A METHODOLOGY TO EVALUATE DESIGN EFFICIENCY BASED ON ASSEMBLY CRITERIA IN SUPPORT OF DESIGN FOR MODULARITY

A. B. Abdullah, Z. M. Ripin and M. Mokhtar

School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus,
14300 Nibong Tebal, SPS, Penang

ABSTRACT

The objective of this paper is to develop a new methodology for evaluating design efficiency based on assembly criteria. The new methodology can be utilised to support the design for modularity approach. The verification of the new approach was carried out by redesigning an electrical table for park, and its components. A modularity design approach which involves of the seven main mechanical assembly and seven assembly criteria type explored. The result indicates an improvement on the overall design efficiency of the table too. The paper emphasises that through modularity approach, complexity of the product can be reduced.

Keywords: Assembly Criteria, Design for Modularity, Design Efficiency

1.0 INTRODUCTION

Companies are striving to produce high quality and reliable product at the lowest cost to remain competitive in the market. Several approaches, methodologies and tools were developed to fulfill this objective. The most important and crucial stage in the product design is the efficiency evaluation and validation phase. Rating the products allows efficiency to be evaluated, so that the potential of product improvement can be identified. Most of the current evaluation methods are not taking into consideration types of assembly or joining method used on a product. The type of assembly method or joining technique used has a significant effect on the product rating. In manual assembly, only the number of components and type of assembly can be directly known, whereas assembly time cannot be measured consistently.

Assembly typically constitutes 40% – 60% of overall production time [1]. Boothroyd and Dewhurst [2] listed several ideal assembly characteristics such as minimise assembly direction and allow simple aligning, orientation and handling of parts. They also had proposed a free-tools assembly that excludes fixtures during the assembly [2]. Although the characteristics of the assembly are fulfilled, there is an influence of the tools fixtures during the disassembly process as indicated by Lily and Flowers [3]. Complete disassembly depends on material used, assembly direction, type of mechanical joint and tool used either in assembly or disassembly processes [4], hence the need to evaluate design efficiency based on assembly criteria can be considered as an important factor for the assembly process.

The objective of this paper is to develop a new methodology to evaluate design efficiency based on assembly criteria such as tools used, cost of the tools, assembly direction, orientation and other related factors. In this work, seven main mechanical assemblies are presented and seven assembly criteria are taken into considerations for product redesigning purposes. As a result a new simpler methodology that can evaluate design efficiency effectively was developed.

The paper is organised into few sections, where section one outline the overview of the assembly process. Section two provides some literature review and the motivation of the research. The methodology of the research is presented in section three and in order to implement the approach an illustration example is discuss in section four. Section five discusses the results of the developed approach and the paper ends with a conclusion and some suggestions for future work.

2.0 MECHANICAL ASSEMBLY

One of the potential benefits from modularity is the characteristics of sharing assembly structure [5]. Assembly can be described as a process of joining together several components to create a final product [6] by mechanical, cohesive or adhesive methods. Components generally need assembly to complete the system. For example, a typical automobile has more than 15,000 parts, which are all assembled by using several joining methods as shown in Figure 1.
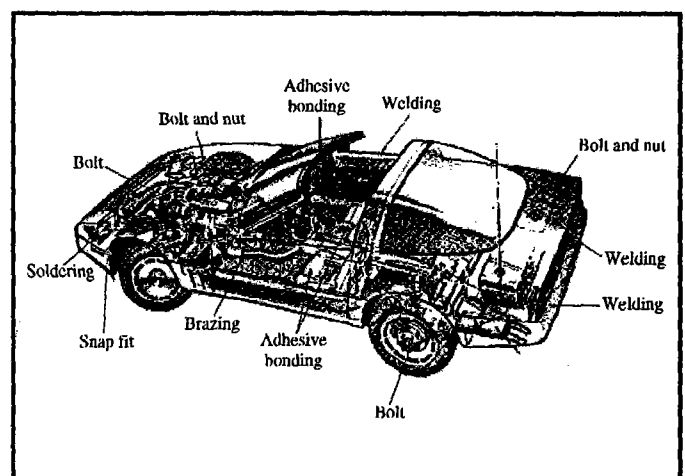

