DEVELOPMENT OF DESIGN EVALUATION SYSTEM FOR ASSEMBLY

By

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LIST OF EQUATIONS

NOMENCLATURE

C_p	Total capital cost of assembly system
N_t	Total number of assemblies produced during the life of the system
C_a	Annual cost of operating the system
N_a	Annual production of the assemblies
C_m	Labor Cost /Assembly
N_p	Number of parts in the assembly
C_f	Individual Handling/Feeding cost
C_i	Individual Insertion cost
C_{fx}	Individual Fixing cost
C_m	Direct labor Cost per assembly, (manual fitting and feeding process)
C	Relative cost towards functions
A	Essential Part
AEM	Assembly Evaluation Method
B	Non - Essential Part
CE	Concurrent Engineering
DFA	Design For Assembly
DOE	Design Of Experiment
E	Assembly Evaluation Score
ECR	Engineering Change Request
F	Weighted functions of components or parts in the product design
FAST	Function Analysis System Technique
FR	Functional Domain
i	The n^{th} row of the compared characteristic in pair wise comparison method
I_{ij}	Importance point of the each functions analyzed in product design
j	The n^{th} column of the compared characteristic in pair wise comparison method
K	Assembly Cost Ratio
DP	Design Parameter in the Physical Domain
PDS	Product Design Specification
PV	Process Domain
S	Area for improving the value of the design
VE	Value Engineering
W_{ij}	Weight of total importance point of the functions analyzed in product design

PEMBANGUNAN SISTEM PENILAIAN REKABENTUK UNTUK PEMASANGAN

ABSTRAK

Pemasangan merupakan satu peringkat yang terpenting dalam pembangunan produk. Rekabentuk untuk pemasangan (DFA) adalah salah satu pendekatan yang utama yang digunakan untuk meningkatkan rekabentuk produk supaya produk yang dihasilkan mudah dipasang, kos pemasangan yang murah disamping nilai produk yang tinggi. Objektif kajian ini adalah untuk membangunkan sistem penilaian rekabentuk untuk pemasangan (DFA). Sistem yang dibangunkan bertujuan menyokong teknik baru dalam DFA dan memberi peluang kepada pengguna untuk menilai dan mengurangkan jumlah kos masa dan pemasangan serta meningkatkan nilai produk pada peringkat awal proses rekabentuk. Sistem ini juga dijangkakan berupaya membantu perekabentuk dalam merekabentuk semula produk dengan menggunakan prinsip dan peraturan DFA. Kaedah Lucas DFA dan Kejuruteraan Nilai (VE) telah dipertimbangkan untuk menghasilkan rangka kerja untuk analisis DFA. Skop kajian termasuklah membangunkan analisis kebolehpasangan sesuatu produk yang sistematik dengan menggunakan aktiviti asas rekabentuk yang berturutan. Pengetahuan asas tentang prinsip dan peraturan DFA digunakan dalam kaedah saintifik kebolehpasangan. Dalam kajian ini, satu perisian telah dibangunkan untuk kemudahan perekabentuk supaya keputusan diperolehi dengan cepat serta dapat menyimpan data rekabentuk untuk rujukan pada masa depan. Dua kes kajian dijalankan dengan menggunakan perisian untuk menunjukkan kaedah yang dibangunkan dalam penyelidikan ini. Keputusan yang diperolehi menunjukkan sistem penilaian yang dibangunkan berupaya meningkatkan nilai dan mengurangkan kos pemasangan rekabentuk semula produk.

ABSTRACT

Assembly is one of the most important stages of product development. Design for Assembly (DFA) is one of the approaches to improve the product designs for easier and less assembly cost with high functionality of the products. The main objective of the research work is to develop an improved DFA system. The developed system is aimed at supporting new techniques for DFA and to provide users opportunity to assess and reduce the total assembly time and cost of the product and improve the product value at the early stage of the design process. The system is also expected to assist the designer in product redesign based on the general DFA rules and principles. In order to achieve this task, Lucas DFA and Value Engineering are reviewed in the current research work towards developing a framework for DFA analysis. The scope of the work includes systematizing the assemblability analysis for a product through generic sequence of design activities with rational basis. The inherent knowledge of the DFA rules and principles are used in a systematic way throughout the assemblability analysis. The prototype software has been developed in this research work for the convenience of the designers. The software could facilitate quick result with best accuracy to be obtained and to preserve the design data for future reference. Two case studies have been performed using the software to illustrate the proposed method with a view to determine its effectiveness in actual application. The case studies results show that the developed evaluation system is able to improve the value and reduced the assembly cost of the redesign product.

CHAPTER 1

INTRODUCTION

1.1 Background

In the present competitive and borderless world, technical improvements may create a new business and any company being able to present a new technical solution may for a limited amount of time, be alone in that market segment. But, as time passes by, the rivals will probably develop and offer customers similar products. There are always competitions of technical ability, design, image, cost, or whatever strategy the company sets. Regardless of the strategies, product development is one of the most important activities in order to improve the competitiveness of a manufacturing company.

The success of a product is dictated by its cost, performance and reliability. Thus, the marketplace will affect pressure on big and small companies to cut down the manufacturing cost and at the same time to increase their profit in order to remain competitive (Johnson, 1997; and Eskalinder, 2001). To make it worse, consumer is seeking new products with competitive price, high quality, and reliability. So, companies have to maintain their market share by enforcing the manufacturing team to develop new products or introduce a product variety in a very short time with high quality, reliability and low cost.

