SOFTWARE FOR INTEGRATION OF END-OF-LIFE OPTION DETERMINATION, DISASSEMBLABILITY EVALUATION AND DISASSEMBLY SEQUENCING OPTIMIZATION

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ABSTRACT

In recent years, many countries have developed new legislations which are aimed at greater emphasis to force vehicle manufacturers to recycle their products at the end of their life. However, before end-of-life vehicles can be recycled, end-of-life disassembly needs to be put in place. It entails large amounts of capital expenditure and time. Besides that, in general, vehicle designers also do not have experience in disassembling and recycling to determine impact of various design aspects on difficulty at the disassembly stage. Therefore, there is a strong need for a tool to determine end-of-life options, to evaluate the disassemblability, and to search for the optimal end-of-life disassembly sequence of the end-of-life vehicles. This research was conducted to fulfill those needs. The main outcome of this research is the methodology developed to aid vehicle designers to analyze the disassemblability and recyclability of end-of-life vehicles. The developed methodology integrated three important aspects in one framework. Those aspects are: (1) end-of-life option determination; (2) disassemblability and recyclability analyses; and (3) disassembly sequence determination. The condition and material composition of the end-of-life vehicle components are the criteria for determining the end-of-life option. The numerical evaluation of disassemblability and the recyclability computation method used in the end-of-life vehicle recycling manual are applied to evaluate the disassemblability and recyclability. In order to optimize the disassembly sequence, Mix Integer Linear Programming (MILP) technique is used. The end-of-life option determination will guide the designer to choose the appropriate end-of-life option of the product. The disassemblability evaluation will aid the designers in reducing the difficulty for disassembly, disassembly time and disassembly cost required. The recyclability analysis will show that the design meets or does not meet the legislation at feasible expenditure in terms of recycling target. The searching for optimum disassembly sequence will minimize the disassembly cost and maximize the end-of-life value and finally increase the profitability. Based on the developed methodology, computer software was developed to ease the tasks of decision making. The Visual Basic programming language, Microsoft Access and LINDO systems were applied in the proposed software. The proposed software was developed specially to assist vehicle designers to evaluate vehicle design with respect to the legislation, recycling and economic value. In order to verify and validate the developed software, an end-of-life car door was introduced with the intention to investigate the appropriate end-of-life option for its components, disassemblability, suitability for recycling, recyclability and the optimum disassembly sequence. The result of the case study showed that the developed software can estimate the disassembly time of the car door without any significant differences with the actual disassembly operation.

ABSTRAK

Sejak kebelakangan ini, kebanyakan negara sudah membuat akta yang bertujuan untuk menggalakkan pengeluar kenderaan agar mengguna semula produk-produknya yang telah mencapai masa akhir hayat. Walau bagaimanapun, sebelum jangka hayat kenderaan boleh diguna semula, proses perungkaian harus dilakukan terlebih dahulu. Proses ini melibatkan kos yang tinggi dan masa yang lama. Secara amnya pereka kenderaan tidak mempunyai pengalaman di dalam proses perungkaian dan guna semula bagi menentukan kesan aspek rekaan yang berbeza ke atas kesukaran ketika proses rungkaian dilaksanakan. Oleh itu, kaedah untuk menentukan pilihan proses akhir hayat, menilai kebolehan rungkaian dan menentukan urutan proses rungkaian yang optimum amatlah diperlukan. Penyelidikan ini dilaksanakan untuk memenuhi keperluan tersebut. Hasil utama daripada kajian ini adalah kaedah yang dibangunkan untuk membantu pereka kenderaan dalam menganalisa kebolehan rungkaian dan guna semula. Kaedah yang dihasilkan menggabungkan tiga aspek penting dalam kebolehan rungkaian dan guna semula. Aspek-aspek tersebut adalah, (1) penentuan pilihan proses akhir hayat; (2) analisis kebolehan perungkaian dan guna semula; dan (3) penentuan urutan proses perungkaian. Keadaan dan bahan bahagian kenderaan adalah kriteria untuk menentukan pilihan akhir hayat. Penilaian berangka untuk kebolehan rungkaian dan pengiraan kebolehan guna semula digunakan untuk menilai kebolehan rungkai dan guna semula. Teknik Mix Integer Linear Programming (MILP) digunakan bagi mengoptimumkan urutan rungkaian. Penentuan pilihan proses akhir hayat akan membantu pereka untuk memilih pilihan proses akhir hayat yang bersesuaian. Pengiraan nilai akhir hayat akan menunjukkan keuntungan atau kerugian yang boleh dicapai daripada pilihan proses akhir hayat yang sesuai. Penilaian kebolehan rungkaian akan membantu pereka dalam mengurangkan kesukaran ketika proses perungkaian, masa dan kos yang terlibat. Analisis guna semula akan menunjukkan sama ada rekaan tersebut memenuhi atau tidak memenuhi akta yang telah ditetapkan. Penentuan urutan proses perungkaian yang optimum akan mengurangkan kos proses perungkaian dan memaksimakan nilai akhir hayat. Berdasarkan kaedah yang dihasilkan, satu perisian komputer dibangunkan untuk memudahkan kerja-kerja menganalisa proses perungkaian. Bahasa pengaturcaraan Visual Basic, Microsoft Access dan sistem LINDO diaplikasikan di dalam perisian yang dihasilkan. Untuk mengesahkan program tersebut, sebuah pintu kereta yang telah mencapai masa akhir hayat digunakan untuk menganalisa pilihan proses akhir hayat, kebolehan rungkaian, kesesuaian untuk diguna semula, dan urutan rungkaian yang optimum. Hasil daripada kajian kes ini menunjukkan bahawa perisian tersebut dapat menentukan masa rungkaian tanpa perbezaan yang banyak apabila dibandingkan dengan proses rungkaian yang sebenar.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	ABSTRACT	iii
	ABSTRAK	iv
	TABLE OF CONTENTS	v
	LIST OF TABLES	ix
	LIST OF FIGURES	xi
	LIST OF ABBREVIATIONS	xiii
	LIST OF SYMBOLS	xiv
	LIST OF APPENDICES	xv
1	**INTRODUCTION**	
	1.1 Background of The Project	1
	1.2 End-of-life Vehicle Legislation	2
	1.3 Effects of End-of-life Vehicle Legislation to Malaysian Automotive Manufacturer	4
	1.4 The Significance of the Disassembly Process	5
	1.5 Current Researches and System Available	6
	1.6 Problem Statement	8
	1.7 Objective and Scope of the Research	9
	1.8 Assumption	10
	1.9 Significant of the Research	10
	1.10 Organization of the Thesis	11

2 LITERATURE REVIEW

2.1 Overview 12
2.2 End-of-Life Option 13
2.3 Design for Disassembly 14
2.4 Disassembly Sequencing 15
2.4.1 Disassembly Process Representation 16
2.4.2 Method for Searching Optimum Disassembly Sequence 23
2.4.2.1 Heuristic Method 23
2.4.2.2 Metaheuristic Method 25
2.4.2.3 Exact Method 26
2.5 Evaluation of Disassemblability 28
2.6 Selected Methods 34
2.7 Summary 35

3 PROPOSED METHODOLOGY

3.1 Overview 36
3.2 Development of Disassemblability Evaluation Method 37
3.2.1 Phase 1: Define the Product 38
3.2.2 Phase 2: Determine the End-of-Life Option and Calculate the End-of-Life Value 38
3.2.2.1 Step 1: Determine the End-of-Life Option 38
3.2.2.2 Step 2: Calculate the End-of-Life Value 39
3.2.3 Phase 3: Evaluate Disassemblability and Calculate Disassembly Cost 47

3.2.3.1 Step 1: Evaluate Disassemblability 47
3.2.3.2 Step 2: Calculate Disassembly Cost 51
3.2.4 Phase 4: Calculate Suitability to Recycling of the Product’s Component and Recycling Rate of the Product 52
3.2.5 Phase 5: End-of-Life Value, Disassemblability and Recycling Rate Report 53
3.2.6 Phase 6: Optimal Disassembly Sequence Determination 54
3.2.7 Phase 7: Disassembly Sequence Repot 58
3.3 Development of the Software for the Disassemblability Evaluation 59
3.4 Summary 61

4 DEVELOPMENT OF DISASSEMBLABILITY EVALUATION SOFTWARE

4.1 Overview 62
4.2 Capturing User Requirement 63
4.3 Defining the Problem 64
4.4 Outline the Solution 67
4.5 Developing Outline into Solution 70
4.6 Test Algorithm for the Correctness 70
4.7 Code the Algorithm into A Specific Programming Language 71
4.8 Run the Program on the Computer 73
4.8.1 Welcoming Menu 73
4.8.2 Disassemblability Evaluation Menu 74
4.8.3 Forecasting and Present Value Calculator 76
4.8.4 Disassemblability Report 76
4.8.5 Disassembly Sequencing Menu 79

	4.8.6 Help Menu	79
	4.9 Evaluate the Program Using Case Study	82
	4.10 Document and Maintain the Program	82
	4.11 Summary	82
5	**CASE STUDY AND RESULTS**	
	5.1 Overview	83
	5.2 Disassemblability and Recyclability Analysis of Right-Back Door of Kelisa (Manufactured Year 1997)	83
	5.3 Validation	106
	5.3.1 Validating the Disassembly Time	107
	5.3.2 Validating the Optimum Disassembly Sequence	116
	5.4 Summary	120
6	**DISCUSSION**	
	6.1 Overview	121
	6.2 Review on Achievement	121
	6.3 Summary	128
7	**CONCLUSION**	
	7.1 Conclusion	129
	7.2 Future Work	131

