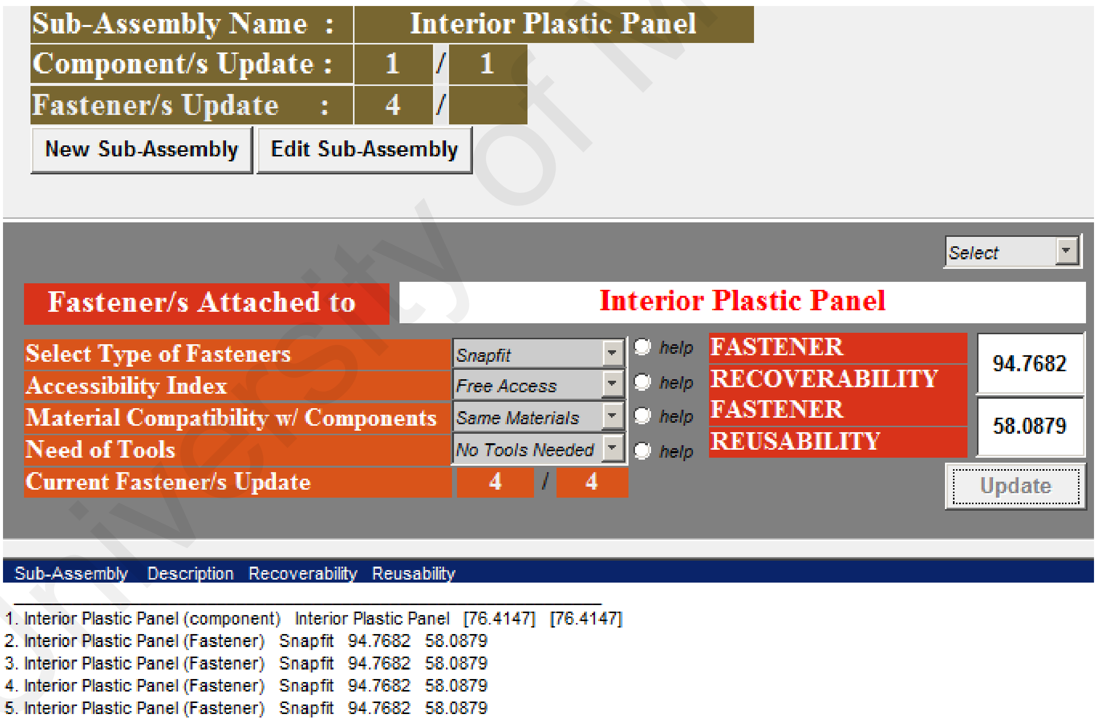


Figure 5:2: Figure above shows the input for each factors of the fasteners for the Interior Plastic Trim sub-assembly.

The figure above shows the 4 fasteners involved in attaching the Interior Plastic Panel Sub-assembly to the car door. The 4 fasteners involved are snap-fit fasteners. These snap-fit fastener based on (de Aguiar et al., 2017) has the highest value with as fastener’s index of 1.07 compared to other fasteners involved. The accessibility index for these fasteners are considered accessible since the interior plastic panel component is easy to detach from the Interior Main Panel sub-assembly. These fasteners are the same materials as the component itself which makes the sorting process easier for recovery, recycling or reuse. No tools were needed to detach the component from the Interior Main Panel sub-assembly. All the fasteners for this sub-assembly cored and average value of 94.77 for recoverability and 58.09 for reusability.

This particular sub-assembly for the Interior Plastic Panel scored a value of 91.10 recoverability value and 61.80 reusability value. This is highly due to the fasteners with high recoverability and middle range reusability value. The component for Interior Plastic Panel sub-assembly scored a recoverability and reusability value of 76.41 is due to the accessibility index of the component of >50% accessible. The Interior Plastic Panel cannot be rated as Free Access in the accessibility index because there is only one side to to open and detach the Interior Plastic Panel component connected to the Interior Main Panel which is the most left side shown in the figure below.

Figure 5:3: Figure above shows the Interior Plastic Panel sub-assembly connected to the Interior Main Panel sub-assembly.