Due to the above factors, a lot of companies seek for, adopt, or apply new design methods as a counter measure or preventive action to the product cost increments. The phases of a product life – cycle can be divided into the stages as shown in Figure 1.1 (Rampersad, 1993):

1. Pioneering phase – a launching period when the product is new at market.

2. Penetration phase – a promotional period when the product is promoted through out the market.
3. Growth phase – a period when the product starts to make and increase the profit.
4. Satiation phase – a period where the product has lost its impetuous and grew slowly.
5. Decay phase – a period of decline at the end of life cycle.

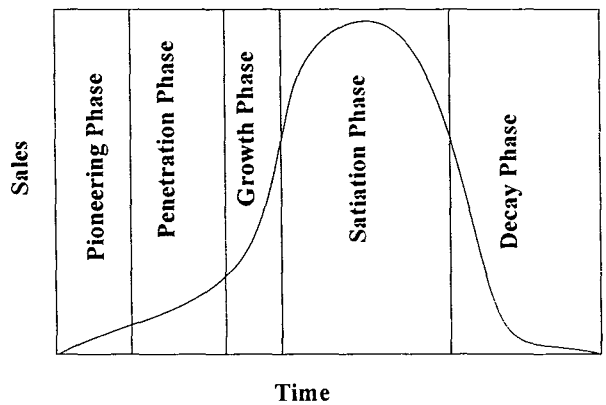

Figure 1.1 Product Life Cycle Phases (Rampersad, 1993)

As time changes, the customer needs are also changing. The changes of the customer needs for a better product will influence the product quality and reliability. The product disappears from the market after certain period drastically as shown in Figure 1.2.

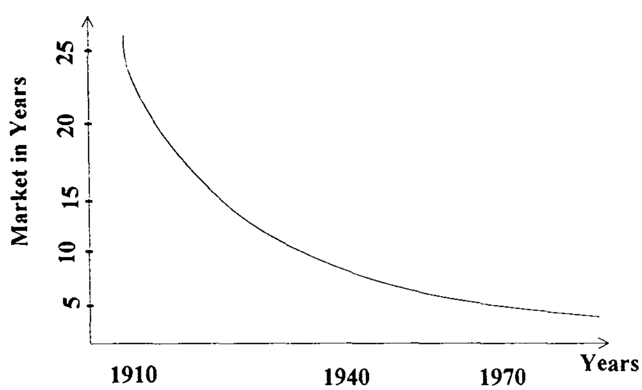

Figure 1.2 The Market Life of Industrial Products (Rampersad, 1993)

1.2 Product Development

Conventional or traditional product development that is conducted sequentially suffers the problem of design paradox. This refers to the mismatch of designer knowledge about the product and number of decisions to be made throughout product development cycle as shown in Figure 1.3. Design decisions must be made in the early design process when product design is not very well understood. As a result the changes in design have to be made in later development stage, when product design evolves and is better understood, to correct design decisions made earlier (Ullman, 1997).

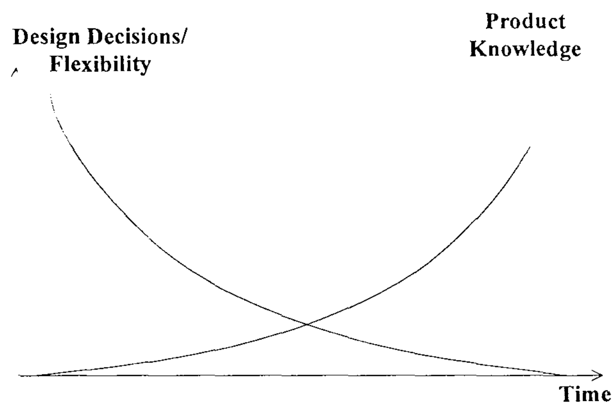

Figure 1.3 The Design Paradox (Ullman, 1997; and Chang et al, 1999)

The conventional product development process apply design – build – break philosophy that tends to separate the design and manufacturing engineers where the manufacturability of a product is not considered in design. The defects related to design often found in the production stage are usually too late to be corrected. Consequently more manufacturing procedures are required, resulting in an elevated product cost (Chang et al, 1999).

With this highly structured and sequential process of the traditional product development, the cycle tends to get extended, elevating the cost and compromising the quality to avoid further delay. Cost and number of engineering change requests (ECR) throughout the product development cycle often conform to a pattern shown in Figure 1.4. It is reported that only 8% of the total product budget is spent for design, however, design in the early stage determines 80% of the lifetime cost of the product (Chang et al, 1999). Changes in later stage are usually necessary to correct improper design decisions made earlier, causing significant cost elevation and delay.

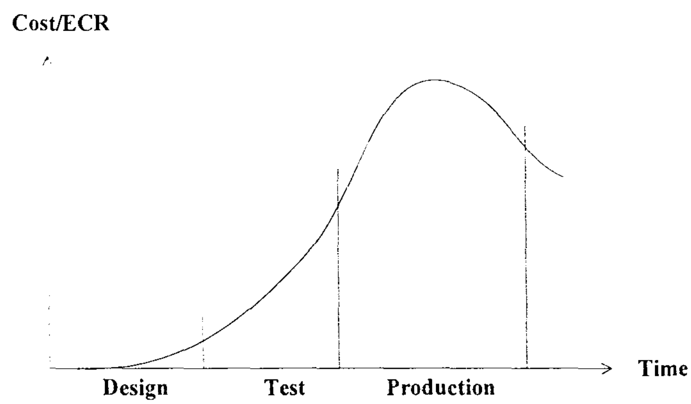

Figure 1.4 Cost/ECR vs. Time in Conventional Design Cycle (Chang et al, 1999)

Apparently, today's industries will not survive the worldwide competition unless they introduce new products with better quality, at lower cost, and with shorter lead – time. Many different approaches and concepts have been proposed during the years, with a common goal — to shorten product development cycle, to improve product quality, and to reduce product cost. Therefore the life cycle of a product must be considered at every cycle phase of product development where the phases can occur simultaneously as shown in Figure 1.5. This will ensure that production time and cost can be reduced compared to the traditional approach.