REFERENCES

Appendices 1 - 6

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Comparison of Methodologies for Searching the Optimum Disassembly Sequence	22
2.2	Comparison of Methodologies for Modeling Disassembly	29
3.1	Logarithmic, Exponential and Power Regression Model	44
3.2	Scoring System of Numeric Analysis of Disassemblability	49
3.3	Provision Allowances for Adoption of Typical Postures Incorporate Ergonomic Considerations in Product Design	50
3.4	An Example Disassembly Time and Cost Calculation	51
4.1	Defining Diagram	65
4.2	Desk Check	72
5.1	Right-Back Door of Kelisa (Manufacture Year 1997)	84
5.2	End-of-Life Value	87
5.3	Numerical Analysis of Disassembly Evaluation of Door Gear	90
5.4	Suitability for Recycling and Disassembly Time	92
5.5	All Possible Released Subassemblies and Disassembly Tasks	99
5.6	Transition Matrix	103
5.7	Disassembly Task Elements	109
5.8	Number of Time Study Readings N’ Required for ± 5% Precision and 95% Confidence Level	111

5.9 5 Good Readings for the Right-Back Door of Kelisa Disassembly Time 112
5.10 Number of Observation Required 112
5.11 Software Output for the Duration of Disassembly Operation 115
5.12 z-Test Result for Removing Handle 1 (Inside) 116
5.13 Cost of Disassembly Actions and Subassemblies Revenue of the Radio Set 118

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	World Automotive Production 1980-2000	1
1.2	Current Research Area	6
1.3	Support Systems Available	7
2.1	The Partial Disassembled PC	17
2.2	Component Fastener Graph of Figure 2.1	17
2.3	A Simple Product	18
2.4	(a) Disassembly Tree, (b) Fishbone Tree for Product Depicted in Figure 2.3	18
2.5	Connection-Oriented State Diagram for Product in Figure 6, (a) Connection Diagram, (b) Connection-Oriented State Diagram, (c) Component-Oriented State Diagram	19
2.6	Disassembly Petri Net (DPN), (a) A Hand Light, (b) DPN of the Hand Light	20
2.7	(a) Direct Graph, (b) AND/OR Graph	20
2.8	Reverse Fishbone Diagram	21
2.9	Disassembly Evaluation Chart	30
3.1	Disassemblability Evaluation Framework	37
3.2	Flow Chart to Determine End-of-Life Options Based on Materials Content	40
3.3	Linear Regression Model	42
3.4	A simple Product Consisting Three Components	55
3.5	Disassembly Graph of Product in Figure 4.3	55

4.1	Hierarchy chart	69
4.2	Welcoming Menu	74
4.3	Disassemblability Evaluation Menu	75
4.4	Forecasting and Present Value Calculator	77
4.5	Disassemblability Evaluation Report	78
4.6	Disassembly Sequencing Menu	80
4.7	Help Menu Main Window	81
4.8	Help Topics (Disassembly Sequencing)	81
5.1	Template for Inputting the Components' and Subassemblies' Information	85
5.2	Help Menu of How to Compute the End-of-Life Value of a Component	87
5.3	Template for Disassemblability Analysis	89
5.4	Redesign Recommendation for the Force Exertion as the Design Attribute	91
5.5	Disassemblability Report – Material Composition	95
5.6	Disassemblability Report – End-of-Life Value versus Disassembly Time	96
5.7	Disassemblability Report – Value Return of Removing	97
5.8	AND/OR Graph of the Kelisa's Right-Back Door Disassembly Operation	98
5.9	Template for Searching Optimum Disassembly Sequence	105
5.10	Optimum Disassembly Sequence Solution	106
5.11	Validation Flow Process	108
5.12	Control Chart of Removing Handle 1 (Inside)	113
5.13	Normal Probability Plot	114
5.14	AND/OR Graph of the Radio Set	117
5.15	Software Output for Radio Set's Optimum Disassembly Sequence	119

LIST OF ABBREVIATIONS

AHP	-	Analytical Hierarchy Process
CAD	-	Computer Aided Design
DPN	-	Disassembly Petri Net
ECoDE	-	Environmental Component Design Evaluation
ELDA	-	End-of-Life Design Advisor
ELSEIM	-	End-of-Life Strategy Environmental Impact Model
EOL	-	End-of-Life
EPA	-	Environmental Protection Agency
GUI	-	Graphical User Interface
LP	-	Linear Programming
MOST	-	Maynard Operation Sequence Technique
MTM	-	Method Time Measurement
NLP	-	Non Linear Programming
OICA	-	Organisation Internationale des Constructeurs d'Automobiles
PMX	-	Partially Mapped Crossover
PPX	-	Precedence Preservative Crossover
TTD	-	Total Time for Disassembly
WP	-	Wave Propagation
TMU	-	Time Measurement Unit

LIST OF SYMBOLS

A	-	A set of process steps or actions
A_2	-	Anderson-Darling test statistic
α	-	Significance level
$\hat{\beta}_0$	-	Intercept in linear regression model
$\hat{\beta}_1$	-	Slope in linear regression model
c	-	Cost vector corresponding to disassembly task or transition
CI	-	Confidence interval
C_t	-	Future cost at the *t* time period
d	-	Discount rate
D	-	Final marking
F	-	The cumulative distribution function of the normal distribution
H	-	The highest time study value
H_0	-	Null hypothesis
H_1	-	Alternative hypothesis
L	-	The lowest time study value
$\ln\left(\hat{\beta}_0\right)$	-	Intercept in exponential regression model which has transformed into linear regression model
$\ln(Cost)$	-	Dependence variable in exponential regression model which has transformed into linear regression model
$\ln(t)$	-	Independence variable in logarithmic regression model which has transformed into linear regression model
$\log\left(\hat{\beta}_0\right)$	-	Intercept in power regression model which has transformed into linear regression model

$\log(\cos t)$	-	Dependence variable in power regression model which has transformed into linear regression model
$\log(t)$	-	Independence variable in power regression model which has transformed into linear regression model
$\mathbf{M_0}$	-	Initial marking
M_G	-	Mass (kg) of product or subassembly
M_{R1}	-	Mass (kg) of materials in components in recycling rate categories R1
M_{R2}	-	Mass (kg) of materials in components in recycling rate categories R2
μ_0	-	Hypothesized population mean
n or N	-	Number of data or sample size
P	-	Probability
PV	-	Present value
r	-	coefficient correlation
r	-	Vector of end-of-life value
R	-	Range
R1	-	Components suitable for economic recycling with SR > 100%
R2	-	Component suitable for economic recycling which has 80% $\leq$ SR $\leq$ 100%
R3	-	Component which is not suitable for economic recycling with SR < 80%
R_Q	-	Recycling rate
S	-	Set of subassemblies
SE	-	Standard Error
SR	-	Suitability for Recycling
T	-	Transition matrix
t	-	Time (year)
σ	-	Standard deviation
x	-	Decision variables (disassembly task)
$\bar{X}$	-	Average
Y_i	-	The ordered observations

z	-	The distance from the mean in relation to the standard deviation of the mean
Z	-	Objective value

LIST OF APPENDICES

APPENDIX NO.	TITLE	PAGE
1	Algorithm Example	140
2	Observation Data of the Kelisa Right-Back Door Disassembly Time	151
3	Control Charts	153
4	Normal Distribution Plot	155
5	Test of μ_0 (Mean of the Actual Disassembly Time) versus μ (Disassembly Time Obtained by the Developed Software)	157
6	List of Publications	160

CHAPTER 1

INTRODUCTION

1.1 Background of the Project

Automotive manufacturing has increased in the last 20 years. According to Organisation Internationale des Constructeurs d'Automobiles (OICA, 2008), world production of motor vehicles reached record levels in 2007 with an increase of around 5.7% to 73 million units (excluding commercial vehicles), as shown in Figure 1.1. This growth has resulted shortened lifetime of most of vehicles and increased the quantity of vehicles disposed to landfill.

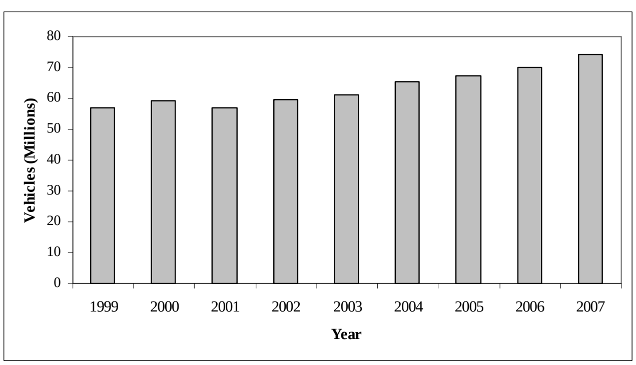

Figure 1.1 World Automotive Production 1999-2007 (OICA, 2008)

At present, approximately 75% to 80% of end-of-life vehicles in terms of weight, mostly metallic fractions, both ferrous and non ferrous are being recycled. The remaining 20% to 25% in weight, consisting mainly of heterogeneous mix of materials such as resins, rubber, glass, textile, etc., is still being disposed (Toyota Motor Company, 2005). However, the number of landfills for disposal of end-of-life vehicles has seen an exponential decrease.