The figure above shows the only access point for the Interior Plastic Panel sub-assembly to be detached from the Interior Main Panel sub-assembly. Free Access cannot be selected for the input for accessibility index the Interior Plastic Panel sub-assembly since the Interior Plastic Panel sub-assembly can only be detach accessibly from the red arrows in the figure shown previously. This was the cause for this particular sub-assembly from achieving its fullest potential of having all the inputs in the factors involved the highest.

5.1.2 Lowest Recoverability: Glass Window Pane sub-assembly

The Glass Window Pane sub-assembly shows the lowest recoverability value of 40.8 when compared to other sub-assembly in this particular car door assembly. This is due to the certain factors found from the fasteners and the component sub-assembly of the Glass Window Pane sub-assembly.

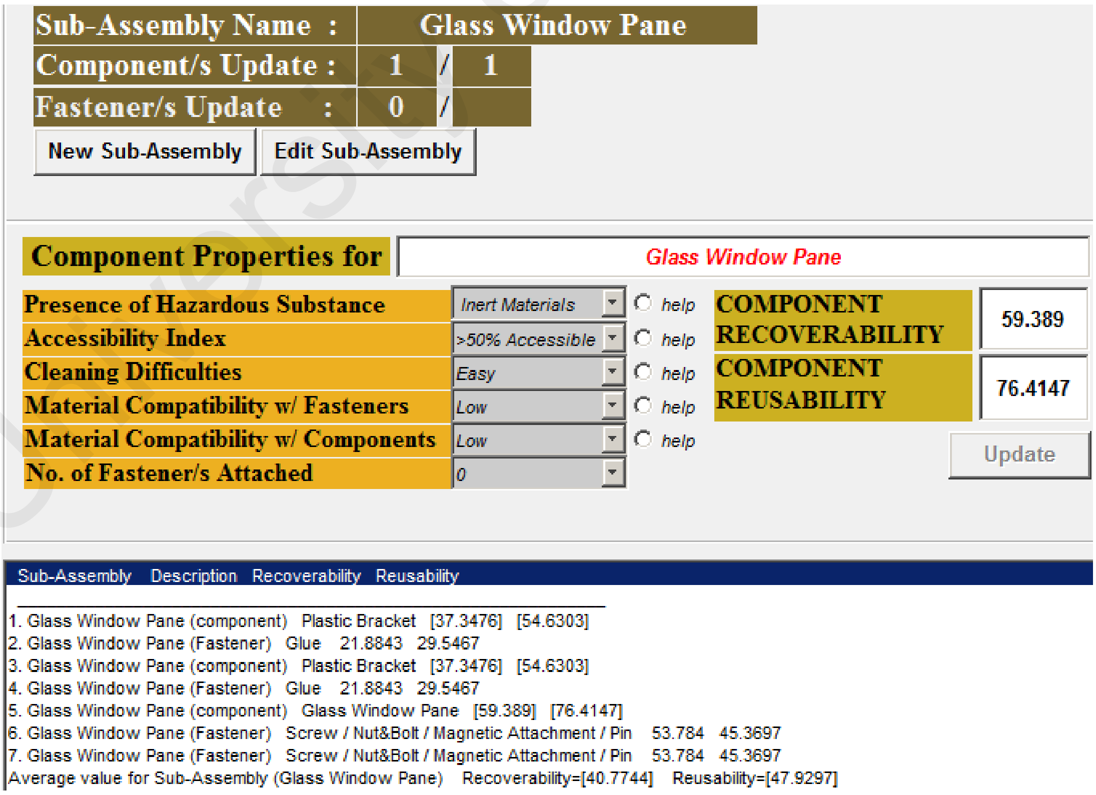


Figure 5:4: Figure above shows the input for different factors in the sub-assembly for Glass Window Pane sub-assembly.

The figure above shows the different input for each factors involved for the Glass Window Panel sub-assembly. This Glass Window Pane sub-assembly consists of 2 plastic brackets, 2 screws and some glue to fastened the brackets onto the glass window pane. The purpose of the screws is to fasten the plastic brackets attached to the Glass Window Pane in order to attach the Glass Window Pane sub-assembly to the Window Motor Mechanism sub-assembly.

