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A Methodology for Optimizing Modular Design Considering Product End of Life Strategies

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Product modularity is a concept of clustering the independent components into logical units that are relatively independent to each other in functions. With the growing interest in environmental protection, the inclusion of product end of life issues during product design has been seen as a promising method to improve product utilization after its retirement. There are very few methodologies that deal with modularity at the conceptual design stage in which incorporate product end of life strategies and end of life cost in the literature. The lack of information during conceptual design will cause failure in overcoming drawbacks that will be apparent later in the detail design. The motivation of this study is to identify the relationship between product end of life strategies and modular design, and to formulate an optimization method to assist designers in designing products with appropriate end of life strategies to reduce environmental impact during product retirement. This paper proposes a practical method in optimizing modular design with different end of life strategies by using an Excel based approach that will be usable by designers.

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NOMENCLATURE

A = assembly
M = module
s = number of modules
n = number of alternative modules
c = number components
i = index for modules
j = index of components
k = index of alternative modules
I_{ijk} = integrated relationship matrix
C_{func} = matrix of function modular clustering driver
X_i = depreciation factor of a specific component i
H_i = disassembly cost
L_{cost} =labour cost
T = time for disassembly
R_c = recycling cost
$C_{removal}$ = cost for special treatment/remove hazardous or toxic waste
P_{comp} = price of component after retirement
n_{comp} = number of component
P_{rec} = price of reclaimed material
m_{mat} = quantity of material
P_{rec-sp} = price of reclaimed material after special treatment
m_{mat-sp} = quantity of reclaimed material after special treatment
$L_{cost-sp}$ = labour cost for special treatment
T_{sp} = time needed for special treatment

1. Introduction

It is known that a large proportion of environmental problems are due to industrial activities. Industries contribute to natural resource depletion during mining or extraction; create CO2 emissions and consume energy consumption during production and generate enormous waste, thus putting strain on the environment. One of the environmental impacts created by industrial activities is the generation of waste after products' usage. Here is where the term product end of life is introduced, in which the product no longer performs the intended function. To reduce the impact of waste generated during a product's end of life, many strategies to improve product end of life are established such as reuse, remanufacturing, recycling, as well as disposal. Many researches, methods and tools have been developed to improve product end of life during product design. However, there is little attention given to the relation between product end of life strategies and product modularity.

Product modularity is a concept of clustering the independent components into logical units that are relatively independent to each other in functions. Nowadays, modularity in product design has been expanded to wider applications in the industry. Modular design is one of the most promising ways to improve product's flexibility that are valuable to production's variety and scale.[1] In particular, product modularity focuses on function and manufacturability issues. With the growing interest in environmental protection, the inclusion of product end of life issues during product design has been seen as a promising method to improve product utilization after its retirement for the purpose of preserving natural resources by prolonging the use of the products or materials. This mainly by the following reasons: firstly, product at the retirement state may have valuable material that can generate new revenue, secondly, product consisting of different material combination and structure causing different treatment during end of life, i.e. reuse, remanufacturing, recycling.

In the literature, it was found that very few methodologies dealt with modularity at the conceptual design stage.[2,3] With a lack of information during conceptual design, there will be failure to overcome drawbacks that will be apparent later in the detail design.[4] In addition, there is an absence in the literature on the explanation of the methods relating product modularity with product end of life strategies. Most of the product modularity researches tend to cater for life cycle issues rather than product end of life strategies[5] for example, has proposed a method to determine modularity that include life cycle perspectives. Tseng et al.[6] presented a liaison graph model to evaluate part connectivity optimized using Group Genetic Algorithm (GGA). Umeda et al.[7] proposed a modular design methodology that derives modular structure based on life cycle parameter and geometric information. A recent study by Yu et al.[8] provides an optimization of product modular design incorporating life cycle issues using GGA. The study presented unique modular driving forces such as function, geometric position, connection, and material. There are relatively few research papers with the objectives of incorporating End of Life (EOL) strategies and its associated cost.