Figure 1: Thousand of assembly needed for automobile [7]

There are several factors to be considered in selecting types of mechanical assembly. The factor involve is whether the components are join permanently or some times need to be dissembled for servicing, repair or recycling. Another factor is simplifying the product and component assembly such as designing components with uni-directional assembly is preferable than multi-directional assembly. Strength of the assembly must also be able to withstand forces. For example components assembled on the compressor tank must have the capability to withstand internal force of compressed air in order to ensure production of compressed air. In assembly process, tool is commonly used, but assembly without the aid of the tool is better because tool setup time can be reduces thus reduce assembly time.

Generally there are ten types of mechanical assembly as shown in Figure 2, but in this work, they are clustered into seven groups. This clustering is possible because welding, soldering and brazing which have similar characteristics can be grouped into one namely cohesive, while spring clip and metal stitching can be grouped as stitch.
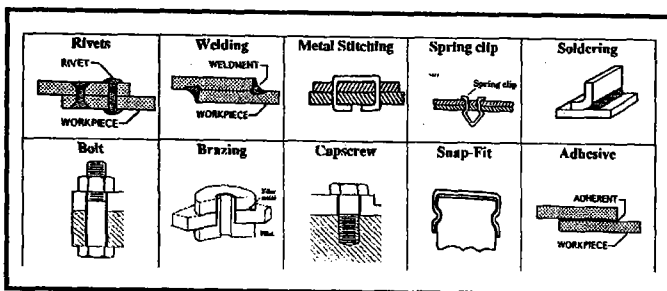

Figure 2: Ten types of conventional mechanical joint [6, 7]

3.0 METHODOLOGY

The methodology consists of three main steps, which are problem definition, assembly criteria and design evaluation.

3.1 Problem Definition

In design process, problem definition is very important, so that the root of the problem can be understood clearly [6]. Decomposition is one of the best methods to identify problem. Decomposition of physical or structure of the component tends to make the identification of the problem easier.

3.2 Definition of Assembly Criteria

From the literature [1,2,3], there are seven assembly criteria that have been identified.

All these criteria are listed and weighted based on the mechanical joint listed in section 2.0. The seven assembly criteria that have been identified are;

1. Tooling – Assembly operation requiring tools, such as for attaching snap rings, springs or cotter pins. The types of tools utilised could either be standard tools, special tools or no tools required.

2. Assembly direction – Ideal assembly orientation is parts which are inserted from the top of the assembly direction or z-axis assembly. By using z-axis assembly for all parts, the assembly would not to be inverted, gravity will help to stabilise

the partial assembly and the operator can easily access the assemble parts.

3. Costing - Cost involved are the cost of typical tools used, for example assembly using welding technique requires expensive equipment compare to the other mechanical assembly such as mechanical stitch, rivet or bolt and nut which are more cheaper.

4. Durability – This criterion is related to the capability of the assembled parts to withstand during application, for example cylinder head, which needs higher strength joint.

5. Recycleability – The characteristics of material such as recyclable, toxic, cost etc. are being considered here. Normally disassembled parts can be recycled completely. The similarities of the component material in the assembly also give advantages to the product.

6. Perpetualability – Mechanical assembly such as bolted joint is a semi-permanent joint, whereas adhesive and cohesive is considered as a permanent joint. For ease of parts removal, semi-permanent joint is more preferable.

7. Manufacturability – This criterion is related to the type of device used in the assembly process, whether standard or custom-made. For example bolt and screw is a standard device but for the mechanical stitch or spring clip, it needs to be specially designed for certain snap-fit assembly or application.

Score of 1, 3 and 5 are given for the assembly criteria to represent the weightage for the assembly types in Table 1. The score for each assembly criteria is given as shown in Table 1(a) – 1(g). This weightage depends on where the joining method is applied and so that the designer can justify and make decision on which type of assembly should be selected.

