

TAXONOMY OF SELECTED DESIGN TOOLS FOR COST-EFFECTIVE DESIGN

by

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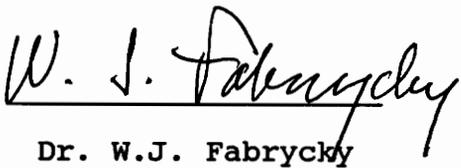
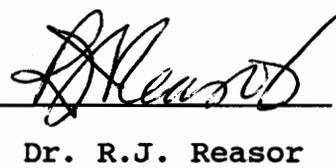
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# **TAXONOMY OF SELECTED DESIGN TOOLS FOR COST-EFFECTIVE DESIGN**

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**INDUSTRIAL AND SYSTEMS ENGINEERING**

## **ABSTRACT**

For a company to be competitive, it must design a product or provide a service in the most effective and efficient way. This project studies four design tools: Quality Function Deployment, Taguchi Methods, Design for Assembly, and Activity-Based Costing. The need for a better design process is addressed by means of a particular taxonomy.

The three objectives of the project are: 1) to make the managers, designers, and others, aware of when and why the design tools are needed; 2) to make the different tools easily understandable; 3) to create a mind-set for good design rules, and to improve the ability of association among the different design tools.

## **ACKNOWLEDGEMENTS**

I would like to say thanks for all the support, education, unlimited patience, and understanding to my father John Miles and my mother Isabel Touya [ gracias por todo ]. I would also like to thanks Mimi and Daddy.

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## 1.0 INTRODUCTION

During the decade of the '80s, U.S. manufacturing industries became acutely aware that approximately 80% of a product's life-cycle cost, as well as its quality is established through decisions made during the product design stage.

Given this fact, new tools and philosophies useful for product design started to appear in the marketplace, such as Design For Assembly, Design For Manufacturing, and expert systems. Additionally, some tools were introduced from Japan, such as Quality Function Deployment and Taguchi Methods.

In addition to these new tools and philosophies, which are concerned with making the product and the company more efficient and competitive, a new accounting philosophy appeared, called "Activity-Based Costing."

This project addresses the need to apply four of the numerous existent tools during the product design stage: Quality Function Deployment, Taguchi Methods, Design for Assembly, and Activity-Based Costing. The reasons for their selection, among others are: 1) all these tools are relatively new in the market, 2) they can be used in conjunction with each other, 3) they approach different solutions for different aspects of the

design, and 4) they are relatively easy to study and to apply.

The scope of the project involves the analysis of these four tools by means of a particular taxonomy in order to see how they influence the achievement of a good product design.

The project has three objectives: 1) to make the manager, designer, etc. aware of when and why the tools are needed; 2) to make the different design tools easily understandable; 3) to create a mind-set with the managers and/or designers of good design rules and to improve their ability to associate among the different design tools.

The first thing that must be done in any tentative correction or improvement of a particular phenomenon is to understand the environment where the improvement is going to take place. Understanding the environment means understanding the deficiencies or the actual problems which caused -in the particular case of this project- a poor product design and/or poor product performance, resulting in the critical consequence of a high product life-cycle cost.

In order to make the problems of the actual product design environment understandable, a cause-and-effect diagram of the four main resources of an organization was created. These resources include: man, material, method, and machine &

process (as shown in Figure 1). This cause and effect diagram shows how the four main resources affect by themselves or in combination the actual problems of the product design. Even though many other deficiencies exists, Figure 1 gives a good idea of what are the main area's problems, how they influence poor product design, and what are possible areas of improvement in order to achieve better product design.

The project emphasizes the need to apply Quality Function Deployment (QFD), Taguchi Methods (TM), Design for Assembly (DFA), and Activity-Based Costing (ABC) as the solutions of these deficiencies in the product design. Figure 2 shows a cause-and-effect diagram of the characteristics of these four tools, displaying the possible solution that each tool can contribute, by itself or in combination with other tools, to achieve a good product design and a good product performance, thus giving rise to a low product life-cycle cost.