According to Ishii,[9] product modularity impacts every stage in the product life cycle. This implies that product modularity has great influences on the design decision when selecting end of life strategies. Moreover, in a more complex product in which different structure variation is requested by customers, design decision on product end of life strategies becomes more complicated. This research tries to identify the relationship between product end of life strategies and modular design with structure variation and formulate an optimization method that can assist designers to design products with appropriate end of life strategies to reduce environmental impact on product retirement.

Frequent variation of product specifications causes assembly and disassembly of components and modules to become more complicated, consequently it complicates the selection of product end of life strategies. Therefore, there is a need for appropriate modules in modular design with different end of life strategies. A product is rarely disassembled into every single component at its end of life, and sometimes it is more economical to decompose it into subassembly thus reducing disassembly cost. As a result, the issue of product modular design with structure variation in relation to optimizing product end of life strategies is worthy of investigation.

This paper tries to identify the relationship between product end of life strategies and modular design and formulate an optimization method that can assist designers to design product with appropriate end of life strategies that can reduce environmental impact during product retirement.

The organization of this paper is as follows: Section 2 is a literature review on modular design. Section 3 explains the mathematical formulation of the optimization. Section 4 contains an illustrative example of the proposed model, followed by result and discussion in Section 5. Then, conclusions and future research are presented in Section 6.

2. Literature Review

2.1 Modularity design

In recent years, modularity has received growing attention as a product design strategy. Modularity refers to the use of common units to create product variants. Modularity design in the industry is valuable to provide useful external variety as well as satisfying customer requirement with the least cost that is still within its manufacturing capability.[10]

Modularity is a concept and process of clustering the independent components into logical units that are relatively independent to each other in functions.[8] In broader terms, modularity is an approach for organizing complex product and process efficiently by decomposing complex product or process into simple portions in order to easily managed separately or as a whole.[11] There is also an available definition in relation between modularity and life cycle of a product including retirement, manufacturability, assembly, etc[12] - modules that contain a high number of components that have minimal dependencies upon and similarities to other components in different module during their life cycle. Here, similarity means within a module, all components be processed identically, and dependency means the interactions between components will cause difficulty in processing.

According to Newcomb et al.,[13] modular design incorporating whole life cycle issues of a product can improve whole life cycle performance. The advantages of using modularity are:

1. Increased product variety and reduce production lead time[14]
2. Decoupling tasks[15]
3. Ease of product maintenance, repair and disposal[16]
4. Economic scale and increased feasibility of components change[17]

Modular product design is architecture based therefore modularity can reduce product life cycle costs that can be applicable in the early stage of design.

2.2 Modularity measure

Product modularity measures are method of modularity evaluation to assist designers access the modularity of a product or redesign. There are several approaches in measuring product's modularity, and one that has been validated as having good performance is Design Structure Matrix-based modularity measure, in which modularity is presented as:

$$\text{Modularity} = \frac{1}{M}\sum_{k=1}^{M}\frac{\sum_{i=n_i}^{m_i}\sum_{j=n_j}^{m_i}R_{ij}}{(m_k-n_k+1)^2}-\frac{\sum_{i=n_k}^{m_i}\sum_{j=1}^{N}R_{ij}-\sum_{i=n_k}^{m_i}\sum_{j=n_k}^{N}R_{ij}}{N\times(m_k-n_k+1)-(m_k-n_k+1)^2}$$

where:

n_k = index of the first component in module k
m_k= index of the last component in module k
R_{ij}=the ith, jth element's value in the original matrix
M=number of modules in product
N= total number of components in a product

The other measure is the modular driving forces (MDFs) that emphasize on the relationship of physical structures, functionality and physical interactions among components, introduced by Yu et al..[8] In the MDFs approach, modularity considers the following aspects:

- Function, relate to the product function, in which each components form a product supporting specific product function.
- Structure, refers to the geometric position and connection structures of components[6]
- Component lifetime, regarded as the period of time during product usage.
- Material compatibility, contributes to end of life options such as reuse, recycling and disposal of product.
- Recyclability, refers to the characteristic of products or components recycling potential after usage.