Table 5:1: Table below shows the each input for the components in the Glass Window Pane Sub-Assembly.

Glass Window Pane Sub-Assembly Inputs for Components					
Component	Presence of Hazardous Substances	Accessibility Index	Cleaning Difficulties	Material Compatibility with Fasteners	Material Compatibility with Components
Glass Window Pane	Inert Material	>50% Accessible	Easy	Low	Low
Plastic Bracket 1	Inert Material	<50% Accessible	Medium	Not Compatible	Low
Plastic Bracket 2	Inert Material	<50% Accessible	Medium	Not Compatible	Low

The figure above depicts the average value of the sub-assembly for Glass Window Pane. The Glass Window Pane and two plastic brackets in the sub-assembly are all inert material where the materials do not post any risk to human health or the environment. This will lead to safer handling during the recoverability or recycling of components hence lessens the cost and time needed to disassembled this particular component. The Accessibility Index is rated >50% accessible for the Glass Window Pane component instead of Free Access since the size of the Glass Window Pane sub-assembly comparatively to opening access hole in the Car Door was >50% accessible henceforth this input was chosen. The Glass Window Pane sub-assembly is attached to the Window Motor Mechanism sub-assembly, another sub-assembly where the only access to detach the Glass Window Pane sub-assembly is through the opening in the interior side of the car door itself. Both Plastic Brackets attached to the Glass Window Pane is rated at <50% accessible since the only way to access it is through the opening of the car door.

The cleaning difficulty of the Glass Window Pane component is rated at easy to clean since a majority 70 % of the surface area of this component is exposed to the environment where the common user is capable of cleaning it. The plastic bracket of the sub-assembly is rated at medium cleaning difficulty since these two plastic bracket is not exposed to the environment. These components are hidden inside the car door where it does not require cleaning. If it does require cleaning, it might be due to the rubber seals, Interior Plastic Seal or some other areas that are not sealing the sides properly where the dirt and debris might enter the openings.

The Glass Window Pane has fasteners attached to it. One of the fasteners is the glue for the brackets to be attached onto it. These glue fasteners are not the same material as the Glass Window Pane component. These glue fasteners may need to be detached before further processing for recycling, reuse or remanufactured since they have low compatibility with the Glass Window Pane. This is especially true for recycling since the purer the material, the higher the quality for the recycled product. In some cases, Glass Window Pane is reused on another vehicle since the Glass Window Pane component is still in good shape. There could be a need for new glue to attach the plastic brackets onto the glass window pane to be then reattached onto the another vehicle motor mechanism sub-assembly since the original glue between the plastic brackets and glass window pane could be brittle due to age. It could the case also that the plastic brackets need to be re-attached onto different locations of the Glass Window Pane component. The Glass Window Pane sub-assembly has another two fasteners which are screws that connect through the plastic bracket for the Glass Window Pane sub-assembly to connect to the motor mechanism sub-assembly. These screws are not compatible with the plastic brackets since there is a need for separation of plastics and metal components during the recycling process for purer recycled grade materials.

The Glass Window Pane component has low compatibility with other components in the sub-assembly. This is because of the Glass Window Pane is made of glass whereas the plastic bracket is made of plastic. The Glass Window Pane component needs to be detached and separated from the plastic brackets during the sorting process before the recycling process can proceed.

With the factors evaluated previously, the Glass Window Pane scored a value of 59.39 for recoverability and 76.41 for reusability whereas the plastic bracket scored a value of 37.35 for recoverability and 54.63 for reusability using the fuzzy inference system and GUI created for this model.