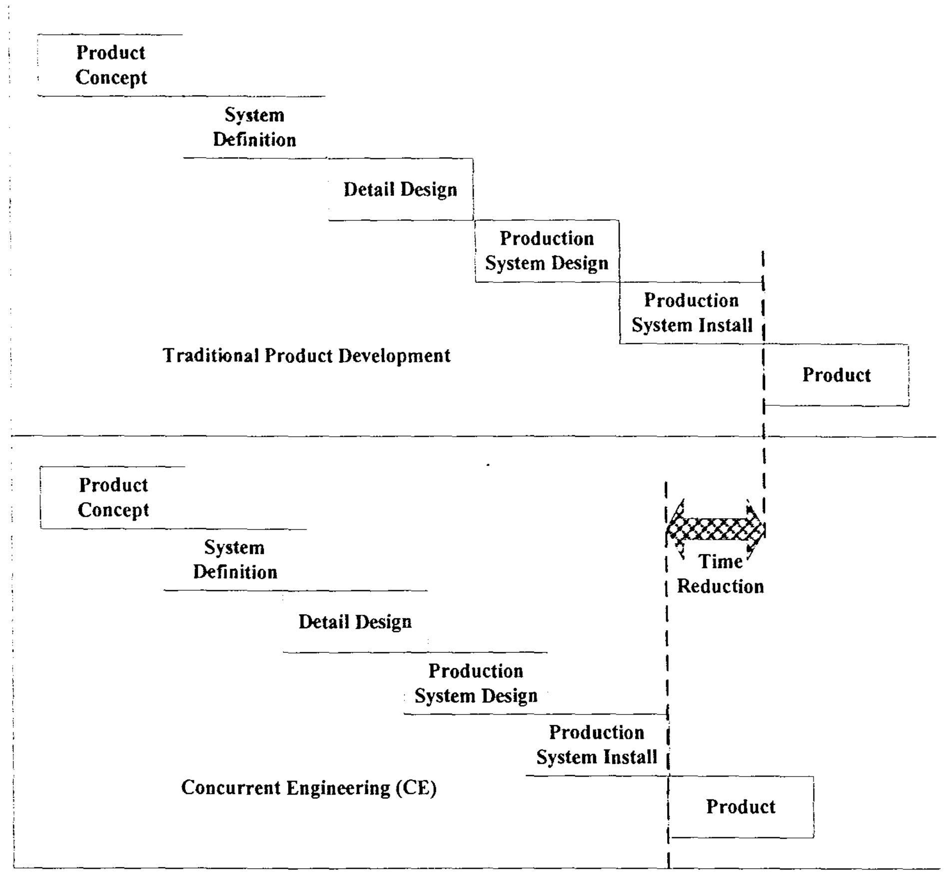

Figure 1.5 Traditional Product Development versus Concurrent Engineering (Eskilander, 2001)

By working as a team or in parallel, two major benefits are achieved:

1. Early identification and possibility to avoid problems that are normally found in later stage of the development chain, and
2. Development time is much shorter compare to the traditional development.

When developing products, a number of decisions made have may affect the entire company. The product must not only fulfill certain functional specifications that attract the customer to buy but must also be able to fit the manufacturing process within the company. This may include the whole product portfolio, as well as specification for each part in the products to fit the certain machine or assembly process (Eskilander, 2001).

There are techniques for focusing the assembly aspects in the product design phase called Design for Assembly (DFA) and Product Evaluation techniques (PE). These techniques are known methods that are used to avoid manufacturing and assembly problems in the process systematically. The basic idea in these techniques is to eliminate the potential problems that are likely to occur in the manufacturing and assembly in early stage of the product development (Eskilander, 2001).

1.3 Research Objectives

This research has two major objectives. The first objective is to develop a product evaluation technique (PE) that integrates the principles from Design of Assembly (DFA) so that the technique can be more comprehensive. The purpose is to identify and analyze the functions of the parts or components during product design activities. Further, it is also able to determine the assemblability of the parts. It is also an attempt to introduce a step – by – step approach to improve the function of the components of the product as well as procedure for redesign for the product.

The second objective of the work is to develop prototype software for the methodology developed. The software is intended to facilitate the application of the proposed technique.

In order to achieve the objectives, the following research activities are performed:

1. Detail Review of the current DFA approaches.
2. Framework development for integrating the principles of Value Engineering and Lucas DFA method.

3. Prototype DFA software development based on the proposed methodology to facilitate the designer to implement the proposed method.
4. Performing two case studies to identify the consistency and completeness of the developed method.