2.3 Product end of life strategies

There are many options in managing a product's end-of-life; however, each option emphasizes on reducing different types of environmental impact while simultaneously being economically feasible. Fig. 1 shows the hierarchy of a product's end-of-life destination.

Fig 1 shows the waste hierarchy and consists of six levels, namely, disposal, energy recovery, recycling, reuse, minimization and prevention. This hierarchy represents the end-of-life strategy from the most favourable to the least favourable options. There are various advantages offered by different strategies at different levels of the product's end-of-life. Reducing the environmental impact emphasizes on pollution prevention as well as how to utilize materials when the product reaches its end-of-life. Extending lifespan and reuse is considered the best in the end-of-life strategy hierarchy. However, these strategies are not always easily implemented due to the requirement of strong material recovery infrastructure, support systems and regulations, which are currently unavailable in Malaysia.

Disposal is the least favorable end-of-life treatment. O'Brien[19] emphasized the need for maximizing the use and reuse of recycled components and materials.

2.4 Prior work on incorporating environmental issues in modular design

There are several literature on incorporating environmental issues in modular design, in which most of them proposes life cycle consideration

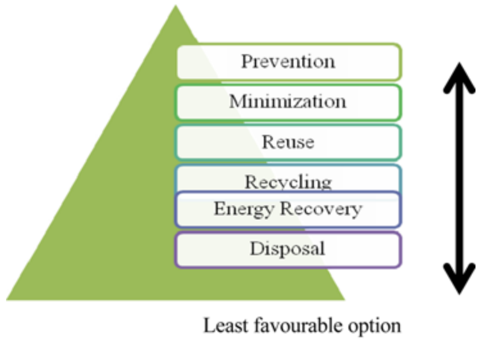

Fig. 1 Waste hierarchy[18]

in modularity design. Kimura et al.[20] proposed a modular design method that considers successive generation of products based on product functionality, commonality and life cycle similarity. Qian and Zhang[21] proposed an environmental analysis model for achieving modularity. A computer-aided generation of modularized conceptual designs was introduced by Gupta and Okudan[2] which incorporated modularity, design for assembly, and design for variety in their approach. Gu and Sosale[5] also presented a modular design methodology which incorporate life cycle issues. The aforementioned literature were only focusing on specific stages of product's life cycle, although can be used as fundamental studies for holistic life cycle issues. Yu et al.[8] proposed a more holistic life cycle perspective into modular design with the use of optimization as a computational method. Recently, Su and Chu[22] have proposed an evaluation tool for estimating carbon emission in the modularized design based on assembly sequence and structure. Similarly, Luh et al.[23] developed generic modularized product architecture for green product development.

The inclusion of end of life issues have also been discussed in the literature, however, most of the researchers emphasized only on one or two particular end of life strategies. Sosale et al.[24] developed a product modularization model specifically based on reuse and recycling parameters by using simulated annealing method. Gu et al.[5] expanded the modular design method with the entire product life cycle consideration. Kimura et al.[20] proposed a modularity design method that incorporates component reuse. Commonality analysis is used in this approach to identify module that can be shared by different usage in order to increase reuse magnitude of the module. Krikke et al.[25] developed a decision making model that is concerned with the structure of a product, such as modularity, reparability, recyclability and the logistic network. Li et al.[26] developed a method for modular formation incorporating end of life issues using the fuzzy graph approach. Kwak et al.[27] introduced an eco architecture analysis to help designers select the most desirable product's architecture which will result with an optimal end of life strategy.

One research conducted by Yu et al.[8] introduced a method to evaluate product modularity considering life cycles issues using Grouping Genetic Algorithm. An economical evaluation and environmental consideration using Eco Indicator 99 is added to improve the environmental performance of the modular design. This study has a few limitations as it is not always practical for designers. Gonzales and Diaz[28] have introduced an end of life decision making method based on bill of materials approach. This research emphasized on disassembly sequence that is reflected on the EOL strategy. Kreng and Lee[29] introduced a modular design optimization method using functional and physical interaction analysis and modular divers.