The project further addresses the achievement of a good product performance and a good product design by providing a better understanding of each of these tools by means of a particular taxonomy. This taxonomy addresses the answers to the 5W1H (Why, When, What, Who, Where, and How) in the application of the four tools. As the taxonomy goes from general to specific information, it provides in an increasingly detailed way the characteristics of each tool so

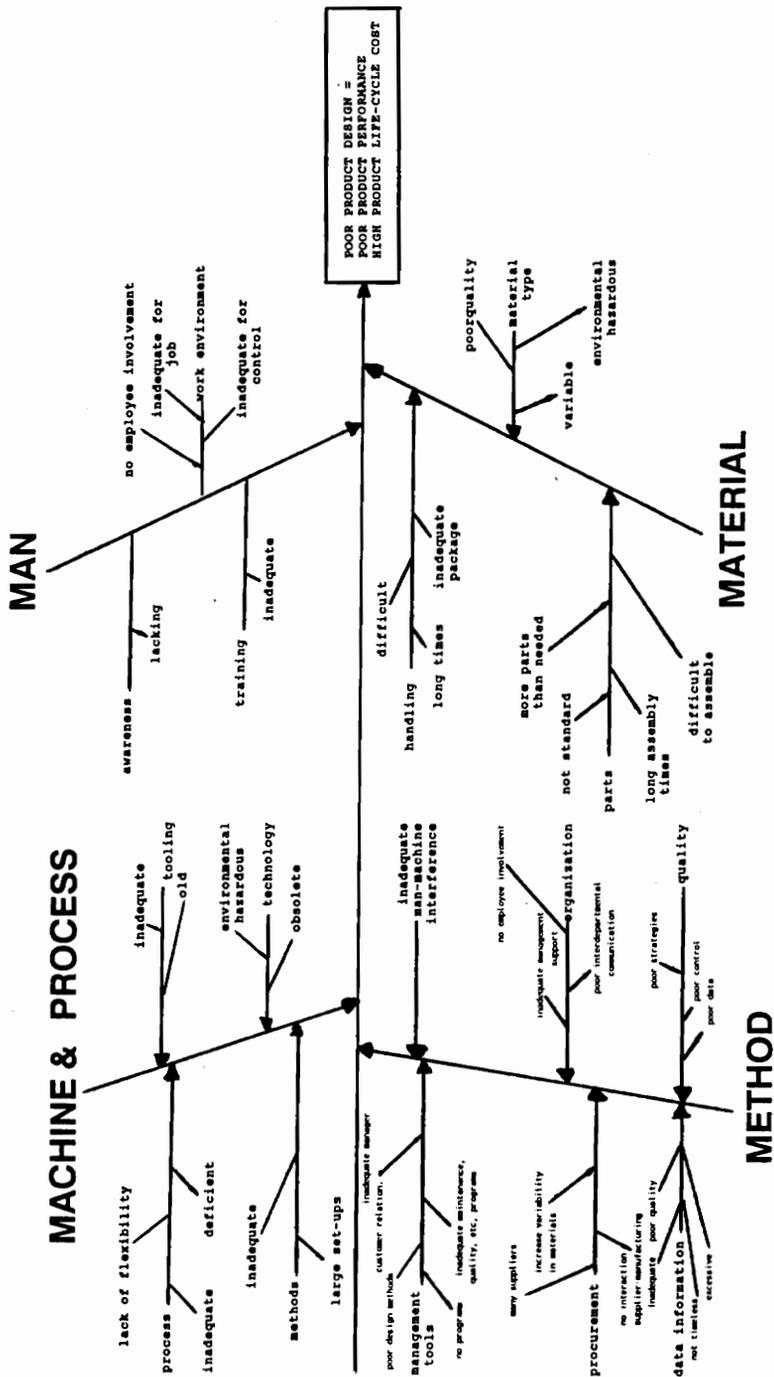


Figure 1 Cause-And-Effect Diagram Of Actual Deficiencies Of The Four Main Organization's Resources



that managers and designers can classify each tool and understand the possible relationships among the different tools. Figure 3 shows the Map of the Taxonomy, which illustrates the thinking behind the creation of the taxonomy. The logic is, given the existence of a decision, whether voluntary or imposed, certain steps are going to be taken to fulfill the needs of that decision. Among those steps, the first one is to learn something about the environment where the tools are going to be applied (type and characteristics of industries) and something about the tools to be applied (general characteristics and interactions). After having this general idea of industry and tools, a table can be created to see if a particular tool is applicable to a particular industry. If this is so, further information about the tools can be learned, such as their benefits, challenges, software availability, etc. If the benefits are the ones needed and the challenges can be overcome, then more detailed information regarding each tool can be given for its possible implementation.