According to European Union Directive (The European Parliament and the Council of European Union, 2000) the disposal of end-of-life vehicles is a major source of hazardous waste and toxic emissions. About 15% of a vehicle’s weight is classified as hazardous waste. In Europe about 12 million tones of vehicles reach its end-of-life every year and 15% of them are disposed to landfill (Pricewaterhouse Coopers LLP, 2002).

Based on the several literatures, integrating end-of-life vehicle concept into the early design of vehicle is one of important aspects that need to be considered in decreasing impact of end-of-life vehicles to environment. According to Alting and Legarth (1995), the choice of product concept, structure, material and process during design stages have consequences to environment during the entire life cycle of product. It is essential to integrate recycling criteria into all phases of vehicle development process in order to ensure the design of environmentally compatible vehicles optimized for recycling (BMW Group, 2002).

1.2 End-of-life Vehicle Legislation

Laws in European Union, Japan, USA and Australia require manufacturer to take back their products at the end of their useful life and recycle them. Most of developed countries also have set new legislation which is planned to force vehicle manufacturers to recover and recycle their products at the end of their life (Mat Saman and Zakuan, 2006).

According to European Parliament and Council of European Union (2000), requirements for dismantling, reuse and recycling of end-of-life vehicles and their components should be integrated in the design and production of new vehicles. Manufacturers should ensure that vehicles are designed and manufactured in such a way as to allow the quantified targets for reuse, recycling and recovery to be achieved. Vehicle manufacturers must endeavor to reduce the use of hazardous substances when designing vehicles; design and produce vehicles which facilitate dismantling, re-use, recovery and recycling; increase the use of recycled materials in vehicle manufacture; and ensure that components of vehicles placed on the market after 1 July 2003 does not contain mercury, hexavalent chromium, cadmium or lead.

On January 1, 2005, End-of-Life Vehicle Recycling Law was fully enforced in Japan. Under the law, automobile manufacturers are obliged to collect and properly dispose chlorofluorocarbons, airbags, and automobile shredder residue. In USA, there is no specific legislation regarding the management of end-of-life vehicles. Every state has its own legislation, so that the target and implementation varies from state to state. The United State Environmental Protection Agency (EPA) is trying to promote recycling concept among vehicle manufacturers (The United State Environmental Protection Agency, 1997). Based on Australian Department of the Environment and Heritage (2002), there is no end-of-life vehicle directive in Australia but some progress has been made towards encouraging end-of-life vehicle recycling through informal encouragement of recyclers and dismantlers. A joint project between the Environment and Heritage Department and Auto Parts Recyclers Association of Australia has produced guide booklets on waste oil recycling which were sent to recyclers and dismantlers throughout Australia during 2003.

In Malaysia the National Automotive Policy has not dealt with the environmental impact of automotive industry development. To date, directives or legislation on end of life vehicles for the automotive industry has not been established. Even if the local end of life vehicle recovery directive has not been established, the economic benefit of reuse should motivate the local automotive manufacturers.

1.3 Effects of End-of-life Vehicle Legislation to Malaysian Automotive Manufacturers

According to Tamar (2001), to compete in the global market Malaysian automotive manufacturers have to strengthen its export markets because they can't only rely on the traditional markets. In UK, Proton, (one of the biggest Malaysian automotive vehicle manufacturers) is eligible for tax breaks under the European Union generalized system of preference but Proton has still to enter into such markets as USA and Japan.

Based on that, Malaysian automotive manufacturers, as one of professional automotive vehicle importers, have to prepare from now to incorporate with the legislation requirements. If not, they will not be allowed to export their products overseas, especially to European Union (EU) countries. These are a big market for Malaysian automotive manufacturers.

The EU legislation forces professional importers of foreign vehicles to meet the legislation requirements, as stated in the directive, so that Malaysian automotive manufacturers have to take into full account and facilitate disassembly, reuse, recycling, and recovery of their automotive components at the design and production stage and reduce the use of hazardous substances and avoid the use of heavy metals in their products. Unfortunately, no tools developed for Malaysian automotive manufacturers and none such researches in Malaysia. So that there is a need to aid Malaysian automotive manufacturers in quantifying the disassemblability and recyclability of vehicle design in order to fulfill the end-of-life vehicle legislation.

1.4 The Significance of the Disassembly Process

Based on Desai (2002), before end-of-life vehicle can be reused, recycled, recovered, and remanufactured, component analysis and end-of-life disassembly need to be in place. Based on the “free take back” policy, the collection and treatment cost must be paid by the manufacturers. This entails large amounts of capital expenditure. If this amount of capital expenditures higher than saving gained by the manufacturers so that most manufacturers would not like to even considering disassembling, reusing, recycling, and remanufacturing the components unless costs are justified and financial gains assured. Because of that the end-of-life strategy and disassembly effort should to be determined in the vehicle development phase, make the disassembly process easy, and optimize the disassembly sequence. The end-of-life options determination and the disassemblability evaluation will show how economically efficient is it to disassemble the end-of-life vehicle and check the opportunity of a component to be recycled. Then the optimum disassembly sequence will maximize the end-of-life value and minimize the disassembly cost of the end-of-life vehicle.

But in general, the designers do not have experience in disassembly and recycling to determine the impact of various design aspects on disassemblability at the end-of-life stage. It is therefore important that a system for disassemblability is available in order to encourage designers to incorporate disassembly issue in order to fulfill the legislation that will fully implemented in 2015 and at the same time the costs of disassembly is justified and the financial gains are assured.

1.5 Current Researches and System Available

Figure 1.2 shows the current researches on the area of end-of-life option determination, disassemblability evaluation and disassembly sequencing.

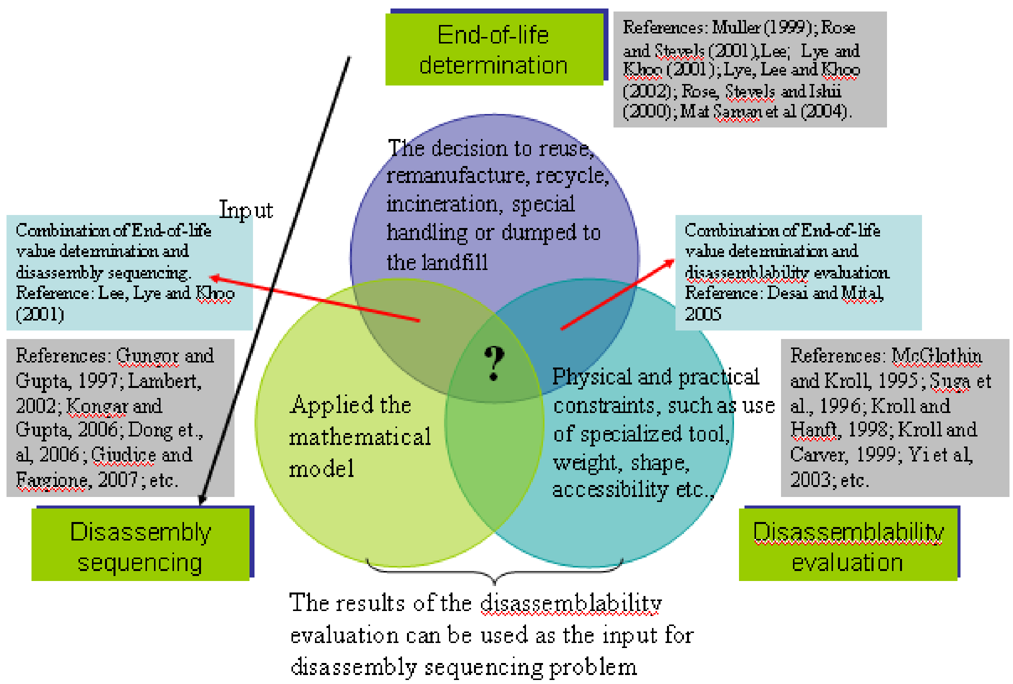

Figure 1.2 Current Research Area

It shows that researchers studied end-of-life option determination, disassemblability evaluation and disassembly sequencing as separate parts. Only few researchers conducted research to integrate the analyses of disassembly sequencing and disassemblability evaluation in one framework. There is a bulk of researches in term of disassembly sequencing optimization with a particular objective function, such as minimization of cost or minimization of time by using mathematical models but certain physical and practical factors can not be effectively incorporated to mathematical models. In addition, allocation of certain end-of-life options also plays an important role in disassembly process. Mathematical models have also failed to consider those factors.

Figure 1.3 shows the systems that are currently available. Most of those systems also fail in considering those three aspects simultaneously.