3. Mathematical Formulation

The detail procedure for generating modular design that considers end of life strategy is as follows:

Stage 1. Evaluation of modular clustering drivers

Step 1: Identify relationship matrix for each components based on modular clustering drivers

Step 2: Generate the integrated relationship matrix using rule based fuzzy inference system

Stage 2. Optimization

Step 1: Determine objective function

Step 2: Determine constraints

Step 3: Encoding

Step 4: Initialization

Step 5: Crossover

Step 6: Mutation

Step 7: Calculate fitness value

Stage 3. EOL strategy evaluation

Step 1: Run EOL evaluation for each module configuration

Step 2: Optimized modular design configuration

This study attempts to generate sets of modular design alternatives inclusive of EOL strategy. The following assumption must be introduced first on the proposed model for simplification that is a set of database on the candidate of components for modular design is given. The product's structure that composed a module is also defined.

Consider a product or an assembly having *M* modules, with each module consisting of *M'* sub modules and *p* components with *m* materials. Each sub module can be composed of different components, which indicates possibilities of different materials combinations. An assembly may have *n* sub modules alternatives, in which each module is characterized by its components, as shown in Fig 2. Each sub modules made up of different combinations of components and materials will have specific EOL options and costs.

The objective is to have an optimized set of modules configurations with suitable EOL strategy and minimal cost.

Denote that *s* as the number of modules, *n* is the number of alternative modules, *c* is the number components, *i* is the index for modules, *j* is the index of components, and k is the index of alternative modules.

3.1 Modular clustering drivers

A module can be composed of different combinations of components, whereby each combination have to satisfy the product function. The functional and physical interaction is derived from a relationship matrix, showing the relationship magnitude between components in a module. The relationship matrix corresponds to the modular clustering drivers, which is defined as the driving force to cluster the components into different modules. In this study, the modular driving forces from Yu et al.[8] is modified and simplified according to the EOL considerations. This study makes several contributions:

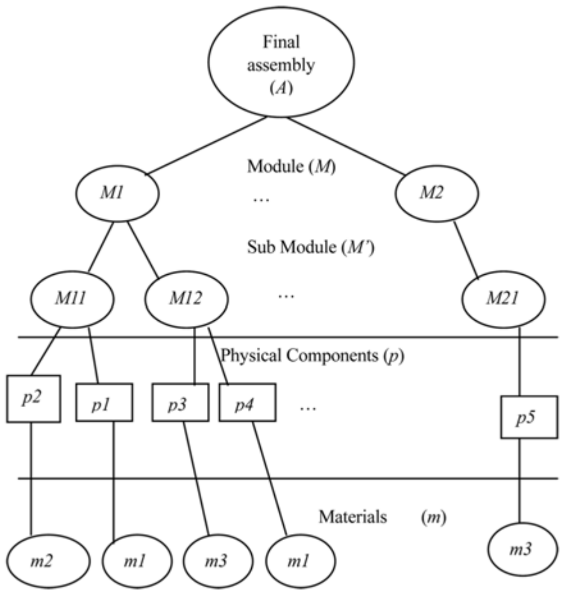

Fig. 2 Example of modularity hierarchy[23]

1. The work by Yu et al.[8] considers LCA and uses Eco Indicator 99 for environmental data, which in practice are difficult to be obtained. Furthermore, this environmental indicator is based on the European countries, which may not be directly applicable to developing nations. A more generalized and easier for interpretation approach is proposed in this study, which is suitable for real-life applications.

2. The costs associated with the end of life selection in modular design are included in the optimization formulation. Thus, it allows the designers to estimate the economic value taken from the end of life options considered during conceptual design.

3. A fuzzy environment in the optimization formulation is introduced in this study, allowing the use of linguistic variables; thus, making the approach practical and easy to understand.

4. The use of Excel-based computation is more practical to the designers due to the general familiarity of the software, requiring no additional add-on applications

5. This study has introduced several economic evaluations on end of life strategies, such as reuse, recycling, special treatment and disposal. These parameters were not considered in the study of Yu et al..[8]

The modified clustering drivers consist of functionality, structure, disassembly ability and materials as shows in Table 1.