3.3 Design Evaluation

Expressions are derived to measure the design efficiency by relating number of components, number of assembly and total score. A calculation formula for design efficiency (E) is as follows:

$$\text{Design Efficiency, } E = \frac{1}{V_n} \left(\frac{\sum_{i=1}^{i=1} W_T}{N_c} \right) \qquad (1)$$

(Note that $N_A \geq 1$, number of assembly criteria depends on the design requirement, which is usually more than one). V_n is number of criteria, for this case $V_n = 7$.

The total score can be expressed as follows:

$$\text{Total Score, } W_T = \sum_{i=1}^{A_n} r_i \qquad (2)$$

Where A_n = Number of assembly

r = Score for each sub-assembly

P_n = Number of components,

Number of components, N_c and number of assembly, N_A are directly obtain from the disassembly and the total score, W_T of each component assembly is the result of product assembly.

Table 1: Assembly characteristics and generalise weightage

Type of Assembly	Costing	Tooling	Perpetualability	Durability	Recycleability	Direction	Manufacturability
Capsrew	Low	Common	Semi-permanent	High	Recyclable	Uni-direction	Standard
Bolt	Low	Common	Semi-permanent	High	Recyclable	Uni-direction	Standard
Rivet	Low	Special tool	Permanent	Medium	Recyclable	Uni-direction	Standard
Snap fit	Low	No	Semi-permanent	Medium	Recyclable	Uni-direction	Custom-made
Stitch	Low	No	Semi-permanent	Medium	Recyclable	Uni-direction	Standard
Cohesive	Medium	Special tool	Permanent	High	Non-recyclable	Multi-direction	Standard
Adhesive	Low	No	Permanent	High	Non-recyclable	Multi-direction	Standard

Table 1 (a)

Cost	Rating
Low	1
Medium	3
High	5

Table 1 (b)

Tool	Rating
No tool required	1
Common tool	3
Special tool	5

Table 1 (c)

Joining	Rating
Semi-permanet	1
Permanent	3

Table 1 (d)

Strength	Rating
High	1
Medium	3
Low	5

Table 1 (e)

Manufacturing	Rating
Standard	1
Custom made	3

Table 1 (f)

Direction	Rating
Uni-direction	1
Bi-direction	3
Multi-direction	5

Table 1 (g)

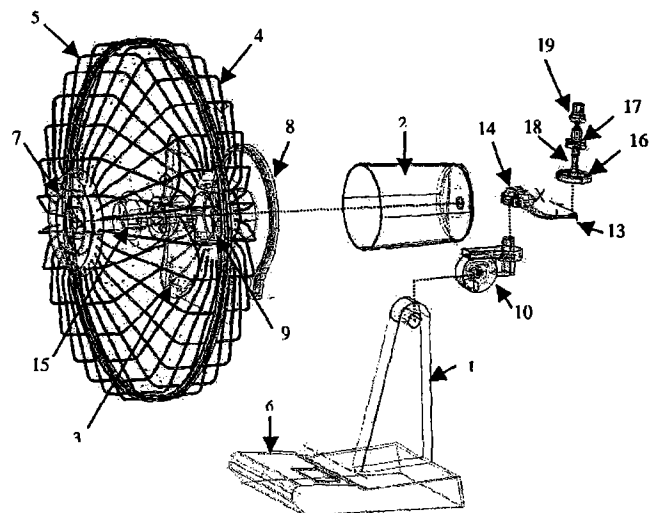| Material	Rating
Recyclable	1
Non-recyclable	3

4.0 IMPLEMENTATION

Case Study – Table Fan

Table fan is one of the commonly devices used by most of the people to blow air to a targeted area. The schematic diagram of a table fan is shown in Figure 3. It has 19 components including the oscillation knob and motor, which are not shown in the diagram.