1.4 An Overview of the Developed Method

The methodology to be developed in the current work attempts to integrate the principles from Lucas DFA method and Value Engineering. It consists of the following phases:

1. Product Information
2. Function Identification toward Assembly
3. Function Analysis
4. Assembly Cost Analysis
5. Product Design Evaluation
6. Product Design Optimization and Improvement
7. Design Alternative Generation , Selection and Evaluation

After the information about the product is gathered, then it will be translated in a simple, step – by – step and systematic manner into the product information system. The product information system is divided into two that is part information and customer information. The part information consists of the parts involved in product design, its quantity and the materials of the parts. The customer information consists of the comment from the customer based on their needs and what should the designer do to improve the design of the product. After that, the functions of the parts or components of the product will be analyzed in order to identify what the parts of the product intention towards assembling. Based on the Technical Function Analysis System Technique or popularly known as Technical FAST, these functions will be divided into basic function, secondary functions and supporting functions so that the performance of the functions in terms of the manufacturability and assemblability can be identified systematically. Then, based on the Lucas DFA principle, the cost of assembly is taken into account in order to evaluate whether the cost of assembly can achieve the intended functions. At this stage, the five methods of value improvement is applied to identify the function – cost improvement by calculating the function – area of the difference between the ideal conditions that is function to cost ratio or value is equal to 1 and actual conditions that is the value is smaller or bigger than one. Based on this method, the user will be guided or exposed to the priority of value improvement automatically. The proposed methods also guide the user on redesign destination by answering the question given in terms of "Yes" or "No". The redesign destinations are "Eliminate", "Integrate" or "Part Simplification". After this stage, a set or several set of alternatives are generated based on the results of evaluations. Then it will be compared based on DFA rules and Pugh Method and select and evaluate the best alternative.

1.5 Significance of Findings

DFA and PE techniques are a strategic tool for optimizing the product design. It comprises various principles and guidelines for the optimizing process. There are several techniques and methodologies within the scope of DFA and PE techniques, which are studied in this research work. The essence of DFA and PE techniques lies in the successful implementation of these tools. If a product is investigated from the early design stage to the design details with rational basis, the design of a product can be improved as much as 80% of the total cost. So, the industries are encouraged to apply

DFA to optimize their product in order to get a huge benefit and survive in the competitive market. This research work suggests a methodology which the designers can improve their designed product in a structured way through the step – by – step implementation by applying DFA and PE techniques.

1.6 Report Structure

This report is divided into the chapters below:

1. Chapter 1 - Introduction: Discusses the background of the project. The objectives and scopes are also discussed in this chapter.
2. Chapter 2 – Literature Review: Discusses the state of art of DFA method. The DFA methods and PE techniques are elaborated. The strengths and weaknesses of the selected methods properties are also discussed.
3. Chapter 3 - Proposed Methodology: This chapter discusses the development of the methodology based on Lucas DFA and Value Engineering.
4. Chapter 4 – Software Development: This chapter details the prototype software that has been developed based on the proposed method. The comparison in terms of the features and the capabilities between the prototype software and the commercial software is also discussed in this chapter.
5. Chapter 5 – Case Studies: This chapter shows the results of the case study that is implemented based on method developed. In order to check its effectiveness, the result of the case studies is also compared with other method that is VE, Lucas DFA, and Boothroyd - Dewhurst DFA in methodology level.
6. Chapter 6 – Conclusions: This chapter presents the conclusions of the research work. The suggestions for further study are also given.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is aimed at discussing DFA and its guidelines. The techniques of Design of Assembly (DFA) and product evaluation (PE) techniques along with their advantages and drawbacks are also discussed. The comparison among DFA methods and product evaluation (PE) techniques are also being made in order to identify the fundamental principles in each methodology.

2.2 Background

Starting from late 1970s, Boothroyd and Dewhurst conducted a series of studies on Design for Assembly (DFA) that consider the assembly constraints like assembly method and assembly costs during design stages so that these constraints can be used as guidelines to find out design changes that can lead to reduction of final design cost (Kuo et al, 2001). The work of Boothroyd and Dewhurst was extended by Stoll (1988) who developed the concept of Design for Manufacture (DFM) that concurrently considers all the design goals and constraints for the products that will be manufactured. The applications of DFMA leads to the enormous benefits to the industries including simplification of the products, reduction in assembly and manufacturing cost, improvement of quality and shortening the time to market (Kuo et al, 2001). In the 1990's more emphasis have been placed on the designing not only for manufacture, but also for the whole life of the product i.e. including manufacture, assembly, service, repair, with disassembly and recyclability. Throughout this entire evolution, however, the basic premise of the product for ease of assembly has been constantly updated.

2.3 Design for Assembly (DFA)

Design for Assembly (DFA) is a formal analysis procedure that brings together multidisciplinary teams to validate and evaluate a product design with respect to the assembly of its components or parts (Tate and Jared, 2000). It always coupled with Design for Manufacture (DFM) to form a Design for Manufacture and Assembly (DFMA). DFA has an important characteristic that it addresses the simplification of the product structure since the indicator of the product quality is the number of the parts in a product (Boothroyd et al, 1994; and, Redford and Chal, 1994).

The industries can get a lot of benefits by adopting the DFA method in the design process. The potential benefits of applying DFA is illustrated in Figure 2.1 (Eskilander, 2001).