The explanations of the modular clustering drivers are stated as follows:

1. Functionality

Functionality is an important aspect related to modular design. Functionality determines the performance of a product. Changes in module configuration must not neglect product functionality. Therefore, the relationship between components of a product module that realizes its function should be identified. To determine the component relationships, one must identify the possible subassembly that support certain required function.

2. Product architecture

According to Ulrich and Eppinger,[30] product architecture is defined as structural representations generated by product function and the

Table 1 Modular Clustering Drivers (MCDs)

Modular Clustering Drivers (MCDs)		Strong	Medium	Weak	None
		9	3	1	0
Functionality (FUNC)		High contribution to main function	One contribute to the main function, the other to subordinate function of this main function	Contribution to the same subordinate function	Contribution to different function or subordinate function
Structure (STRUC)	Geometric Position (GP)	One component inside another	Constrained by other 2 components	One component contacted another	Having no direct relation
	Connection/Joining (CONN)	Connection by welding or chemicals	Connection with fasteners (i.e., bolt, nuts)	Connection by spacing (i.e., snap fits)	No connection
Material (MAT)	Compatibility (COMP)	Same material	Compatible material	Not completely compatible material	Incompatible materials
Disassemblibility (DISS)		Manual disassembly	Required special tooling		Cannot disassemble

interaction of physical components. Product structure consists of geometric position and joining.[6] The geometric position is determined by the degree of freedom of the components, whereby joining is measured by connection method of the components such as welding, adhesive bonding or mechanical fastener.

3. Disassembility

Gonzales and Daz[28] indicated that disassembly is playing a key role in determining EOL strategies, since it is essential in ensuring the purity of recycled materials. Different disassembly method usually results in different disassembly cost[31] that will reflect the choices of EOL strategies. Therefore, in this study, disassembility is selected as one of the important modular clustering drivers.

4. Materials

Material determines the economic value of a product during its retirement. The type of materials has direct influence on the easiness of recycling since it determines recycling profit from the value of its secondary materials.

3.2 Integrated relationship matrix

After the modular clustering drivers identified, the next step is to build the relationship matrix for each of the modular clustering drivers. In this paper, there are five modular clustering driverstherefore five relationship matrixes are generated.

The relationship of component i to component j in for the realization of functionality is expressed as C_{func} with its associated grade numbers from 9, 3, 1 and 0 representing strong, medium, weak, none relationship which adopted modular driving force grade scale introduced by Yu et al. (2011). The mathematical notation of matrix representing functionality in modular clustering drivers is as follows:

$$C_{func} = \begin{pmatrix} N/A\ C_{func,12} \cdots C_{func,1(n-1)} & C_{func,1n} \\ \cdots C_{func,1(n-1)} & C_{func,1n} \\ . & . \\ . & . \\ . & . \\ N/A & C_{func,(n-1)n} \\ & N/A \end{pmatrix} \quad (1)$$

Five relationship matrices that have been generated are combined as an integrated relationship matrix using fuzzy inferential approach that allowing to use linguistic parameters. A set of rule base are developed in order to get the output for each index in the integrated relationship matrix as shown in Table 2. In the previous research proposed by Yu et al.[8] the integrated relationship matrix is constructed from all summation of modular driving force values. Here, a fuzzy inference system is employed to compose the integrated relationship matrix in order to obtain a more realistic value. This method also can be expanded to incorporate new factor.

3.3 Optimization procedure of modular design considering EOL strategy evaluation

The most important step in solving an optimization problem is to define a coding to the design variables that is represented by a chromosome.

In this paper Excel-based optimization software called SolveXL is used to run the computation since it is more practical and having good interoperability with any CAD based design environment.