The explanation of Figure 3 is the general idea behind the creation of the taxonomy. It is known that a taxonomy is the arrangement or classification of objects according to certain criteria. However, it is almost impossible to classify the application of the four tools in the different industries with fixed conditions as in the case of animals or plants, for

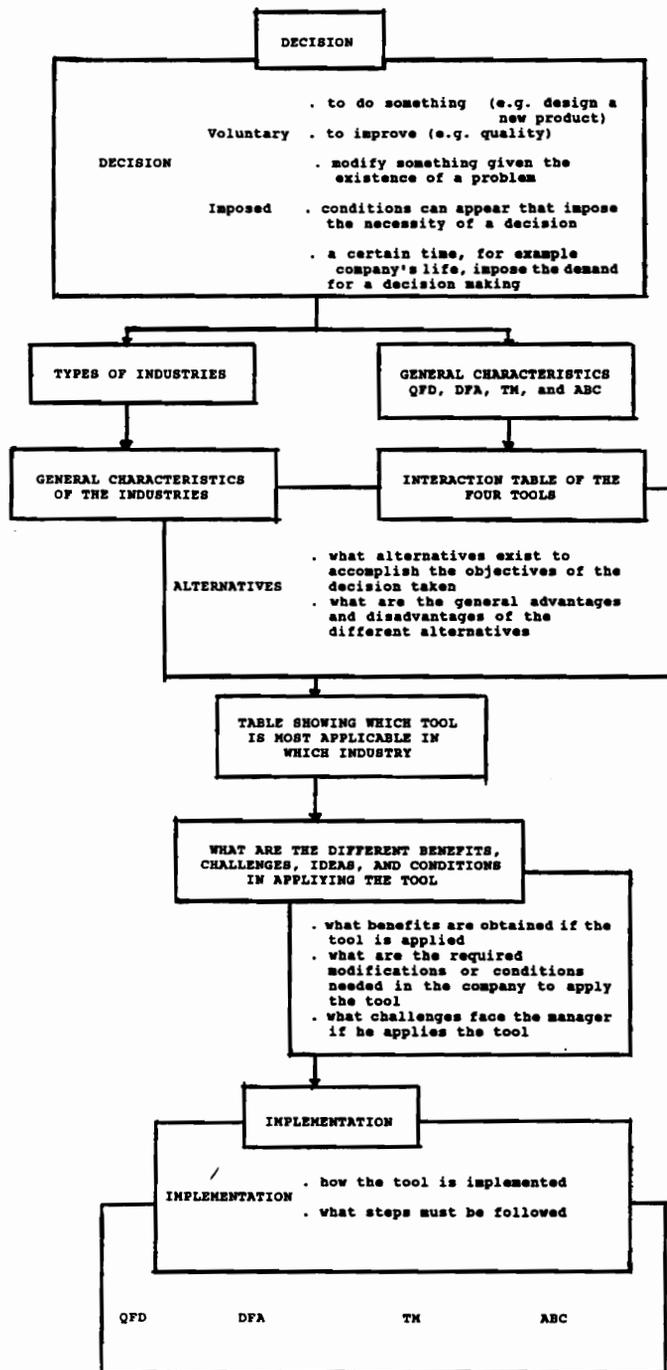


Figure 3 Map of the Taxonomy

example. Additionally, it is impossible to generate a set of simple design rules which will differentiate the case "Do I need the application of design tool X?". As Alan Wu (American Supplier Institute) mentions in a letter addressed to Eduardo Miles, " ... the more realistic answer to every question should be 'it depends'. There are always exceptions in every situation. For example, the success or failure of Taguchi Methods applications greatly depends on the knowledge of the methods ... There are successful as well as not-so-successful stories in every industry, every company environment ... but one should not try to use another's standard as a rule. One needs to evaluate each individual situation, then set guidelines for implementation." Thus, the taxonomy created here is a very particular one which addresses general characteristics that differentiate the four design tools and their application in the different industries, thus allowing for the identification of relationships among them.

The taxonomy is composed of six basic tables, shown in a very simple way in Figure 4. Tables I and II represent the industries' characteristics, Tables III and IV represent the general characteristics of the tools, Tables V and VI represent the intersection between the industrial and the tools tables, as well as the general benefits and challenges of each tool. Finally, the Implementation Table represents the detailed analysis of each tool. A more detailed view of Figure