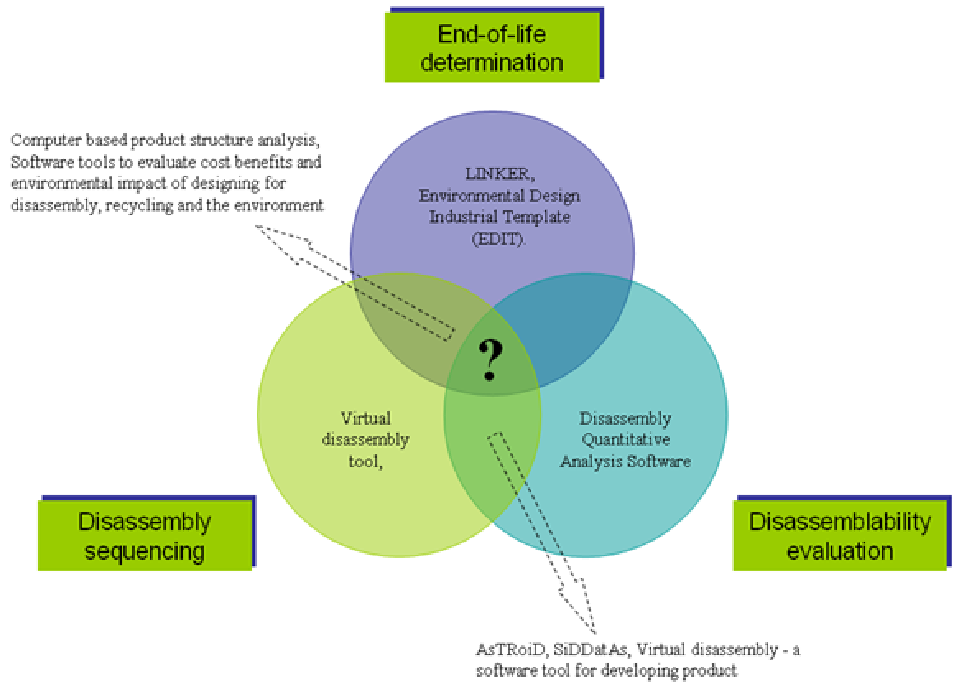

Figure 1.3 Systems Available

In the area of disassemblability evaluation, metrics used in the proposed tools can be generally divided into two categories, absolute metric (such as time, cost, energy for disassembly, and entropy for disassembly) and relative metric (such as design effectiveness). Disassembly effectiveness is as shown in equation (1.1) (Kroll and Craver, 1999).

$$\text{Disassembly system effectiveness} = \frac{5 \text{ x (theoritical minimum number of parts)}}{\text{Total difficulty score}} \quad (1.1)$$

Based on Kroll and Craver (1999) absolute metrics only can be used in relative manner, if it is used for evaluating single design, the result may be not tell how good the design is. As an example, a time estimation tool may tell the designers that estimated disassembly time is, say 4.3 minutes, but is this good or bad? No feedback can be provided by this metric (time) to the designers for further improvement. The relative metric (disassembly design effectiveness) also fails because of an important difference between assembly and disassembly (this metric is based on the assembly design efficiency). While every part is assembled separately, several parts may be removed by one disassembly operation. Other reasons that the relative metrics fail are:

i. An unrealistic implied assumption that the hypothetical product can consist of only very loosed-connected parts, so only ‘remove’ tasks (i.e., grasping a loose part, moving it away from the assembly, and dropping it into a nearby bin) are needed in the disassembly.

ii. Defining the reference designs, or in other words, deciding what should be considered a 100% effective design.

Clearly, single metric does not tell much about the design weakness. Only combining the individual metrics into a single measure allows monitoring of the overall improvement. Based on these, it can be concluded that researchers only provided insufficient solution to disassembly problem.

1.6 Problem Statement

The problem that is addressed in this research can be defined as follow:

There is no such research, methodology or software which is aimed to determine the end-of-life option, evaluate the disassemblability, and optimize the disassembly sequencing simultaneously as to minimize the environmental impact, maximize the net revenue resulting from the recovery of the components and minimize the disassembly cost.

1.7 Objective and Scope of the Research

The objective of this research is to design a system to aid the automotive vehicle designers in evaluating the disassemblability of the end-of-life vehicle.

This proposed system is limited to aid the automotive vehicle designers in:

i. Determining the end-of-life option of the end-of-life vehicle components.

ii. Evaluating the disassemblability of the disassembly process of the end-of-life vehicle components.

iii. Finding the optimum disassembly sequence.

The scopes of this research are:

i. The method will aid the automotive vehicle designer in determining the end-of-life option, evaluating the disassemblability, and optimizing the disassembly sequence.

ii. The condition of the components and their material composition will be the criteria in selecting the end-of-life option and the number of the component are not considered in evaluating the disassemblability

iii. As the case study, the disassemblability evaluation of steel-based components of passenger vehicle is performed. It is based on data of Malaysian Automotive Association (2007) where 78% of the 6,193,409 unit vehicle registered in Malaysia from 1982 to 2006 is the passenger vehicle. In the case of steel, it is now used in over 1000 parts of vehicle. The share of steel (in terms of weight) in a passenger vehicle is around 68% (ACORD, 2000). In this research, a vehicle door (right-back door of Kelisa, manufacturing year of 1997) was selected.

1.8 Assumption

The proposed methodology is implemented under several assumptions:

i. In computing the end-of-life value it is assumed that the recycling facility has 100% efficiency.

ii. The disassembly cost is assumed as the labor cost per unit of time.

iii. The operators doing the disassembly operations are assumed have average skill and work in the normal condition.

iv. The material of the components developing the product is known.

1.9 Significance of the Research

It is believed that this research will provide a major contribution for Malaysian automotive manufacturers to comply with end-of-life vehicle legislation. The output of this research will be effective and help Malaysian automotive manufacturers to become more effective and competitive. Currently there are no such works in Malaysia so that this research will aid Malaysia to develop their local expertise.

1.10 Organization of the Thesis

This thesis consists of 7 chapters. Chapter 1 presents the background of the project, problem statement, objectives and scope of the research, assumptions used, and the significance of the research.

Chapter 2 presents a detailed literature survey covering a number of relevant topics, such as of end-of-life concept, disassembly sequencing and disassemblability evaluation.

Chapter 3 presents a methodology for this research which consists of the development of disassemblability evaluation system and the development of software for disassemblability evaluation.

Chapter 4 presents the steps required to develop the disassemblability evaluation software.

Chapter 5 presents the application of the developed software to analyze the disassemblability and recyclability of the end-of-life vehicle.

Chapter 6 discusses the work that has been carried out in developing the methodology and software tool of end-of-life vehicle disassembly and recyclability analyses. It provides the whole picture of the research with its ultimate result.

Chapter 7 provides a summary of the main research outcomes of this thesis including the vital lessons resulting from the research. In addition, this chapter unveils opportunities for future research.

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APPENDIX 1

ALGORITHM EXAMPLE

Mainline

Statement number

```
Compute_Component_EOL_Value
  Read Component_No, Component_Name, Component_Mass                    (1)

  Prompt for Component_Material                                         2
  Get Component_Material

  Select_EOL_Option                                                     3
  Compute_Present_Value                                                 4
  Compute_EOL_Value                                                     5
END
```