Components	Material	Components	Material
1. Stand	Plastic	11. Switch Panel	Plastic + Steel
2. Motor housing	Plastic	12. Motor	Steel
3. Fan blade	Plastic	13. Oscillator control device	Plastic
4. Rear guard grill	Steel	14. Oscillator control plate	Plastic
5. Front guard grill	Steel	15. Spinner	Plastic
6. Base cover	Plastic	16. Oscillator gear 1	Plastic
7. Decorative face plate	Plastic	17. Oscillator gear 2	Plastic
8. Guard lock nut mounter	Plastic	18. Oscillator gear 3	Plastic
9. Guard lock nut	Plastic	19. Knob control	Plastic
10. Neck	Plastic		

Figure 3: An exploded view of table fan with components and material listing

Figure 4 illustrates the components mapped in the form of assembly digraph to show the interaction and joining method between each component. Arrows devotes the assembly direction, numbers in bracket indicate number of screws and bolt used in joining the components. Note that identical parts assembled at the same time and having the same assembly characteristics (e.g. four screws need to fasten a single component to another) are assigned as different number of assembly.
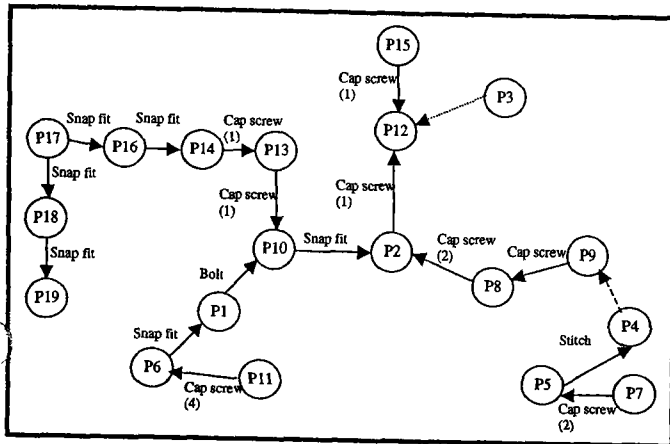

Figure 4: Assembly digraph of the tale fan

5.0 REDESIGN PROCESS

Similar to the original design, redesign also includes the process of gathering customer needs, planning and development, concept generation, embodiment design and the final phase is testing and prototyping. Here one additional step, which is reverse engineering [9], is introduced. In redesign process, a product is predicted, observed, disassembled, analysed, tested, experienced and documented in terms of its functionality, form, physical principles, manufacturability and assemblability [10].

In this work, redesign is carried in order to verify the design efficiency. Through reducing part number, modifying/changing the required operations such as joining method it can increase the design efficiency [11]. The modularity approach is introduced in order to clustering the components at the higher interaction and separating from the loose interactions component to easily identification of detached modules that could assist recycle, redesign or service purposed. For example, components in a product that are made from different material, which have different life duration and required different recycling and disposal methods. By using modular approach, components of similar material can be grouped into same module. The disassembly process flow chart is shown in Figure 5.
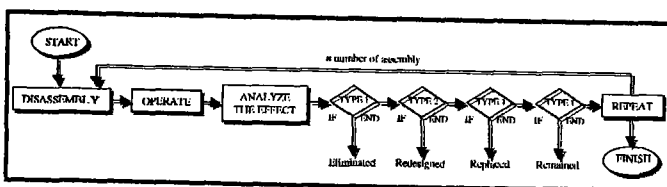

Figure 5: The extended substrate operate procedure (SOP) flow chart

The redesign process is based on the Subtract Operate Procedure (SOP) developed by Lefever and Wood [11]. In this procedure every single component in the product is disassembled one by one to find the effect of disassembling towards the product. From the analysis, components that can be eliminated, redesigned or remained can be identified. Note that components must be reassembled after analysing the effect. For the components that cannot be disassembled are considered as single components. Table 6 simplifies the result from the SOP procedure. In the disassembly analysis, there are three levels of effects, which are no effect, effect and strong effect. The three level of effect is based on the effect, which reflects to the product or system functionality when it is being disassembly, for example front and rear guard grill, there are no effect due to the disassembly to the product or system. The components is consider to have an effect to the system, but not the functionality of the product, for example control knob can only effect the oscillation system of the fan but not the main function of the fan. Strongly effected parts can led to the overall system of the fan to malfunction due to removal of the parts.