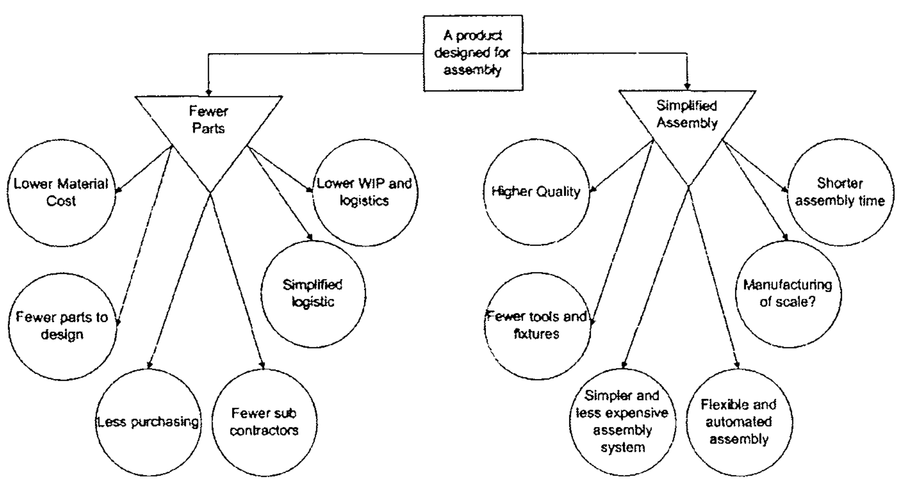

Figure 2.1 The general benefits of DFA (Eskilander, 2001)

The application of DFA will simplify the assembly process of the product. This can be achieved through shorter assembly time, higher quality of the product, required less tools and fixture, higher potential to be assembled in the flexible and automated system etc. Furthermore, fewer parts are needed to be assembled that will result in less parts to be designed, less material used and less inventory load.

2.4 DFA Guidelines and Principles

The objective of DFA is to integrate the product design and process planning into one common activity. DFA embraces some underlying principles, which helps maintain communication between all elements of the manufacturing system and permit flexibility to adopt and modify the design during each stage of the product realization (Boothroyd et al, 1994; and, Redford and Chal, 1994). The principles are (Magrab, 1997; and Ullman, 1997):

1. Simplify, integrate, and minimize total number of parts - Fewer parts mean less everything that is needed to manufacture a product such as total assembly time, product cost, inventory control etc.
2. Standardize and use common parts and materials - standard components require little lead-time, makes the inventory management easy and reduces the tooling time.
3. Mistake-proof product design and assembly (poka-yoke) – Components should be designed to be assembled in one direction. Notches, asymmetrical holes, and stops can be used to mistake-proof the assembly process.
4. Design parts for handling and orienting - Parts should be designed to be self-oriented when fed into process will reduce the assembly times. Product design must avoid parts that can become tangled, wedge or disoriented. The designed parts

should incorporate symmetry, low centers of gravity, easily identified features, guide surface and point for easy handling.

5. Minimize flexible parts and interconnection – Avoid flexible and flimsy parts such as belts, gaskets, tubing, cables and wire harnesses are more susceptible to damage and also make material handling and assembly more difficult
6. Design for efficient joining and fastening - Screws require more time to assemble. Therefore, they need to be standardized to minimize variety and use fasteners such as self-threading screws and captured washers. Consider the use of snap-fit whenever possible.
7. Develop a modular design - Modular design is able to standardize diversity by using different combinations of standard components so that the final assembly can be simplified due to less part is assembled and each module can be quickly fully checked prior to installation.
8. Design parts to be multi-functional - Combine function wherever possible. For example, design a part to act both as a spring and as a structure member, or to act both as an electrical conductor and as a structural member.
9. Design for multi-use - Design the parts for multi-use. For example, a spacer can also serve as an axle, lever, standoff, etc.

2.5 Various Methods of DFA

There are several tools and techniques for implementing DFA. They can be classified based on the technique's tendencies of work. The commonly available methods are:

i. Hitachi Method (AEM)
ii. Boothroyd – Dewhurst DFA Method
iii. Lucas DFA Method

2.5.1 Hitachi Method (AEM)

Assemblability Evaluation Method (AEM) was developed by Hitachi Ltd. to improve design quality for better assemblability. The main objective of AEM is to facilitate design improvements by identifying 'weakness' in the design at the earliest possible stage in the design process, by the use of two indicators (Redford and Chal, 1994):

i. An assemblability evaluation score ratio, *E*, used to assess design quality by determining the difficulty of operations.

ii. An assembly cost ratio, *K*, used to project elements of assembly cost.

AEM starts by classifying the assembly operations into 20 elemental assembly tasks that relate to insertion and fastening. Each task is assigned a symbol. Every elemental task is subjected to a penalty score that reflect the degree of difficulty of the task. The penalty scores are then ranked and compared to the elemental task with the lowest penalty score. Then, the factors that influence elemental tasks are extracted as coefficients and the penalty scores are modified accordingly. The sum of the various penalty scores for a part are then modified by the attaching coefficients and subtracted from the best possible score (100 points) to give the assemblability evaluation score for the part. The total assemblability evaluation score for the product is now defined as the sum of the assemblability scores for the individual tasks, divided by the number of tasks. This now may be considered as a measure of design efficiency where a score of 100 would represent a perfect design. Hitachi considers that an overall score of 80 is an acceptable design (Redford and Chal, 1994).

2.5.2 Boothroyd – Dewhurst DFA Method

Design for Assembly Method (DFA) was developed by Boothroyd and Dewhurst. It is aimed at minimizing the cost of assembly within the design constraints imposed by other design requirements. The method considers both manual and automatic assembly (Boothroyd et al, 1994; and Vance, 1991).