Subordinate modules

```
Select_EOL_Option
  IF Component_Material = “Toxic” THEN                                  6
    EOL_Option = “Special Handling”
  ELSE
    IF Component_Material = “Metal with alloy” THEN
      1st_Choice_EOL_Option = “Reuse”
      2nd_Choice_EOL_Option = “Remanufacture”
      3rd_Choice_EOL_Option = “Secondary Recycling”
      4th_Choice_EOL_Option = “Disposal”
      5th_Choice_EOL_Option = “Incinerating”
    ELSE
      IF Component_Material = “Metal without alloy” THEN
        1st_Choice_EOL_Option = “Reuse”
        2nd_Choice_EOL_Option = “Remanufacture”
```

```
        3rd_Choice_EOL_Option = "Primary Recycling"
        4th_Choice_EOL_Option = "Disposal"
      ELSE
        IF Component_Material = "Polymer" THEN
          1st_Choice_EOL_Option = "Reuse"
          2nd_Choice_EOL_Option = "Remanufacture"
          3rd_Choice_EOL_Option = "Primary Recycling"
          4th_Choice_EOL_Option = "Secondary Recycling"
          5th_Choice_EOL_Option = "Incinerating"
          6th_Choice_EOL_Option = "Disposal"
        ELSE
          IF Component_Material = "Ceramic" THEN
            1st_Choice_EOL_Option = "Reuse"
            2nd_Choice_EOL_Option = "Remanufacture"
            3rd_Choice_EOL_Option = "Secondary Recycling"
            4th_Choice_EOL_Option = "Disposal"
          ELSE
            IF Component_Material = "Ceramic" THEN
              1st_Choice_EOL_Option = "Reuse"
              2nd_Choice_EOL_Option = "Remanufacture"
              3rd_Choice_EOL_Option = "Secondary Recycling"
              4th_Choice_EOL_Option = "Incinerating"
              5th_Choice_EOL_Option = "Disposal"
            ENDIF
          ENDIF
        ENDIF
      ENDIF
    ENDIF
  ENDIF
END

Compute_Present_Value
  Select_Cost_To_Be_Forecasted                                7
END

  Select_Cost_To_Be_Forecasted

  Prompt Cost_Equivalent_To_New_Material_Historical_Data      8
  Get  Cost_Equivalent_To_New_Material_Historical_Data
  Historical_Cost_Data = Cost_Equivalent_To_New_Material_Historical_Data
```

```
Develop_Regression_Model
Calculate_Cost_To_Be_Forecasted
Cost_Equivalent_To_New_Material = Cost
Calculate_Present_Value
Present_Value_of_ Cost_Equivalent_To_New_Material = Present_Value

Prompt Disassembly_Cost_Historical_Data                          9
Get _Disassembly_Cost_Historical_Data
Historical_Cost_Data = Disassembly_Cost_Historical_Data
Develop_Regression_Model
Calculate_Cost_To_Be_Forecasted
Disassembly_Cost = Cost
Calculate_Present_Value
Present_Value_of_Disassembly_Cost = Present_Value

IF  EOL_Option = “Reuse” THEN                                    10
  Prompt Collection_Cost_Historical_Data
  Get _Collection_Cost_Historical_Data
  Historical_Cost_Data = Collection_Cost_Historical_Data
  Develop_Regression_Model
  Calculate_Cost_To_Be_Forecasted
  Collection_Cost = Cost
  Calculate_Present_Value
  Present_Value_of_ Collection_Cost = Present_Value
ELSE
    IF EOL_Option = “Remanufacture” THEN
      Prompt Collection_Cost_Historical_Data
      Get _Collection_Cost_Historical_Data
      Historical_Cost_Data = Collection_Cost_Historical_Data
      Develop_Regression_Model
      Calculate_Cost_To_Be_Forecasted
      Collection_Cost = Cost
      Calculate_Present_Value
      Present_Value_of_ Collection_Cost = Present_Value

      Prompt Remanufacture_Cost_Historical_Data
      Get _Remanufacture_Cost_Historical_Data
      Historical_Cost_Data = Remanufacture_Cost_Historical_Data
      Develop_Regression_Model
      Calculate_Cost_To_Be_Forecasted
```

```
  Remanufacture_Cost = Cost
  Calculate_Present_Value
  Present_Value_of_ Remanufacture_Cost = Present_Value

  Prompt Component_Cost_Historical_Data
  Get _Component_Cost_Historical_Data
  Historical_Cost_Data = Component_Cost_Historical_Data
  Develop_Regression_Model
  Calculate_Cost_To_Be_Forecasted
  Component_Cost = Cost
  Calculate_Present_Value
  Present_Value_of_ Component_Cost = Present_Value
ELSE
  IF  EOL_Option = “Primary recycling” THEN
    Prompt Collection_Cost_Historical_Data
    Get _Collection_Cost_Historical_Data
    Historical_Cost_Data = Collection_Cost_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Collection_Cost = Cost
    Calculate_Present_Value
    Present_Value_of_ Collection_Cost = Present_Value

    Prompt Recycling_Cost_Historical_Data
    Get _Recycling_Cost_Historical_Data
    Historical_Cost_Data = Recycling_Cost_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Recycling_Cost = Cost
    Calculate_Present_Value
    Present_Value_of_ Recycling_Cost = Present_Value

    Prompt Market_Value_of_Material_Historical_Data
    Get _ Market_Value_of_Material_Historical_Data
    Historical_Cost_Data = Market_Value_of_Material_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Market_Value_of_Material = Cost
    Calculate_Present_Value
    Present_Value_of_ Market_Value_of_Material = Present_Value
```

```
ELSE
  IF EOL_Option = “Secondary recycling” THEN
    Prompt Collection_Cost_Historical_Data
    Get _Collection_Cost_Historical_Data
    Historical_Cost_Data = _Collection_Cost_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Collection_Cost = Cost
    Calculate_Present_Value
    Present_Value_of_ Collection_Cost = Present_Value

    Prompt Recycling_Cost_Historical_Data
    Get _Recycling_Cost_Historical_Data
    Historical_Cost_Data = Recycling_Cost_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Recycling_Cost = Cost
    Calculate_Present_Value
    Present_Value_of_ Recycling_Cost = Present_Value

    Prompt Scrap_Value_of_Material_Historical_Data
    Get _ Scrap_Value_of_Material_Historical_Data
    Historical_Cost_Data = Scrap_Value_of_Material_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Scrap_Value_of_Material = Cost
    Calculate_Present_Value
    Present_Value_of_ Scrap_Value_of_Material = Present_Value
ELSE
    IF EOL_Option = “Incinerating” THEN

      Prompt Collection_Cost_Historical_Data
      Get _Collection_Cost_Historical_Data
      Historical_Cost_Data = Collection_Cost_Historical_Data
      Develop_Regression_Model
      Calculate_Cost_To_Be_Forecasted
      Collection_Cost = Cost
      Calculate_Present_Value
      Present_Value_of_ Collection_Cost = Present_Value
```

```
  Prompt Unit_Cost_of_Energy_Material_Historical_Data
  Get _ Unit_Cost_of_Energy_Historical_Data
  Historical_Cost_Data = Unit_Cost_of_Energy_Historical_Data
  Develop_Regression_Model
  Calculate_Cost_To_Be_Forecasted
  Unit_Cost_of_Energy = Cost
  Calculate_Present_Value
  Present_Value_of_ Unit_Cost_of_Energy = Present_Value

  Prompt Incinerating_Cost_Historical_Data
  Get _ Incinerating_Cost_Historical_Data
  Historical_Cost_Data = Incinerating_Cost_Historical_Data
  Develop_Regression_Model
  Calculate_Cost_To_Be_Forecasted
  Incinerating_Cost = Cost
  Calculate_Present_Value
  Present_Value_of_ Incinerating_Cost = Present_Value

ELSE
  IF  EOL_Option = “Disposal” THEN

    Prompt Collection_Cost_Historical_Data
    Get _Collection_Cost_Historical_Data
    Historical_Cost_Data = Collection_Cost_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Collection_Cost = Cost
    Calculate_Present_Value
    Present_Value_of_ Collection_Cost = Present_Value

    Prompt Disposal_Cost_Historical_Data
    Get _ Disposal_Cost_Historical_Data
    Historical_Cost_Data = Disposal_Cost_Historical_Data
    Develop_Regression_Model
    Calculate_Cost_To_Be_Forecasted
    Disposal_Cost = Cost
    Calculate_Present_Value
    Present_Value_of_ Disposal_Cost = Present_Value
```

```
            ELSE
              IF EOL_Option = "Special Handling" THEN

                Prompt Collection_Cost_Historical_Data
                Get _Collection_Cost_Historical_Data
                Historical_Cost_Data = Collection_Cost_Historical_Data
                Develop_Regression_Model
                Calculate_Cost_To_Be_Forecasted
                Collection_Cost = Cost
                Calculate_Present_Value
                Present_Value_of_ Collection_Cost = Present_Value

                Prompt Special_Handling_Cost_Historical_Data
                Get _ Special_Handling_Cost_Historical_Data
                Historical_Cost_Data = Special_Handling_Cost_Historical_Data
                Develop_Regression_Model
                Calculate_Cost_To_Be_Forecasted
                Special_Handling_Cost = Cost
                Calculate_Present_Value
                Present_Value_of_ Special_Handling_Cost = Present_Value

              END IF
            END IF
          END IF
        END IF
      END IF
    END IF
  END IF
END

Develop_Regression_Model
Read Number_of_Historical_Data                                       11

  For q = Number_of_Historical_Data                                  12
    Year(q) = q
    Cost(q) = Historical_Cost_Data
    f(q) = 1
  Next

  IF Forecasting_Model = "'linear regression" THEN                   13
```

```
    FOR q = 1 To Number_of_Historical_Data
        IF NOT f(q) <= 0 THEN
            n(1) = n(1) + f(q)
            For w = 1 To f(q)
                n(2) = n(2) + Year(q)
                n(3) = n(3) + Cost(q)
                n(4) = n(4) + Year(q) ^ 2
                n(5) = n(5) + Cost(q) ^ 2
                n(6) = n(6) + (Year(q) * Cost(q))
            NEXT
        ENDIF
     NEXT
 ELSE
IF FORECASTING_Model = "'logarithmic regression"
    FOR q = 1 To Number_of_Historical_Data
        IF NOT f(q) <= 0 THEN
            n(1) = n(1) + f(q)
            For w = 1 To f(q)
                n(2) = n(2) + Ln(Year(q))
                n(3) = n(3) + Cost(q)
                n(4) = n(4) + Ln(Year(q)) ^ 2
                n(5) = n(5) + Cost(q) ^ 2
                n(6) = n(6) + Ln(Year(q)) * Cost(q)
            NEXT
        ENDIF
    NEXT
ELSE
 IF Forecasting_Model = "'exponential regression"
    FOR = 1 To Number_of_Historical_Data
        IF NOT f(q) <= 0 THEN
            n(1) = n(1) + f(q)
            For w = 1 To f(q)
                n(2) = n(2) + Year(q)
                n(3) = n(3) + Ln(Cost(q))
                n(4) = n(4) + Year(q) ^ 2
                n(5) = n(5) + Ln(Cost(q)) ^ 2
                n(6) = n(6) + (Year(q) * Ln(Cost(q)))
            NEXT
        ENDIF
    NEXT
```

```
    ELSE
    IF Forecasting_Model = "'power regression"
        FOR q = 1 To Number_of_Historical_Data
          IF NOT f(q) <= 0 THEN
            n(1) = n(1) + f(q)
            For w = 1 To f(q)
              n(2) = n(2) + Ln(Year(q))
              n(3) = n(3) + Ln(Cost(q))
              n(4) = n(4) + Ln(Year(q)) ^ 2
              n(5) = n(5) + Ln(Cost(q)) ^ 2
              n(6) = n(6) + Ln(Year(q)) * Ln(Cost(q))
            NEXT
          ENDIF
        NEXT
      ENDIF
      n(7) = n(2) / n(1)                                              14
      n(8) = n(3) / n(1)                                              15
      h = n(1) * n(6) - n(2) * n(3)                                   16
      p = n(1) * n(4) - n(2) ^ 2                                      17
      o = n(1) * n(5) - n(3) ^ 2                                      18
      n(9) = Sqr(p / n(1) ^ 2)                                        19
      n(10) = Sqr(o / n(1) ^ 2)                                       20
      n(11) = Sqr(p / (n(1) * (n(1) - 1)))                            21
      n(12) = Sqr(o / (n(1) * (n(1) - 1)))                            22
      n(14) = h / p                                                   23
      IF  Regression_Model = "Linear" OR "Logarithmic" THEN           24
        n(13) = (n(3) - n(14) * n(2)) / n(1)
      ELSE
        n(13) = Exp((n(3) - n(14) * n(2)) / n(1))
      ENDIF
      n(15) = h / Sqr(p * o)
      a = n(13)
      b = n(14)
END

Calculate_Cost_To_Be_Forecasted
  CASE OF Regression_Model                                            25
     "linear regression":
          Cost = a + b * (Expected_Life_of_Product + Number_of_Historical_Data + 1)
     "logarithmic regresion":
```

```
        Cost = a + b * Ln(Expected_Life_of_Product + + Number_of_Historical_Data + 1)
     "exponential regression":
        Cost = a * Exp(b * (Expected_Life_of_Product + Number_of_Historical_Data + 1))
     "power regression":
          Cost = a * (Expected_Life_of_Product + Number_of_Historical_Data + 1) ^ b
  ENDCASE
END

  Calculate_Present_Value
  Read Discount_Rate, Expected_Life_of_Product
  Present_Value =  Cost / ((1 + Discount_rate) ^Expected_Life_of_Product)        26
  END

  Compute EOL_Value
  IF  EOL_Option = "Reuse" THEN                                                  27
        Miscellaneous_Cost = Present_Value_Of_Collection_Cost
        EOLValue = Present_Value_Of_Component_Cost – Miscellaneous_Cost
        Out put_EOL_Value
  ELSE
       IF EOL_Option = "Remanufacture" THEN
         Miscellaneous_Cost = Present_Value_Of Collection_Cost + Present_Value_Of_
         Remanufacture_Cost
         EOLValue = Present_Value_Of _Component_Cost  - Miscellaneous_Cost
         Out put_EOL_Value
       ELSE
         IF  EOL_Option = "Primary recycling" THEN
           Miscellaneous_Cost = Present_Value_Of _CollectionCost + Present_Value_Of
           _Recycling_Cost
           EOLValue = Component_Mass * Present_Value_Of _ Market_Value_of_Material –
           Miscellaneous_Cost
           Out put_EOL_Value
         ELSE
           IF EOL_Option = "Secondary recycling" THEN
             MiscellaneousCost = Present_Value_Of _Collection_Cost + Present_Value_Of
             _Recycling_Cost
             EOLValue = CompMass * Present_Value_Of _Scrap_Value_of_Material –
             Miscellaneous_Cost
             Out put_EOL_Value
         ELSE
             IF EOL_Option = "Incinerating" THEN
```

```
                Miscellaneous_Cost = Present_Value_Of _ Collection_Cost +
                Present_Value_Of _Incenaraing_Cost
                EOLValue = Energy_Produced * Present_Value_Of _Unit_Cost_of_Energy –
                Miscellaneous_Cost
                Out put_EOL_Value
              ELSE
                IF  EOL_Option = “Disposal” THEN
                  Miscellaneous_Cost = Present_Value_Of _Collection_Cost +
                  Component_Mass * Present_Value_Of _Disposal_Cost
                  EOLValue = - Miscellaneous_Cost
                  Out put_EOL_Value
                ELSE
                  IF EOL_Option = “Special Handling” THEN
                    Miscellaneous_Cost = Present_Value_Of _Collection_Cost + Comp_Mass
                    * Present_Value_Of _Special_Handling_Cost
                    EOLValue = - Miscellaneous_Cost
                    Out put_EOL_Value
                  END IF
                END IF
              END IF
            END IF
          END IF
        END IF
      END IF
  END
```