(A) Extended SOP Algorithm

There are eight steps involve in the SOP process.

Step 1: *Disassembly*, can be defined as the process of systematic removal of desirable constitute parts from an assembly while ensuring that there is no impairment of parts due to the process [12]. In this case one component is disassembling while constraint 1 must be fulfilled. If not, constraint 2 can be considered as other alternatives.

Step 2: *Operation*, The product is tested through full range of customer needs and engineering requirements.

Step 3: *Analyse*, The effects can be completed through visual analysis or tools for the case of non-obvious effects based on the four types of classifications.

Step 4: *Elimination*, If fulfilling type 1.

Step 5: *Redesigned*, If fulfilling type 2.

Step 6: *Replacement*, If fulfilling type 3.

Step 7: *Remained*, If fulfilling type 4.

Step 8: *Repetition*, Repeat the procedure in n times, where n is number of components in the products.

Two conditions of the assembly that taken into considerations.

Condition 1: The functionally dependent components must be reassembled.

Condition 2: The component that cannot be disassembled is considered as one component.

Types of effect are listed as followed;

Type 1: Those components causing no change in the Degree of Freedom (DOF) as well as no other effects can be eliminated from the design.

Type 2: Those components causing no change in the Degree of Freedom (DOF), but can effects due to their removal, can be parametrically redesigned to compensate for these effects.

Table 2: SOP Worksheet

Disassembly Sequence	Qty.	Components Name	Effect	Comment
1	1	Decorative face plate	No effect	Change front guard grill design
2	1	Front guard grill	No effect	Unsafe to used
3	1	Spinner	Strongly Effected	Mounting fan blade
4	1	Fan blade	Strongly Effected	Generate comfort air
5	1	Guard lock nut	No effect	New joining method to mount rear guard grill
6	1	Rear guard grill	No effect	Unsafe to used
7	1	Guard lock nut mounter	No effect	New joining method to mount guard lock nut
8	1	Knob Control	Effected	Oscillation system
9	1	Motor housing	No effect	Motor open to air (unsafe)
10	1	Oscillator gear 2	Effected	Oscillation system
11	1	Oscillator gear 3	Effected	Oscillation system
12	1	Oscillator gear 1	Effected	Oscillation system
13	1	Oscillator control device	Effected	Oscillation system
14	1	Oscillator control plate	Effected	Oscillation system
15	1	Motor	Strongly Effected	Motoring system
16	1	Neck	Strongly Effected	Connect body to stand
17	1	Switch Panel	Strongly Effected	Switching system
18	1	Stand	Strongly Effected	Main structure
19	1	Stable base	No effect	Shift switch panel location

Type 3: Those components causing changes in the Degree of Freedom (DOF) but has as no other effects can be replaced by another components.

Type 4: Those components causing changes in the Degree of Freedom (DOF) and have other effects must be remained in the design.

From Table 2, there are seven components, which have no effect (disassembly sequence 1,2,5,6,7,9,19), six components with effect (disassembly sequence 8,10,11,12,13,14) and six components with strong effect (disassembly sequence 3,4,15,16,17,18). Only not effected components are now focused without contemplating the safety factor.

As a result three components out of seven not affecting the components are selected as a potential component to be redesigned, the guard lock nut, decorative faceplate and base. Figure 8, shows the guard lock nut before and after redesigning the guard lock nut mounter. The mounter is eliminated resulting in changing of joining method of rear guard grill from screw to snap fit. There are three options in selecting new joint method, and based on the assembly weightage discussed before, the snap-fit joining method gives better result in terms of ease of disassembly. Similarly to the case of the decorative face-plate where screws is change into snap fit assembly method. Base ground cover was also found to be unimportant and does not affect the overall product functionality, so that it can be eliminated. Other changes are on the location of switch panel, which is shifted to the stand that allows for better product commonality.