According to Yu et al.,[8] if product P is divided into n modules, then:

$$P = M_1 U\ M_2 U\ \ldots\ U\ M_k \quad (2)$$

Given the integrated relationship matrix $I = [I_{ijk}]$, where:

$I_{ijk} = n$

$n = 0,1,\ldots n$

$i = 1,2,\ldots,m$

$j=1,2,\ldots c$

$k=1,2,\ldots a$

The objective function is to get maximum EOL profits. Therefore, the formulation will be as follows:

$$\text{Max: } Z = \Sigma\Sigma\Sigma\ I_{ijk} C_j M_{ik} \quad (3)$$

whereby each component j has a specific cost C_j and M_{ik} is module i in kth alternative modules.

$$M_{ik} = \begin{cases} 1 & \text{if component } j \text{ belongs to module } k \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

3.3.1 Encoding scheme

Fig. 3 illustrates the encoding scheme proposed in this paper. A Genetic Group Algorithm is employed to solve optimization, since it is an effective method for clustering problems.

Each gene represents a module to avoid inefficient computation caused by lengthy chromosomes. Fig. 3 shows that gene A is expressed as A={1, 3, 5}, B is expressed as B={2, 3, 1} and gene C expressed

Table 2 Rule based for Integrated Relationship Matrix (IRM)

Rule		FUNC		CONN		COMP		MAT		DISS		Index in IRP
1	IF	Strong	AND	Strong	AND	Strong	AND	Strong	AND	Strong	THEN	Strong
2	IF	Strong	AND	Strong	AND	Strong	AND	Strong	AND	Medium	THEN	Strong
3	IF	Strong	AND	Strong	AND	Strong	AND	Medium	AND	Medium	THEN	Strong
4	IF	Strong	AND	Strong	AND	Strong	AND	Medium	AND	Low	THEN	Medium
5	IF	Strong	AND	Strong	AND	Medium	AND	Medium	AND	Low	THEN	Medium
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.	.											
100	IF	None	AND	None	AND	None	AND	None	AND	None	THEN	None

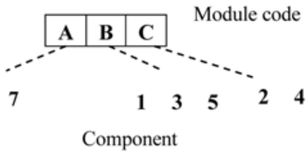

Fig. 3 Chromosome design

as C={7} which means that module A consist of component 1, 3, 5, module B consist of component number 2, 3, 1 and C consist of component number 7.

Table 3 shows the modular design configuration that will be generated from the GA computation.

3.3.2 Initial population

Chromosomes should be generated in the initial population to get the better fitness value and effective module selection. The initial population is derived from this algorithm:

Step 1: A feasible number of modules are generated randomly.

Step 2: Assign first component to any module.

Step 3: Assign remaining components to the modules with higher interaction value in the IRM. Repeat this step until all components are assigned into modules.

3.3.3 Genetic operators

The genetic operator involves crossover and mutation applied to the chromosomes to introduce new individuals into the population. Crossover is essential in GA computation because it contains the reproduction procedure from the parents' chromosome. The aim of crossover is to produce solutions in the search space from successful chromosomes that have been created. In this GA computation, the crossover rate is set at 0.90 to raise the diversity of the generated population.

The GGA crossover operation is as follow:

Step 1: Generate randomly two crossover points after chromosome has been determined.

Step 2: Replace second chromosome into the first chromosome.

Step 3: Remove the same components and empty modules into the second chromosomes and insert new chromosome.

Step 4: Select module with maximum IRM value, calculate new fitness value.

Step 5: Check maximum number of modules after crossover operation. If does not meet the requirement, then insert with new components or add new modules.

Table 3 New modular design configuration

	Component			EOL strategy
Sub Module A	7			Recycling
Sub Module B	1	3	5	Disposal
Sub Module C	2	4		Reuse

Step 6: Assign the rest of the component into possible modules. Repeat step 2-5.