APPENDIX 2

OBSERVATION DATA OF THE KELISA RIGHT-BACK DOOR DISASSEMBLY TIME (SECOND)

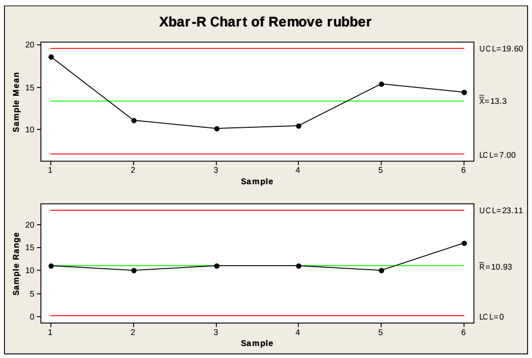
Job Elements / Data	Remove Handle 1 (Inside)	Remove Handle 2 (Inside)	Remove locker	Remove cover	Remove door gear	Remove small glass
	1	2	3	4	5	6
1	11	12	4	6	41	4
2	4	9	3	5	22	9
3	5	8	7	4	35	4
4	9	22	3	7	18	2
5	6	12	4	4	21	4
6	11	12	8	4	41	3
7	9	14	6	4	29	2
8	7	14	4	8	30	3
9	7	12	5	4	22	6
10	7	11	4	7	30	6
11	9	10	3	11	24	3
12	6	6	7	4	27	3
13	7	9	6	10	27	6
14	5	13	3	4	37	6
15	9	15	6	7	35	8
16	11	7	5	8	22	3
17	11	11	5	6	20	4
18	12	10	4	3	23	9
19	3	6	6	5	26	8
20	8	18	5	7	35	5
21	11	8	2	6	35	5
22	6	8	3	5	33	4
23	7	10	3	7	25	4
24	4	7	5	6	22	3
25	4	18	6	2	14	7
26	6	6	6	4	36	5
27	6	12	4	2	42	6
28	3	17	5	5	27	7
29	7	10	6	3	42	8
30	7	13	7	7	32	5
Average	7.06	11.03	4.77	5.45	28.32	5.10
Stdev	2.57	3.92	1.51	2.15	7.64	2.03

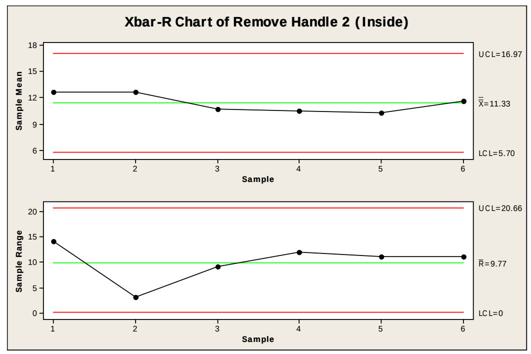
APPENDIX 2
OBSERVATION DATA OF THE KELISA RIGHT-BACK DOOR DISASSEMBLY TIME (SECOND) (continued)

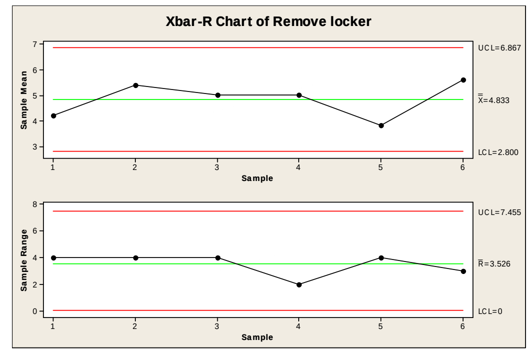
Job Elements / Data	Remove rubber	Remove large glass	Remove Handle (Outside)	Remove metal handle	Remove bracket
	7	8	9	10	11
1	23	2	7	30	17
2	22	2	6	38	10
3	18	2	9	33	10
4	18	4	5	47	20
5	12	4	11	26	20
6	11	2	11	34	14
7	8	4	11	28	16
8	18	3	12	25	9
9	10	3	12	33	10
10	8	3	9	41	11
11	6	7	11	41	12
12	6	3	8	41	12
13	11	5	9	36	9
14	10	4	9	21	13
15	17	6	12	45	14
16	6	3	13	49	17
17	12	4	10	29	16
18	9	5	12	29	22
19	8	4	8	40	16
20	17	5	14	35	11
21	11	6	11	31	18
22	13	6	8	35	13
23	21	4	6	31	13
24	16	5	11	29	21
25	16	3	11	36	12
26	11	5	10	36	20
27	21	6	10	35	19
28	17	4	11	25	13
29	18	7	12	44	15
30	5	7	10	32	14
Average	13.10	4.39	9.94	33.71	14.45
Stdev	5.29	1.53	2.16	6.87	3.78