(B) Design for Modularity Approach

The emphasis of modular design is to identify module and various modular design methods have been proposed

quantitatively and qualitatively. Many researchers have discussed on these topics and it will not be repeated. In this work, two approaches are presented as a combination to fulfill the material compatibility and assembly criterion, which are done by Gershenson et al. [13] and Huang and Kusiak [14]. The former defines modularity in life-cycle point of view and modules are developed based on components-process similarity and dependency and the latter focus on the assembly incidence and interaction between components to identify modules.

Based on methodology developed by Gershenson et al. [13], modules can be identified from material similarity and dependency. Due to its length, the steps involved in module identification are not discussed. Components are mapped in interaction matrix (Figure 6). As a result, four modules are identified as shown in Figure 7 after rearrangement.

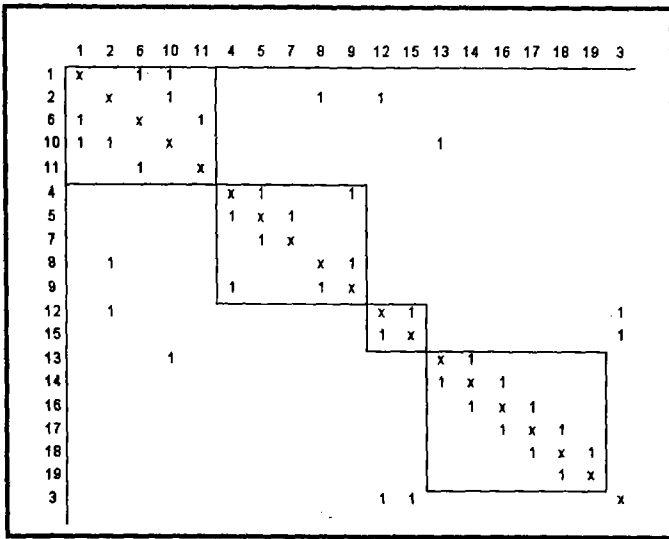|	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	x					1				1									
2		x					1		1			1							
3			x										1		1				
4				x	1					1									
5				1	x	1													
6	1					x					1								
7						1	x												
8		1						x	1										
9			1					1	x										
10	1	1								x			1						
11							1				x								
12	1	1										x			1				
13										1			x	1					
14													1	x		1			
15		1										1			x		1		
16														1		x	1		
17															1	1	x	1	
18																	1	x	1
19																		1	x

Figure 6: Interaction matric, M_A

Figure 7: Modularity matrix, M_M

Module 1: Front guard, rear guard and decorative plate.

Module 2: Neck, stand, switch panel and base.

Module 3: Oscillating controls device, oscillator control plate, gear 1, gear 2, gear 3 and control knob.

Module 4: Guard lock nut, motor and housing
Standard parts: Fan blade and spinner.

6.0 RESULTS AND DISCUSSION

The overall result shows that the percentage of the overall design efficiency has increased. This can be interpreted as an improvement of the product efficiency as shown in Table 3. Although the reduction of parts count was quite small (only two components), but due to the changes of the fastening method, product efficiency can be improvement a lot. Numbers of modules are increase leading to a reduction of component complexity and the number of standard parts is also increase as the base is removed from the stand module.

Table 3: New table fan design improvement

Parameter	New Approach		
	Old design	New design	Improvement
Parts Number	19	17	10.5%
Number of Assembly	23	18	21.7%
Module Number	4	6	-50.0%
Total Score	184	165	10.3%
Overall Efficacy	6	17	28.0%