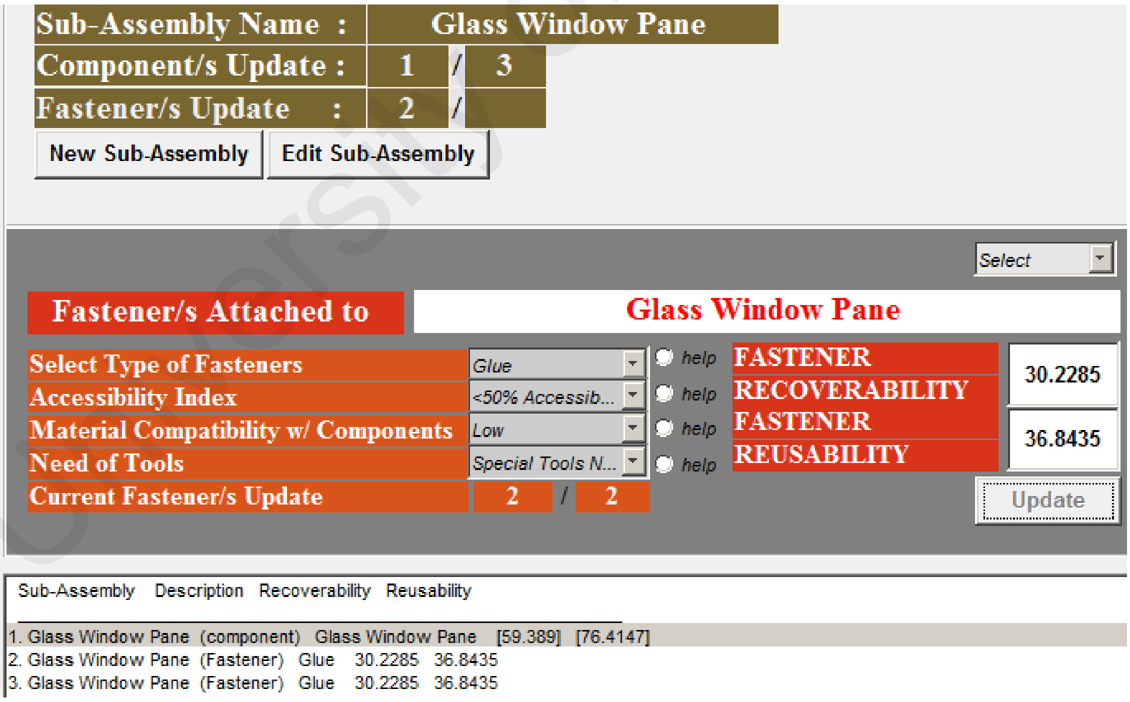


Figure 5:5: Figure above shows the glue fastener evaluated for Glass Window Pane sub-assembly.

The glue fastener for the Glass Window Pane sub-assembly is evaluated using the factors involved in this model. The input value of this fastener and output value of this fastener is based on (de Aguiar et al., 2017) hierarchy of fastener's index where the author shows a different hierarchy for different types of fasteners used based on the authors' results. The accessibility index chosen is <50% accessible because the glue fastener in between the Glass Window Pane and plastic bracket has a <50% accessibility. The only way to access is to use the special tool or solvent to be applied on the side of the glue where it can be seen hence the need of tools is selected to Special Tools Needed. The material compatibility is selected as low for the glue fastener since there is a need to detach the glue from the sub-assembly for a higher quality grade recycling for the plastic bracket and Glass Window Pane components.