3.4 Economic evaluation on EOL strategies

In this study, each EOL strategies will have specific cost. Adopting the work of Tseng and Chen,[33] the EOL cost is differentiated as follow:

- Reuse

$$Reuse = X_i - H_i \tag{5}$$

$$H_i = L_{cost} \times T \tag{6}$$

where:

X_i is the depreciation factor of a specific component i
H_i is disassembly cost
L_{cost} is labour cost
T is time for disassembly

- Recycling

$$Recycle = R_c - H_i \tag{7}$$

$$\textit{Recycle grade} \begin{cases} 1 & \text{if material purity is high} \\ 2 & \text{if material purity if medium} \end{cases}$$

where:

R_c is recycling cost

- Special treatment

$$Special\ treatment\ (SP) = H_i = (L_{cost\text{-}sp} \times T_{sp}) + C_{removal} \tag{8}$$

$C_{removal}$ = cost for special treatment/remove hazardous or toxic waste
$L_{cost\text{-}sp}$ = labour cost for special treatment
T_{sp} = time needed for special treatment

- Disposal

$$Dispose = -H_i \tag{9}$$

After knowing all the necessary EOL costs, the profit gain from the EOL strategies can be evaluated as follow:

Profit gain by reuse = $(P_{comp} \times n_{comp}) - Reuse$
Profit gain by recycle = $(P_{rec} \times m_{mat}) - Recycle$
Profit gain by special treatment = $(P_{rec\text{-}sp} \times m_{mat\text{-}sp} - SP)$
Profit gain by disposal = 0

where:
P_{comp} = price of component after retirement
n_{comp} = number of component
P_{rec} = price of reclaimed material
m_{mat} = quantity of material
$P_{rec\text{-}sp}$ = price of reclaimed material after special treatment
$m_{mat\text{-}sp}$ = quantity of reclaimed material after special treatment

4. Illustrative Example

A case study taken from the study of Kwak et al.[27] is selected to show the applicability of this method. Consider a door trim composed of nine components. The names of the components are listed in Table 4.

5. Result and Discussion

The five MCDs are generated based on the designers' expert point of view. After all the information have been prepared, the integrated relationship matrix (IRM) using fuzzy inference system is developed. Each index on this matrix represents the overall value of physical and functional interaction for each component. An Excel-based formulation is then prepared to run the computation in Solve-XL.

The optimization resulted in four modular configurations with associated EOL strategies. The GGA managed to obtain convergence to select modular design that has maximum value of EOL strategy.

It is found that the optimization recommend four different module as shown in Table 5. Each module reflects similar physical and functional interaction and its EOL strategy. It can be seen from the result that in module 1, the component is clustered based on similar materials type. This shows that material type has a significant influence on the choices of EOL strategy specifically recycling. Profit gain for each EOL strategy is also provided. This is valuable information for designers to understand the product's value after its retirement. Thus, designers/manufacturers can decide to take back product for economic reason either reusing or recycling the components.

Fig. 5 illustrates the modification of the modular design of the door trim. The original design used three modular clusters based on functionality and structure. The optimized modular formation proposed four modules based on the functionality, structure, as well as its EOL strategy. With this proposed modular design method, designers can maximize their design for lowest environmental impact with regards to EOL strategy. The EOL strategy in this study also consider the purity of material that separates the recycling strategy into two grade; grade one is reclaimed material with high purity and grade two is reclaimed material that has medium purity. Here, designers can consider redesigning the assembly or product by changing materials that are valuable during EOL. In this sense, designers are actually prolonging the use of materials, leading to environmental benign practices.

Table 4 List of door trim components

Component Code	Component	Material	Mass (g)
A	Front door upper trim	PP	250
B	Front door lower trim	PP	1000
C	Arm rest panel	PP+PE	250
D	Pad door anti-rattle	STL+EPDM	250
E	Switch main 1	COMPOSITE	85
F	Switch main 2	COMPOSITE	40
G	Switch cover	ABS	30
H	Pocket 1	PP	200
I	Pocket 2	PU	10

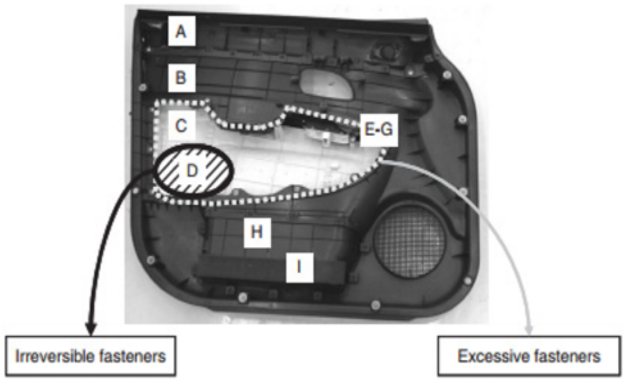

Fig. 4 Design of the door trim (adopted from Ref. 27)