For the new design, the base and stand are separated due to the elimination of the ground base cover, the location of switch panel is on the stand. After redesign, number of modules is then recalculated using similar algorithm and the results shown that the number of module increased to six and number of standard component increase to three. Overall score for the product has changed due to the reduction of components and changes in

joining method. By using this, product efficiency can be calculated. The result of product efficiency before and after redesign is discussed afterwards. The assembly digraph shown in Figure 8 illustrates the redesigning process of the fan. Figure 9 illustrates the joining methods alternatives for guard lock nut mounter changes. Here the snap fit joint is selected due to the easier disassembly factor and strength required for the assembly. Figure 10 shows an old design of the base and the stand and Figure 11 shows the schematic diagram of the new design of both the base and the stand.
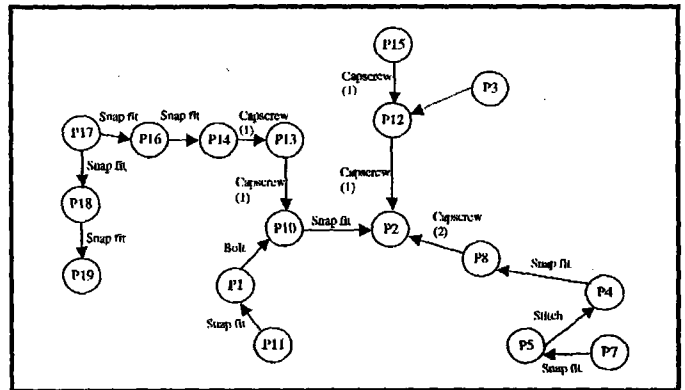

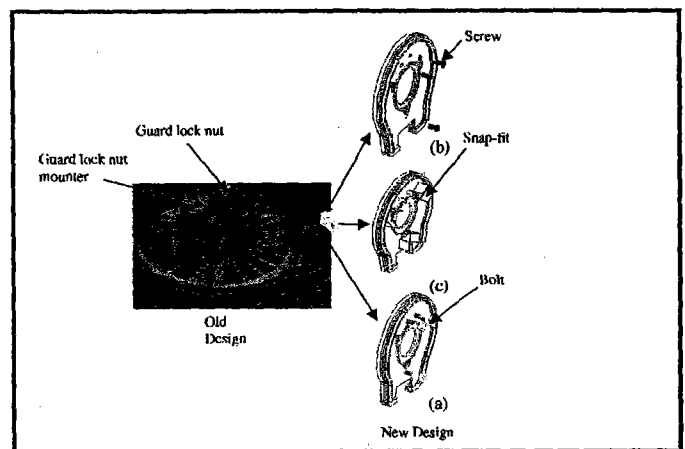*Figure 8: New assembly digraph of the table fan after redesign*

Figure 9: Three possible joining method due to elimination of guard lock nut mounter
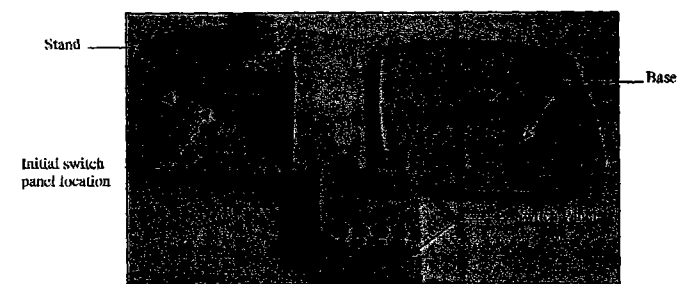

Figure 10: Old design of stand with base and switch panel

To validate the result using this method, a comparison to the published method is carried out, as shown in Table 4, a method that developed by Ehud et al. [15]. The result shows the similar pattern as indicated by proposed approach, where efficiency increase about 50% and the difficulty score reduce more than 33%.

Table 4: The result of the new table fan design from other approach

Parameter	Ehud et al. Method [3]		
	Old design	New design	Improvement
Number of Parts	19	17	10.5%
Non-required Parts	4	2	50%
Number of Tasks	23	18	21.7%
Value-added Tasks	4	1	75%
Number of Tools	5	3	40%
Number of Tools Changes	13	9	30.8%
Difficulty Score	247	165	33.1%
Efficiency Rating	8.1%	12.1%	49.4%

Finding from this study are compared to the other tools developed by Boothroyd and Dewhurst [2], which emphasis more on the complexity factor of the design assembly to measure the design efficiency. The result is summarised in Table 5.