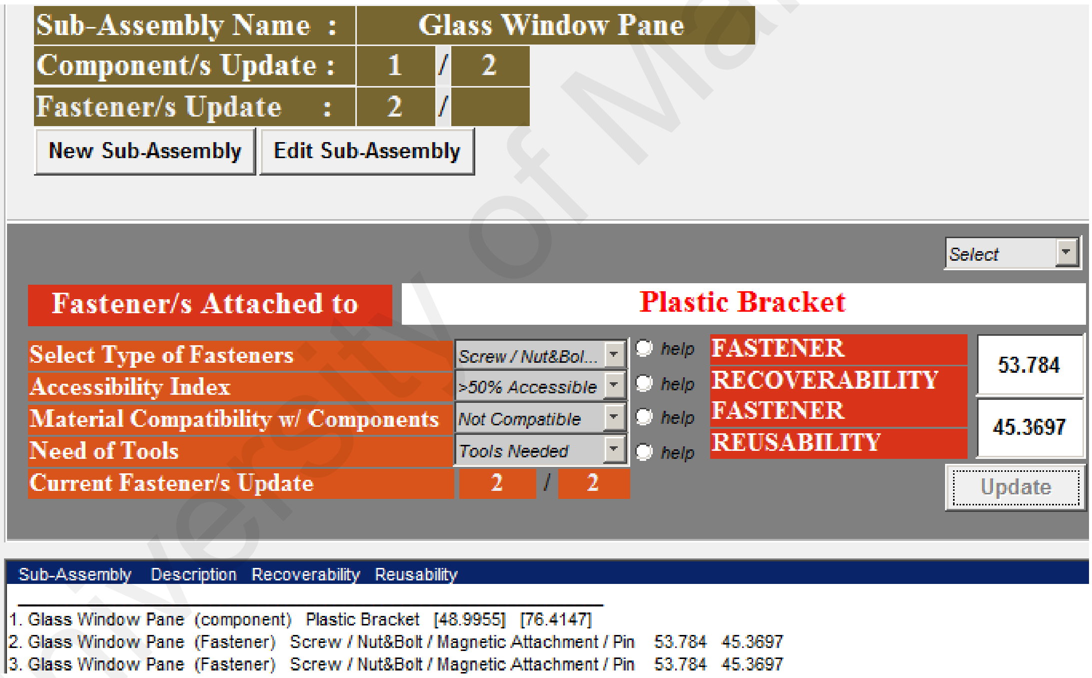


Figure 5:6: Figure above shows the screw fastener evaluated for Glass Window Pane sub-assembly.

Another two fasteners are attached on the plastic bracket of Glass Window Pane sub-assembly which both are screws. The input value of this fastener and output value of this fastener is based on (de Aguiar et al., 2017) hierarchy of fastener's index where the author shows a different hierarchy for different types of fasteners used based on the authors' results. The accessibility index to access this fastener is set to >50% accessible since the screw used to unfasten the screw on the plastic bracket is >50% accessible through the hole in the car door. The material compatibility of this fastener with components is selected as not compatible for this component because the screw fastener is made of metal whereas the component is made of plastic. Both of the material need to be separated during sorting stage before proceeding to the recycling process. Basic hand tools are needed for the removal of this fastener which is either a Philip's screw driver or a 10mm socket wrench.

5.2 Results obtained using a design tool developed by (de Aguiar et al., 2017) to diagnose product recyclability during product design phase

The results differ a little when compared to the 1st model since there are similar factors involved when analyzing the car door components. The additional factors involved for this model by (de Aguiar et al., 2017) is Percentage of Fasteners Index, Quantity of Types of Fasteners Index, Infrastructure Index and End of Life Contaminant Index. This design tool takes into account of the number of fasteners involved in the component when compared to the whole of the product.

Percentage of Fasteners' Index is the number of fasteners in the current component comparatively to the total number of fasteners on the product or sub-assembly. Quantity of types of Fasteners Index is the number of types of fasteners in a particular component. Infrastructure Index is the availability of infrastructure to recycle the particular product depending on the location of the product whereas the End of Life Contaminant Index is the presence of contaminants of each component in the sub-assembly after the end of its life before recycling.

5.2.1 Highest Recoverability and Recyclability: Window Inner Door Trim sub-assembly

The highest recoverable and recyclable sub-assembly calculated from this design tool is the Window Inner Door Trim. This particular sub-assembly together with Outer Door Handle Mechanism, Window Rubber Seal and Interior Plastic Seal have the lowest percentage of fasteners' index of 0.89%. The Quantity Type of Fastener Index for this sub-assembly is one since only Snap-Fit fastener is used in this sub-assembly which is the most desired in this particular factor used. Disassembly time is lessened when lesser type of fasteners is used. The type of fasteners used in this particular sub-assembly is the snap-fit fastener which according to the author (de Aguiar et al., 2017) of this design tool is the most desired fastener in a product. The Accessibility Index is rated as 1 which is also known as free access since this sub-assembly is easily removed from the car door without much effort needed.