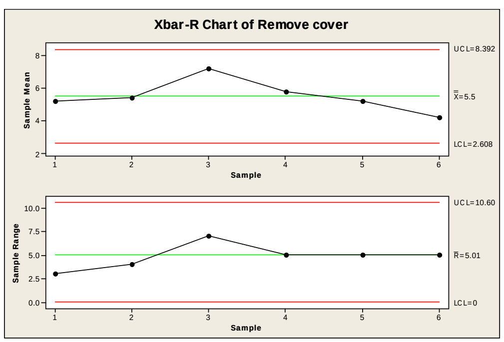
APPENDIX 3

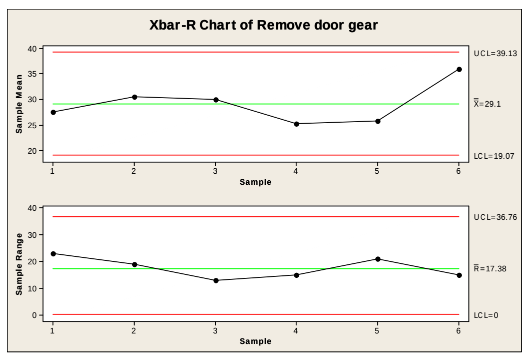
CONTROL CHART

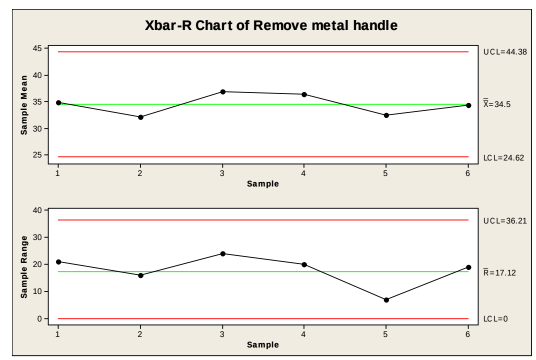






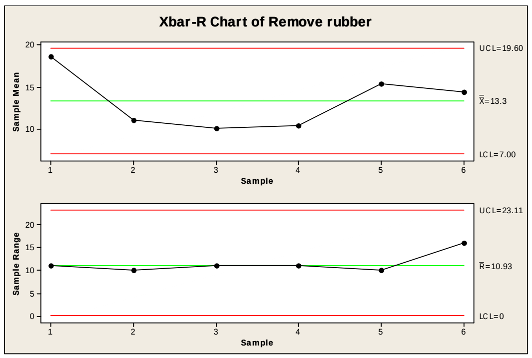


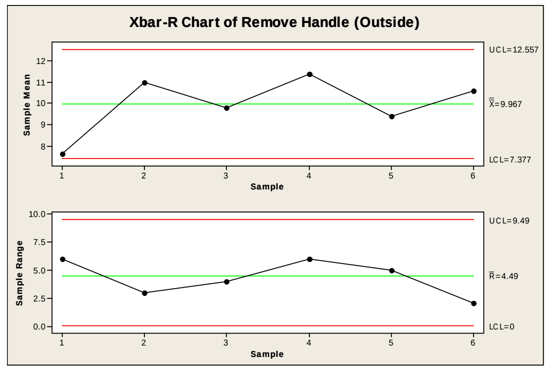


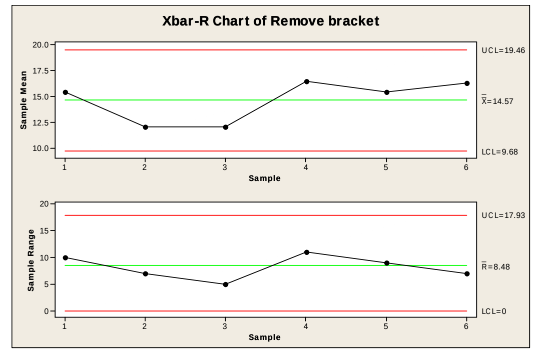


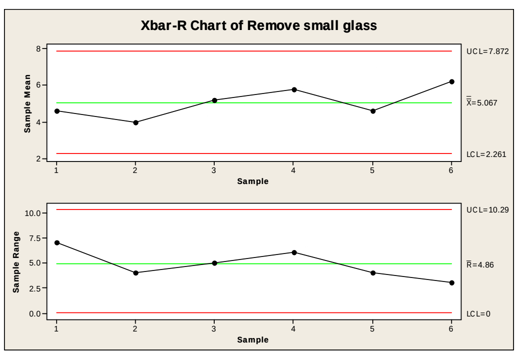
APPENDIX 3

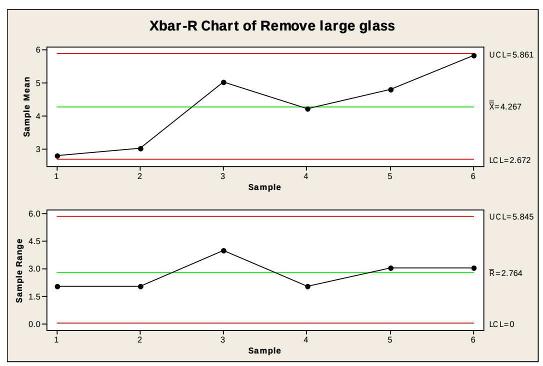
CONTROL CHART
(continued)