The product is initially measured on its feasibility to minimize parts by elimination or combination with other parts in the assembly provided that the functional requirements are satisfied. After that, grasping, manipulating, and inserting time of the part into the assembly are measured. Design evaluation is done by measuring the design efficiency using the formula below (Boothroyd et al, 1994):

$$Design\ effciency = \frac{"Ideal"\ assembly\ time}{"Actual"\ assembly\ time} = \frac{3 \times\ min\ parts}{Assembly\ Time} \qquad (2.1)$$

The theoretical minimum number of parts is the sum of the number assigned to each separate part in the assembly. The 'ideal' assembly time is calculated assuming an assembly containing the theoretical minimum number of parts. The 'actual' assembly time is the sum of the penalties assessed for handling and insertion difficulties associated with each actual part in the assembly based on compilation of standard time study data as well as dedicated time study experiments.

After evaluation, the part assembled is redesigned for ease of assembly by first eliminating and combining parts using the method from the theoretical minimum number of parts determination (Boothroyd et al, 1994).

2.5.3 Lucas DFA Method

The Lucas DFA method is the result of a collaboration project between Lucas Engineering and System and the University Of Hull. Lucas DFA method is based on the completion of an assembly flowchart, and performing a series of analysis. The thrust of Lucas DFA evaluation procedure is relying on function analysis, handling analysis and fitting analysis. The objectives of this method include (Lucas, 1990; Huang and Mak, 1999; and Shi, 1998):

i. Reducing parts count.
ii. Ensuring feasible assembly process at minimum cost.
iii. Achieving reliable and efficient automatic assembly.
iv. Highlight areas for future consideration when business environments permit.
v. Standardization of components, assembly sequence and methods across a range of related products.

The evaluation procedure is carried out using the procedure shown in Figure 2.2. However, only manual DFA operation is considered in this study. As product design begins, it is crucial to decide whether the product is unique or whether there are similarities. Similarities signify opportunities for standardization of components and/or assembly procedures, and the establishment of a product family theme.

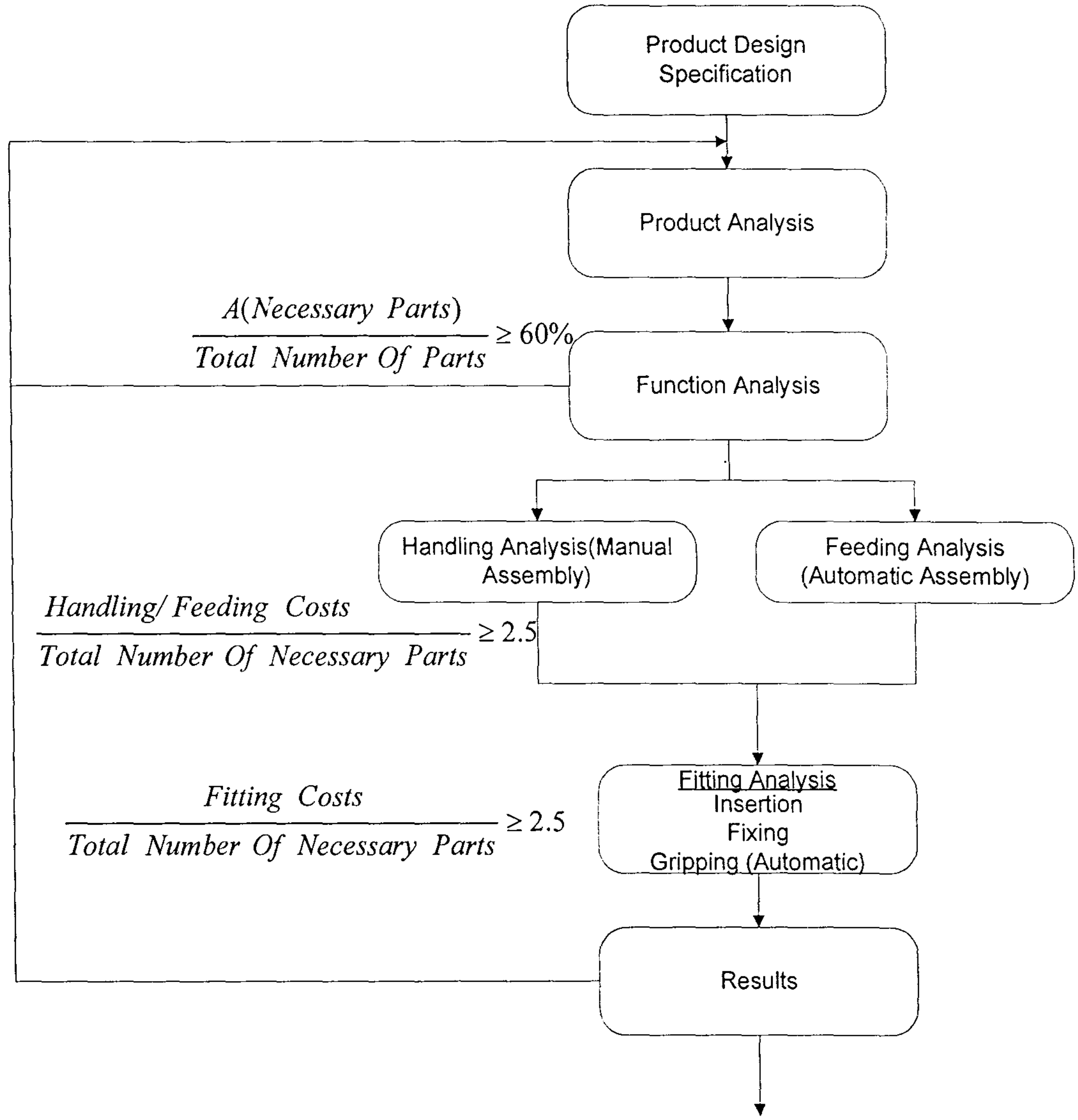

Figure2.2 Lucas DFA method (Redford and Chal; 1994)

As illustrated in Figure 2.2, three indices are used to measure the assemblability of a design, that is:

1. Design Efficiency – concerned with part count.
2. Feeding / Handling ratio – assess difficulty of part feeding or handling method.
3. Fitting ratio – assess the part insertion or assembly operations.