Table 5: Method by Boothroyd and Dewhurst (1996) for comparison

Other Evaluation Method	Reference	Before Redesign	After Redesign	Improvement
Complexity factor = $\sqrt{N_p + N_t + N_i}$	Boothroyd and Dewhurst, (1996)	8.18	7.42	9.3%

Where;

N_p = Number of parts

N_i = Number of interfaces

N_t = Number of part types

This approach is also applied to other existing consumer products in the market. The result indicates that most of the products initially have quite high design efficiency for example ..% for the flour mixer, 76% for an electric blender and 54.5% for the juice extractor. The reason is that most of the product gives high score due to the fact that more than 70% of the parts are plastic molded components and used snap fit assembly method. It is anticipated that by applying the new approach proposed in this paper, the result could be further improved.

7.0 CONCLUSIONS

The main objective of the methodology is to evaluate design efficiency by taking assembly criteria as a consideration. In this work, seven assembly criteria are presented, and weighted based on their performance reflected to the seven types of mechanical joint considered in this approach. The result from the case study indicates that through redesign with the guide of the modular product design approach, the efficiency of the design can be increased. The result also indicates that through modular approach, complexity of the product can be reduced. In future works, this approach will be used in redesigning more complex products or systems in order to verify the significant

and interaction of each parameter in evaluating design efficiency. Besides that a computer based method will be developed for systematic design evaluation.

REFERENCES

[1] Andreasen, M., Kahler, S., Swift, K. and Lund, T., *Design for Assembly*, 2nd Edition, IFS Publications Ltd., UK and Springer-Verlag, New York, 1988.

[2] Boothroyd, G. and Dewhurst, P., *Product Design for Assembly*, Mc Graw Hill, Inc. New York, 1989.

[3] Lily, H. S. and Flowers, W. C., "Application of a Design for Remanufacture framework to the selection of product life-cycle fastening and joining methods", *Robotic and Computer Integrated Manufacturing*, 15, pp. 179- 190, 1999.

[4] Tsai, C. K., "Disassembly sequence and cost analysis for electromechanical product", *Robotic and Computer Integrated Manufacturing*, Vol. 16, pp. 43-54, 2000.

[5] He, D. W. and Kusiak, A., "Design of Assembly for modular products", *IEEE Transaction on robotics and Automation*, Vol. 13 No. 5, pp. 646-655, 1997.

[6] Lindbeck, J. R., Product Design and Manufacturer, New Jersey: Prentice Hall, Inc., 1995.

[7] Kalpakjian, S., *Manufacturing Engineering and technology*, 3rd Edition, Addison Wesley Publishing Company, New York, 1995.

[8] Kusiak, A., Larson, N. T. and Wang, J., "Reengineering of design and manufacturing processes", *Comp. Ind. Eng.*, Vol. 26 No. 3, pp. 521-536, 1994.

[9] Ingle, K., *Reverse Engineering*, Mc Graw Hill, Inc. New York, 1994.

[10] Otto, K. and Wood, K., "Product evolution: a reverse engineering and redesign methodology", *Research in Eng. Design*, Vol. 10 No. 4, pp. 226-243, 1998.

[11] Lefever, D. and Wood, K., "DFA techniques into Reverse Engineering and Redesign", *ASME DTM*, 1996.

[12] Brennan, L., Gupta, S. M. and Taleb, K. N., "Operations Issues in assembly/disassembly environment". *Int. J. Operational and Production Management*, Vol. 14 No. 9, pp. 57-67, 1994.

[13] Gershenson, J. K., Prasad, G. J. and Allamneni, S., "Modular product design: A life cycle view", *Journal of Integrated Design and Process Science*, Vol. 3, No. 4, 1999.

[14] Huang, C. C. and Kusiak, A., "Modularity in design of products and systems", *IEEE Trans. On Systems, Man and Cybernetics-Part A: Systems and Humans*, Vol. 28 No. 1, pp. 66-77, 1998.

[15] Ehud, K., Brent, B. and Antony, P., "Methodology to evaluate ease of disassembly for product recycling", *IIE Transactions*, Vol. 28, Issue 28, pp. 837-845, 1996.