The Infrastructure Index is rated as 3 which is also known as international since Malaysia do have rubber recycling facilities where one of it is Green Rubber Group. The Material Compatibility Index for this sub-assembly is rated as 3 which is also known as Low Compatibility. The low compatibility of this sub-assembly is due to the polymer fibers found along side with the component. The polymer fibers functions to clean the window pane when the user winds down the car window. During the recycling process, there is a need to remove the fibers to increase the grade of the rubber recycled. The material group index is rated as 2 which is also known as non-inert since the polymer fibers found on the sub-assembly is considered as non-inert materials. This is because this polymer fiber has a small possibility of posing a risk unto human health or the environment since the polymer fiber is flaking a little. The end of life contaminant index for this sub-assembly is rated as 1 since there are no painting, gluing or welding found on the product other than the small amount of polymer fiber that is flaking off that is doubt to cause major contaminant to the environment.

The factors involved weighted in this sub-assembly resulted the highest recoverability and recyclability compared to the other sub-assemblies involved.

5.2.2 Lowest Recoverability and Recyclability: Door Lock Mechanism

The lowest recoverable and recyclable component calculated from this design tool is the Door Lock Mechanism Sub-assembly. The percentage of fasteners' index was calculated to be 16.07% with 18 fasteners involved which it is the second highest value whereas the door rubber seal sub-assembly scored a value of 21.43% with a number of 24 fasteners involved. The Quantity of Fastener Type Index was rated as 2 since there are two type of fasteners involved in this sub-assembly which are 17 screws and 1 snap-fit. The type of fastener index was rated at an average value of 2.67 which is the combination of two fasteners involved, screw and snap fit fastener. The accessibility index was rated at 3 which is 50% or more inaccessible. The only way to acquire the door lock mechanism sub-assembly was through the hole of the car door which is almost the same size as the door lock mechanism sub-assembly.

The Infrastructure Index was rated at 3 which is also known as international since there is no proper infrastructure currently in this country that retrieves this type of components to be recycled. There is only improper infrastructure where auto "half cuts" sells these used components for reuse by consumers without proper remanufacturing or cleaning. The Material Compatibility Index was rated at 4 since there are multiple materials in the sub-assembly that required to be separated before the recycling process can be thoroughly done to reduce the recycled material grade. The materials involved are metal and plastics which is a bad combination during sorting phase before recycling process can proceed. The Material Group Index is rated at 1 since all the components in this sub-assembly is an inert material where it does not harm the environment or humans involved. The End of Life Contaminant Index is rated at 1 since the components used in this sub-assembly does not does not required painting, gluing or welding.

The factors involved weighted in this sub-assembly resulted the lowest recoverability and recyclability compared to the other sub-assemblies involved.

5.3 Results obtained using the Disassembly Evaluation Chart Method by (Fatmawati, 2007)

The Disassembly Evaluation Chart Method has a few interesting results when compared to the other two previous methods used. This method used was proven to be taxing as each components and fasteners need to be evaluated based on the time and difficulties needed to be disassembled. The difficulty rating was also subjective to the person ability to disassemble the sub-assembly.

5.3.1 Fastest rate for recoverability of sub-assembly based on time needed to disassemble: Window Inner Door Trim

The least time needed to disassemble the part/sub-assembly of this particular model of the car door is the Window Inner Door Trim. The total estimation time taken to disassemble this sub-assembly was 2.7 seconds. The accessibility of this sub-assembly as rated as 1 since there are no obstructions that prohibits the access of the Window Inner Door Trim. The positioning is rated as 1 as well since the user positioning himself to remove the sub-assembly was relatively easy to do. The force difficulty rating was rated as 1 as well since there is not much force needed to remove the sub-assembly. The base time to disassemble the sub-assembly was rated as 3 as according to the timer taken to disassemble the sub-assembly. The special difficulty rating was rated as 1 since there is not much special tools or positioning needed to disassemble the sub-assembly. All these factors involved led to the fastest rate of disassembly of this particular sub-assembly.