These ratio indices are compared with threshold values established from old or current designs. The indices are not based on cost rather they give a relative measure of the difficulties of assembly based on time. The Lucas DFA procedures include (Lucas, 1990; and Huang and Mak, 1999):

i. Product design specification (PDS) - PDS is a document that lists all the customer and business needs that the product must fulfilled.

ii. Product Analysis – The purpose of this analysis is to seek for using the common parts within and across the range of the products so that the tooling variation can be minimized and tooling utilization can be maximized, avoid the tooling duplication by assembling the same direction and seek for handling tool minimization by applying common feeding feature in large component.

iii. Function Analysis – The purpose of this analysis is to identify whether each part in the assembly exists for fundamental reasons. At this step, the part is going to be categorized into two that is necessary parts or 'A' part, which carry out vital function to the performance of the product such as drive shaft, adjusting screws etc and non-necessary part or 'B' part which, that purpose is not critical to the product functions such as fasteners, locators etc. The design efficiency is formulated as:

$$Design\ \ Effeciency = \frac{A}{A+B} \times 100\% > \ 60\% \quad \cdots \quad (2.2)$$

The acceptable value for design efficiency is more than 60%. If the design efficiency value is less than 60% then, it should iterate back to the PDS (step i) as illustrated in Figure 2.2.

iv. Handling Analysis – Handling analysis considers how the components and the sub assemblies manufactured in various places are going to be presented to the point of assembly. When assessing components for manual assembly, the less complex process is used. The process of handling analysis is defined in Appendix A – 1, A – 2 and A – 3. The calculation is:

$$Handling\ \ ratio = \frac{Total\ \ Relative\ \ Handling\ \ Cost}{Total\ \ Number\ \ of\ \ Essential\ \ Parts} < \ 2.5 \cdots\cdots\cdots\cdots (2.3)$$

The handling ratio gives a good indication of the suitability of the design for the assembly because it takes the consideration of:

a. Size of the parts in product design – Small size of the parts may be difficult to handle and orientate and need specialized handling aids such as tweezers, optical aids etc.
b. Part characteristics – Part tangling, nesting and fragility, etc. will cause the problems to the assembly during handling process.
c. Part orientations – The orientation of the part either symmetrical or rotational orientation, if required will affect the assembly time and cost.

The acceptable value for handling ratio is less than 2.5. If the handling ratio value is more than 2.5 then, it should iterate back to the PDS (step i) as illustrated in Figure 2.2.

v. Fitting Analysis - The function of this step is to identify the expensive fitting process and gives the indicators as to how these processes can be changed in order to reduce the cost. This analysis work is based on Assembly Sequence Flowchart (see Figure 2.3) where the assembly operation is represented by a geometrical symbol. Fitting Analysis for manual assembly considers the following process:

a. Work – holding (O) – represents by a symbol of a circle. It is a process where placing a temporary part to act as fitting aid such as spacer, guide, etc. is implementing

b. Inserting and fixing (□) – represents by a symbol of a rectangle. It is a process where an alignment, clearances, positioning requirements for insertion operations; fastener type, fastener condition etc. for fastening devices is implementing.

c. Non – assembly operations (Δ) – represents by a symbol of a triangle. It is a process where adjustments, re-orientations, calibrations, inspections, etc. is implementing.

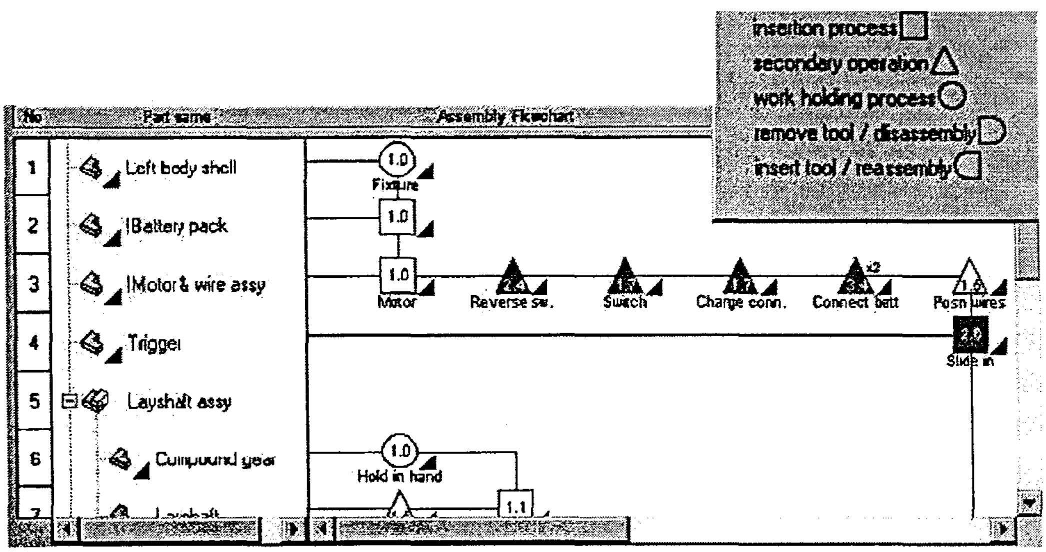

Figure 2.3 Assembly sequence flow chart (TeamSet, http://www.teamset.com/dfa.html)