Table 5 Optimum module configuration

Sub Module	Sets of component				EOL strategy	Profit gain (RM/g)
Sub Module 1	A	B	H	I	Recycling grade 1	37.5
Sub Module 2	C				Recycling grade 2	11.25
Sub Module 3	E	G	F		Reuse	5
Sub Module 5	D				Disposal	0

Based on the optimization result, some design recommendations can be given as follow:

- Components E and G use excessive fastener yielding low disassembility's grade and EOL profit. Fasteners should be reduced to avoid time of disassembly.
- Component D can be redesign by selecting high recyclability materials to increase EOL profit and avoid disposal option.
- Component C has low material compatibility. Using single material in this component is beneficial to increase EOL profit, however further calculation should be done when switching to other material for efficient product price.

There are many configurations of modular design that can be generated, without considering EOL strategy. However the proposed approach gives insight to designers to make intelligent decisions in an attempt to reduce environmental impact with the best EOL strategy.

6. Conclusion

Reducing environmental impact during product design stage has

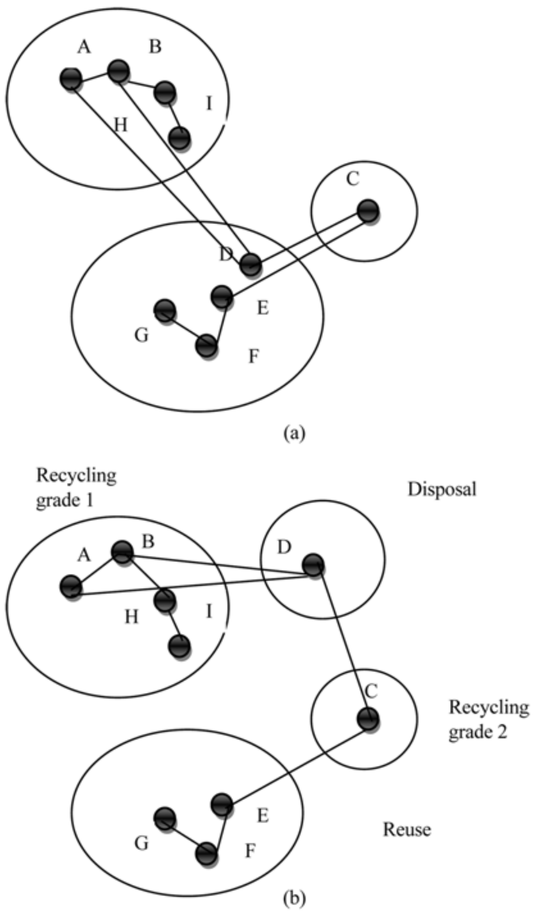

Fig. 5 (a) Original design modular configuration, (b) Optimized modular configuration considering EOL strategy

become very important nowadays. Preventive approaches undertaken during design activities are considered more effective in reducing environmental impact rather than curative approaches. One of the promising preventive approaches is to incorporate product end of life strategy into the design stage.

In this paper, new methodology for optimizing modular design which considers EOL strategy is proposed. First, modular clustering drivers are generated to assess physical and functional interaction between components. Second, an integrated relationship matrix is computed using fuzzy inference system to obtain total value of physical and functional interaction between components. Then optimization using GGA is conducted to obtain modular design with EOL strategies.

In the future, adding more modular design parameters such as disassembly sequence, product architecture variation that leads to EOL profit is a worth to investigate. Future research in this area can focus on the interference among parts or component in EOL modularity design. In addition, appropriate decision making strategies that solve the tradeoff between conflicting objectives in CAD-based modular design can be valuable a more practical implementation.

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