5.3.2 Slowest rate for recoverability of sub-assembly based on time needed to disassemble: Door Rubber Seal

The most time needed to disassemble the sub-assembly of the entire assembly of the car door was the Door Rubber Seal along with the 24 snap fit fasteners. The estimation time taken to disassemble the whole disassemble was 1026.1 seconds. The accessibility rated for the Window Rubber Seal was 5 since there was no area to access the Door Rubber Seal whereas the snap fit fastener was rated as 3 since the fastener was hidden between the Door Rubber Seal and the metal part of the car door. The process of accessing the Window Door Rubber Seal was to pull left and right to release the snap fit hook fasteners that hook the Door Rubber Seal to the car door assembly. The positioning was rated at 5 for the Door Rubber Seal since to disassemble there was a need to position the hand on top of the rubber seal with a readiness to move left and right to pry the Door Rubber Seal from the fastener. If it was a first time user who disassemble this sub-assembly, there is a chance that the Door Rubber Seal might tear. The positioning for the fastener was rate at 1 since it is already exposed for the pliers to grip it right after the disassembly of the Door Rubber Seal. The force for the Door Rubber Seal was rated at 2 since there is a need of a little force to move to Door Rubber Seal at each particular position to the left and the right for removal. The force rated for the snap fit fastener was 6 since there was a need of much force to pull using the pliers. The base time rated for the Door Rubber Seal was 5 seconds whereas the snap fit fastener was rated at 24 seconds. The base time was exceptionally high at 24 seconds was due to under equip of tools. A snap fit tool removal would speed up the process of removal of these snap fit fasteners. The special column was rated as 1 for both the Door Rubber Seal and snap fit fasteners since no special tools was applied to the component and fasteners. The total estimation time for the Door Rubber Seal and Fasteners were 309.9 seconds and 716.2 seconds with a total for both component and snap fit fasteners was 1026.1 seconds.

5.4 Comparison between Automotive Evaluation Complementary Tool, Design Tool model by (de Aguiar et al., 2017) and Disassembly Evaluation Char Methodology by (Fatmawati, 2007)

The table below shows the comparison of the current model of case study done with the other two models used. Some of the values of the sub-assembly are almost the same while the others are far apart. This is mostly due to the different factors used in each of the model presented previously.

Table 5:2: Table below shows the value of Highest to Lowest using different models of recoverability.

Automotive Evaluation Complementary Tool	A design tool to diagnose product recyclability during product design phase	Analysis of Product Disassemblability Using The Disassembly Evaluation Chart Methodology	Highest to Lowest
Interior Plastic Trim	Window Inner Door Trim	Window Inner Door Trim	
Window Inner Door Trim	Window Rubber Seal	Interior Plastic Seal	
Glass Window Slider	Interior Plastic Seal	Side Mirror Wiring	
Window Motor Mechanism	Outer Door Handle Mech.	Glass Window Pane	
Outer Door Handle Mechanism	Glass Window Slider	Car Door Side Foam	
Interior Main Panel	Sliding Door Hinge	Window Rubber Seal	
Door Rubber Seal	Window Outer Door Trim	Interior Main Panel	
Car Door	Car Door Side Foam	Interior Handle	
Window Outer Door Trim	Window Motor	Outer Door Handle Mechanism	
Interior Handle	Side Mirror Wiring	Window Motor	
Sliding Door Hinge	Interior Plastic Trim	Sliding Door Hinge	
Main Door Wiring	Interior Handle	Door Lock Mechanism	
Window Rubber Seal	Interior Main Panel	Window Outer Door Trim	
Window Motor	Glass Window Pane	Glass Window Slider	
Car Door Side Foam	Window Motor Mech.	Window Motor Mechanism	
Door Lock Mechanism	Car Door	Interior Plastic Trim	
Interior Plastic Seal	Main Door Wiring	Main Door Wiring	
Side Mirror Wiring	Door Rubber Seal	Door Rubber Seal	
Glass Window Pane	Door Lock Mechanism		

The Disassembly Evaluation Chart focuses mainly on the estimation time for disassembling a particular sub-assembly/component. This method does not take into account of the Presence of Hazardous Substances, Material Compatibility, End of Life Contaminants and Cleaning Difficulties. It was firstly used by Hitachi Limited in 1993 to determine only the disassemble-ability of an assembly of a product.

The method used by (de Aguiar et al., 2017) has almost the same recoverability value with Automotive Evaluation Complementary Tool. One such assembly that almost has the same value is the Window Inner Door Trim. The Window Inner Door Trim rank at 1st in this method whereas for the Automotive Evaluation Complementary Tool was ranked at 2nd place. This is due to certain similar factors and certain factors that is not involved since some factors were used from the Design Tool by (de Aguiar et al., 2017).