The formula for fitting analysis is given by:

$$Fitting\ ratio = \frac{Total\ Relative\ Fitting\ Cost}{Total\ Number\ of\ Essential\ Parts} < 2.5 \quad (2.4)$$

The acceptable value for fitting ratio is less than 2.5. If the handling ratio value is more than 2.5 then, it should iterate back to the PDS (step i) as illustrated in Figure 2.2.

In Lucas DFA, the total manual assembly cost is formulated as:

$$Cost\ of\ manual\ assembly = \frac{C_p}{N_t} + \frac{C_a}{N_a} + C_m \quad (2.5)$$

C_p represents the total capital cost of assembly system, where it is given by:

$$C_p = N_p \Sigma (C_f + C_i + C_{fx}) \quad (2.6)$$

Other variables in the total manual assembly cost (Equation 2.5) and total capital cost of the assembly system (Equation 2.6) are:

N_t = Total number of assemblies produced during the life of the system

C_a = Annual cost of operating the system

N_a = Annual production of the assemblies

C_m = Labor Cost /Assembly

N_p = Number of parts in the assembly

C_f = Individual Feeding/Handling cost

C_i = Individual Insertion cost

C_{fx} = Individual Fixing cost

From Equations 2.5 and 2.6, it can be seen that the cost of assembly could be reduced if the N_p, C_f, C_i and C_{fx} are reduced. As a result, the annual production of the assembly increased with the same amount of the annual cost of the operating system and the reduction of the labor cost because the output rate is higher.

2.6 Comparison of the DFA Methods

Having reviewed the three DFA methods they are then compared on their relative merits and drawbacks.

Hitachi Method (AEM)

The advantage of Hitachi method is that it analyzes the assembly operations of each component of the product. The penalty points are awarded for every motion or operation that differs from the simple downward motion.

The drawback of Hitachi Method is that it only focuses on the insertion and fastening process. It neglects the handling process. Furthermore, with Hitachi Method, there is no support on how to redesign the product when the evaluation shows poor results.

Boothroyd – Dewhurst DFA Method

The advantage of the Boothroyd – Dewhurst method is on the quantification based on the design efficiency of how to redesign the product. The part that has low DFA index which is theoretically considered unnecessary is eliminated. The part that required high assembly time should be redesigned to better resemble the assembly process i.e. requiring the shortest assembly time.

The drawback of Boothroyd–Dewhurst DFA method is that it does not show the evaluation of the whole assembly sequence. Therefore, the assembly operations such as fitting, gripping and etc., which may be causing problems, are not acknowledged. This method also has no support on how to redesign whenever the evaluation shows poor results.

Lucas DFA Method

The advantage of the Lucas DFA is that it shows the evaluation of the assembly sequence of the fitting process so that the users acknowledge which are the problematic operations. This method differentiates the handling and fitting analysis so that the user is able to distinguish either the handling or the fitting causing the problems so that the effort to trouble shoots can be reduced.

The drawback of Lucas DFA is that the function analysis does not show the reason why should the parts exist. The analysis merely reasons on the mobility, material and serviceability issue. Furthermore, there is no support on how to redesign when the evaluation shows the poor results that resulted in higher iteration rate.

Table 2.1 shows the comparison of the reviewed DFA Methods based on their usage. The comparison is based on the criteria on the left column of the table. The weight of the comparison is based on 'Better', 'Average', and 'Worse' (Redford and Chal, 1994; Nevins and Whitney, 1994; and, Huang and Mak, 1997).

Table 2.1 Comparison of DFA methodologies

Method / Criteria	Boothroyd DFA	Lucas DFA	Hitachi AEM
Training and/or practice	◒	●	●
Systematic	●	●	●
Quantitative	●	●	●
Teaches Good Practice	●	●	●
Design effort	○	○	○
Management Effort	◒	●	●
Implementation cost and effort	●	●	●
Rapidly effective	●	●	○
Stimulates creativity	●	○	●
Product planning team approach	◒	○	●
Advantages	A, E, H	D, E, F	A, E
Disadvantages		C	
Application	A	A, B, C, D, E,	A, B

● Better ◒ Average ○ Worse

The criteria in terms of assemblability comparison of DFA methods are shown below in Table 2.2. The criteria include analysis capabilities and cost factors.

Table 2.2 Comparison table for DFA methodologies (Kocabicak, 1999)

Criteria in the existing systems	Boothroyd DFA	Lucas DFA	Hitachi Method (AEM)
Parts reduction analysis	++	++	+
Handling analysis	+	+	+
Insertion analysis	+	+	++
Suitability for different kinds of assembly	+	+	-
Complexity of analysis method	Medium	Medium	High
Training effort cost	Medium	Medium	High
Cost of software	Medium	Medium	High
Assembly system investment calculation	-	-	-

From Table 2.2, the '++' indicates that the compared DFA method has a better criteria in the existing system. Meanwhile, the '+' indicates that the compared DFA method has a good criteria in the existing system. From the table, it can be concluded