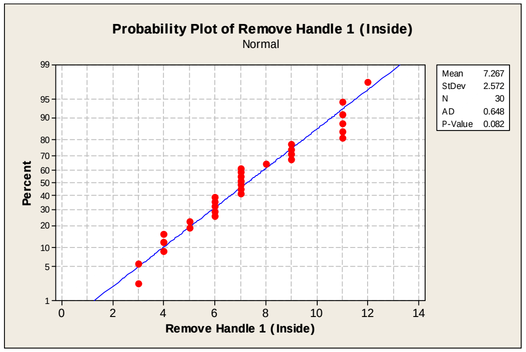


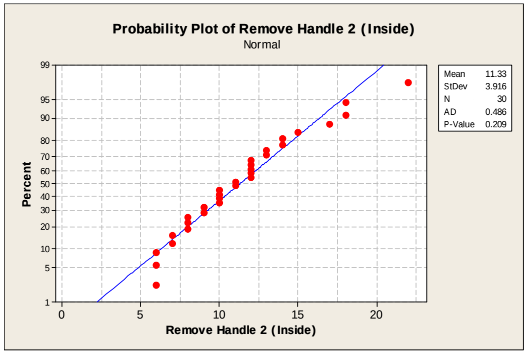


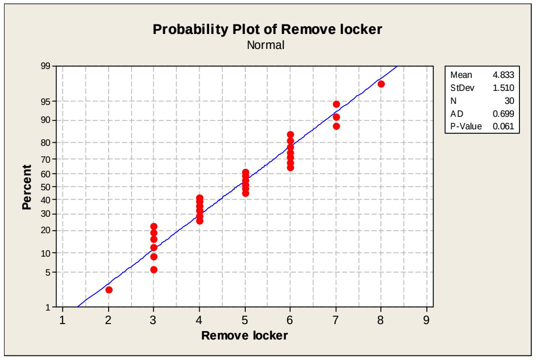


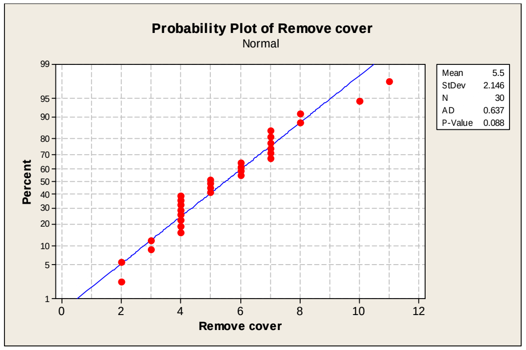
APPENDIX 4

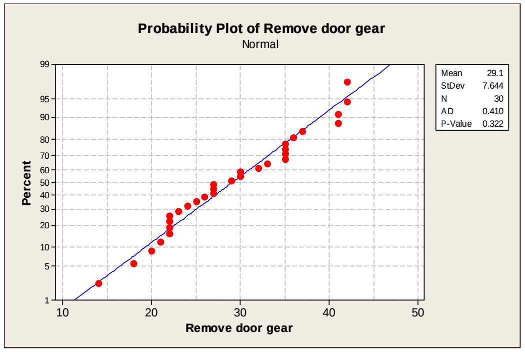
NORMAL PROBABILITY PLOT

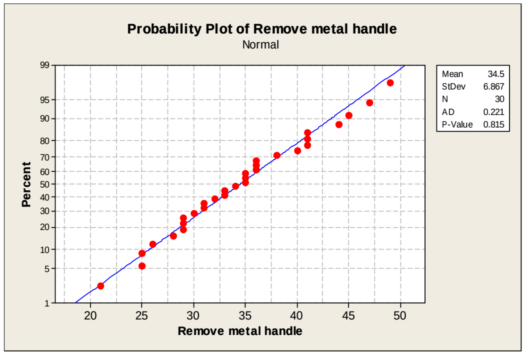






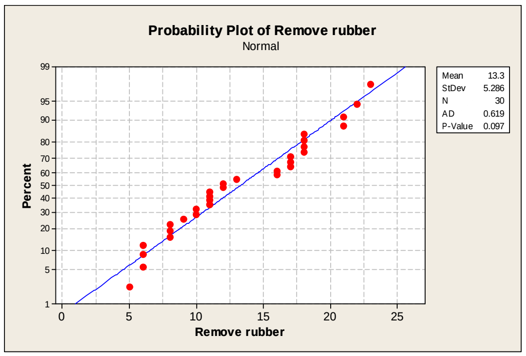


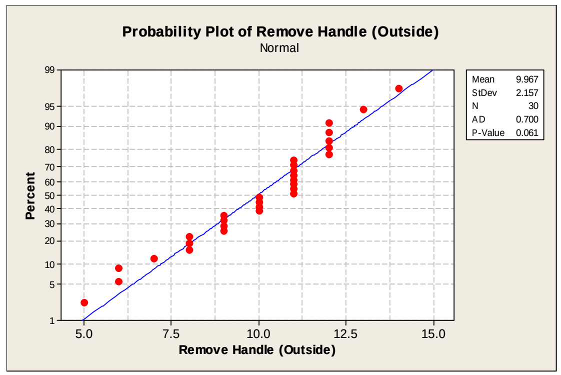


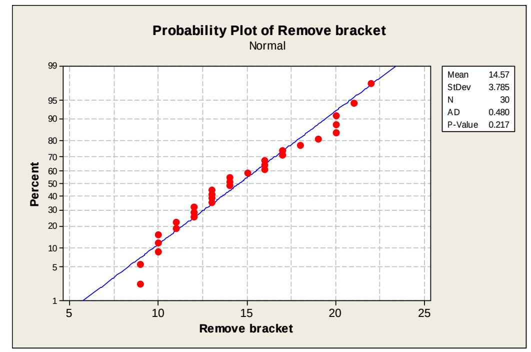


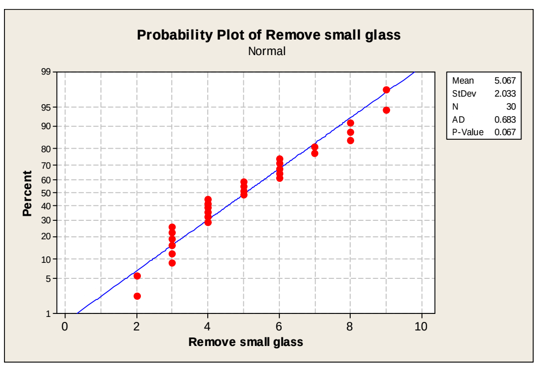
APPENDIX 4

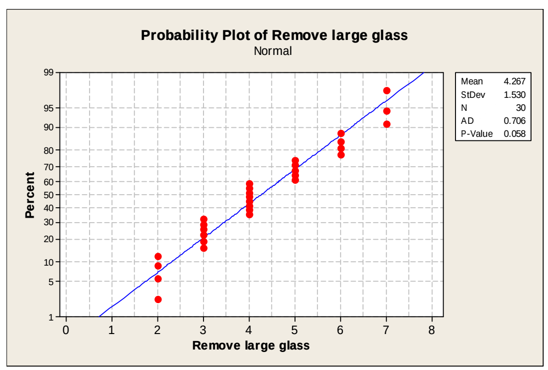
NORMAL PROBABILITY PLOT
(continued)











APPENDIX 5

Test of μ_0 (Mean of the Actual Disassembly Time) versus μ (Disassembly Time Obtained by the Developed Software)

<table>
<tr><th>Variable</th><th>Test Result</th></tr>
<tr><td>Remove Inner handle 1</td><td><pre>Test of mu = 7.956 vs not = 7.956
The assumed standard deviation = 2.57218

Variable   N   Mean   StDev SE Mean   95% CI   Z
Remove Handle1   30 7.26667 2.57218 0.46961 (6.34624, 8.18709) -1.47

Variable   P
Remove Handle 1   0.142</pre></td></tr>
<tr><td>Remove Inner handle 2</td><td><pre>Test of mu = 10.044 vs not = 10.044
The assumed standard deviation = 3.91578

Variable   N   Mean   StDev SE Mean   95% CI   Z   P
Remove Handle 2   30 11.3333 3.9158   0.7149 (9.9321, 12.7346) 1.80 0.071</pre></td></tr>
<tr><td>Remove locked handle</td><td><pre>Test of mu = 4.5 vs not = 4.5
The assumed standard deviation = 1.52

Variable   N   Mean   StDev SE Mean   95% CI   Z   P
Remove locker 30 4.83333 1.51050 0.27751 (4.28942, 5.37725) 1.20 0.230</pre></td></tr>
<tr><td>Remove door cover</td><td><pre>Test of mu = 5.652 vs not = 5.652
The assumed standard deviation = 2.14556

Variable   N   Mean   StDev SE Mean   95% CI   Z   P
Remove cover 30 5.50000 2.14556 0.39172 (4.73223, 6.26777) -0.39 0.698</pre></td></tr>
</table>

APPENDIX 5

Test of μ_0 (Mean of the Actual Disassembly Time) versus μ (Disassembly Time Obtained by the Developed Software) (continued)

Variable	Test Result
Remove door gear	Test of mu = 26.892 vs not = 26.892 The assumed standard deviation = 7.64447 Variable N Mean StDev SE Mean 95% CI Z P Remove door gear 30 29.1000 7.6445 1.3957 (26.3645, 31.8355) 1.89 0.059
Remove metal handle	Test of mu = 31.752 vs not = 31.752 The assumed standard deviation = 6.86696 Variable N Mean StDev SE Mean 95% CI Z P Remove metal handle 30 34.5000 6.8670 1.2537 (32.0427, 36.9573) 1.76 0.078
Remove rubber	Test of mu = 14.58 vs not = 14.58 The assumed standard deviation = 5.28596 Variable N Mean StDev SE Mean 95% CI Z P Remove rubber 30 13.3000 5.2860 0.9651 (11.4085, 15.1915) -0.88 0.380
Remove handle Outside	Test of mu = 9.648 vs not = 9.648 The assumed standard deviation = 2.16 Variable N Mean StDev SE Mean 95% CI Z Remove Handle Outside 30 9.96667 2.15732 0.39436 (9.19373, 10.73960) 0.81 Variable P Remove Handle Outside 0.419
Remove bracket	Test of mu = 14.04 vs not = 14.04 The assumed standard deviation = 3.78 Variable N Mean StDev SE Mean 95% CI Z P Remove bracket 30 14.5667 3.7846 0.6901 (13.2140, 15.9193) 0.76 0.445

APPENDIX 5

Test of μ_0 (Mean of the Actual Disassembly Time) versus μ (Disassembly Time Obtained by the Developed Software) (continued)

Variable	Test Result
Remove small glass	Test of mu = 4.86 vs not = 4.86 The assumed standard deviation = 2.03306 Variable N Mean StDev SE Mean 95% CI Z Remove small glass 30 5.06667 2.03306 0.37118 (4.33916, 5.79417) 0.56 Variable P Remove small glass 0.578
Remove large glass	Test of mu = 4.104 vs not = 4.104 The assumed standard deviation = 1.53 Variable N Mean StDev SE Mean 95% CI Z Remove large glass 30 4.26667 1.52978 0.27934 (3.71917, 4.81416) 0.58 Variable P Remove large glass 0.560

APPENDIX 6

LIST OF PUBLICATIONS

1. Articles in Internationally Reviewed Scientific Journal

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. EDAS – Software for End-of-Life Disassembly Analysis. *It has been accepted for publication in International Journal of Sustainable Design (IJSDes)*. Vol. 1, No. 3. Inderscience Publishers.

2. Article in Other Scientific Journal

Afrinaldi, F., Mat Saman M.Z., Mohamed Shaharoun, A. (2008). The Evaluation Methods of Disassemblability for Automotive Components-a Review and Agenda for Future Research. Journal Mekanikal. Special Issue No. 26, pp. 49-62.

3. Book Chapter

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. (2008). “End-of-Life Product Disassembly Analysis”, Chapter 8 of *Advance in Manufacturing and Industrial Engineering*, Penerbit Universiti Teknologi Malaysia (UTM), Johor, Malaysia.

4. Papers at International and Regional Conferences

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. (2009). A Decision Making Software for End-of-Life Vehicle Disassemblability and Recyclability Analysis. *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM 2009)*. 8-11 December 2009. Hong Kong, 2261-2265.

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. (2009). A New Methodology for End-of-Life Product Disassembly Analysis. *1st International Congress on Sustainability Science and Engineering (ICOSSE09)*. 9-12 August 2009. Cincinnati, USA.

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. Methodology of End-of-Life Product Disassembly Analysis. *Proceeding of the International Graduate Conference on Engineering and Science (IGCES2008)*. 23-24 December 2008. Johor Bahru, Malaysia.

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. Computer-based End-of-Life Product Disassemblability Evaluation Tool. *Proceeding of The 9th Asia Pacific Industrial Engineering & Management Systems Conference*. 3-5 December 2008. Nusa Dua Bali, Indonesia, 2320-2331.

Afrinaldi, F., Mat Saman, M.Z., Mohamed Shaharoun, A. The Evaluation Methods of Disassemblability for Automotive Components-a Review and Agenda for Future Research. *Proceeding of the 2nd Regional Conference on Vehicle Engineering and Technology 2008*. 15-16 July 2008. Kuala Lumpur, Malaysia, 377-384.