The lowest recoverability value for Automotive Evaluation Complementary Tool was the Glass Window Pane. This sub-assembly is the ranked 6th before the last for the Design tool by (de Aguiar et al., 2017). The Glass Window Pane was ranked at 6th for the Design Tool was due to the % fastener index that is involved in the sub-assembly which takes into the account of a small percentage of glue that is used in the sub-assembly to glue the plastic bracket to the Glass Window Pane. The Automotive Evaluation Complementary Tool does not take into account of % of fastener index because the presence of different fasteners of different materials will offset the recovery and recyclability of the component. The presence of impurities such as having glue and plastic bracket on the Glass Window Pane might affect the purity of the material recovered from recycling or product recovery. It is more desirable for recycling facilities to have same materials or compatible materials to be recycled instead of having incompatible materials to be recycled. This makes the Automotive Evaluation Complementary Tool takes into account of the small impurities there are in the component before recovering or recycling the sub-assembly.

The Design Tool used by (de Aguiar et al., 2017) does not take into account of the factors of the following. One of the factors is the cleaning difficulties of each sub-assembly of the component. The cleaning of a component can sometimes be crucial when recovering and remanufacturing of components by companies. The process cannot take place when the component is dirty or in need of cleaning. This factor is dependent on whether this component is to be reuse, remanufactured or recycled which is also based on whether the design engineer of automotive equipment considers remanufacturing of components during the end of life. Another factor that is not taken into account is the need of tools for the disassembly of each sub-assembly. The use of proper tools has direct effect of disassembly rate since an ideal disassembly is of without the use of tools. Complex or special tools are often not preferred since it might involve complications.

The Automotive Evaluation Complementary Tool highest recoverability was the Interior Plastic Trim although it was ranked second when using the Design Tool by (de Aguiar et al., 2017) and ranked third from the last for Disassembly Evaluation Chart Method. It was ranked second by the Design Tool because this method includes a factor known as End of Life Contaminant index. This factor takes into account of the contaminant incurred by surface finish of a product. The infrastructure index puts the Interior Plastic Trim to second place since currently in Malaysia there is only improper infrastructure such as auto spare parts “half-cuts” that collects used components and resells it at a price subjective to the condition of the components. The Disassembly Evaluation Chart Method

CHAPTER 6: CONCLUSION

In this study, an automotive evaluation complementary tool (software GUI) based on fuzzy logic inference approach has been presented to evaluate the recovery and reusability value of end of life vehicle components. The factors used in the evaluation of end of life vehicle include presence of hazardous substances, accessibility index, difficulties of cleaning automotive components, type of fasteners index, material compatibility and type of tools needed for disassembly. Evaluation and comparison of the proposed model has been done in three different case studies to verify and to prove the usefulness of the evaluation complementary tool. The model has proved to be fast and efficient in predicting the recoverability and reusability of components and sub-assemblies as compared to previous related work done which are based on manual inputting of data in tables. The results from the proposed model has also shown considerable consistency with previous models however, some disparities are noticeable due to the dissimilarities in factors considered. The current model considers two new factors that are non-existent in previous evaluation models.

This research has significance to assist designers and engineers in predicting the recoverability and reusability of different components during the end of life of vehicles as governmental agencies implement stricter policies to reduce the amount of automotive wastes. It should allow automotive companies to determine these critical factors at the onset of development to comply with certain standards. The proposed model will therefore act as a complementary tool for automotive designers and engineers to reduce the automotive pollution at a more effective way.

CHAPTER 7: RECOMMENDATIONS

The main challenges were encountered during the case study due to the unavailability of proper tools for dismantling. Another challenge was that there is no proper infrastructure in Malaysia that recover end of life vehicles. Thus the factors involved could not be properly established for this country since different countries will have different factors involved when recovering a vehicle. Overall, there should be proper tools available for dismantling vehicle sub-assemblies and components in research workshops. This is to ensure smooth dismantle-ability for a more accurate results. Future work should involve a field research towards obtaining a comprehensive database of factors for predicting recoverability and reusability of end of life vehicles via the fuzzy membership functions.

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