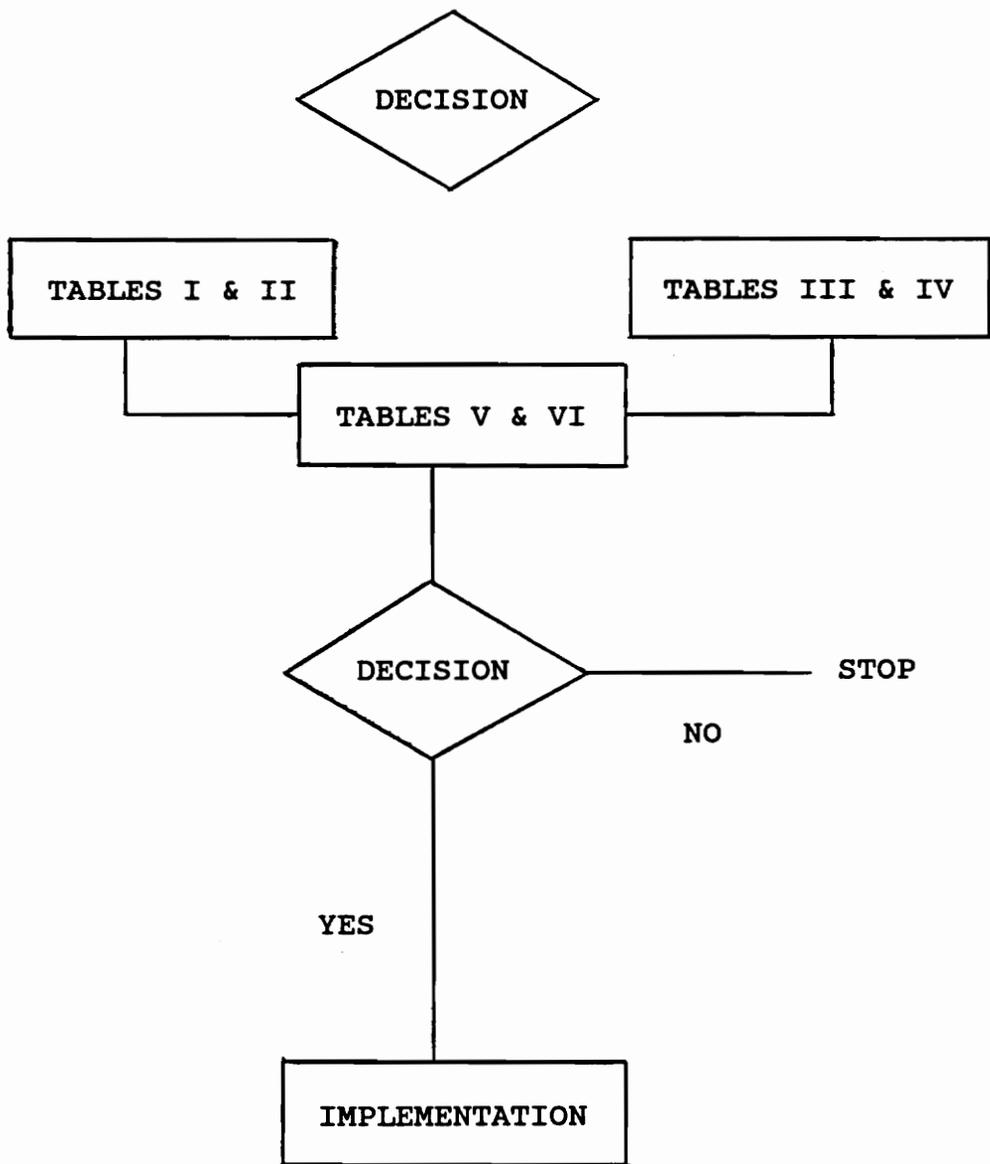


Figure 4 A Simple View of the Taxonomy

4 is given in Figure 5, which illustrates its relation with the general map of the taxonomy (Figure 3). Figure 5 shows how, from the general information of the design tools (Tables III & IV) and the general information of the industries (Tables I & II), Table V was derived. Table V gives rise to Table VI, which indicates the benefits, challenges, software, and general philosophy of each tool. Subsequently, from Table VI emerges the Implementation Table, which presents how the tools can be used and what the different steps to apply them are. The general explanations of each table are as follows:

**TABLE I** gives a general classification of different industries in the United States

**TABLE II** gives general characteristics of the industries selected for further analysis in the project

**TABLE III** gives general characteristics of the four product design tools addressed in the project

**TABLE IV** gives an idea of the possible interaction of applying one design tool after another has been applied

**TABLE V** indicates which design tool is most applicable in a given industry

**TABLE VI** gives general characteristics of the application of the tools: why or when to apply the tool; what are the challenges to face; software.

**IMPLEMENTATION TABLE** gives a general idea of what are the different steps are needed in the application of each tool

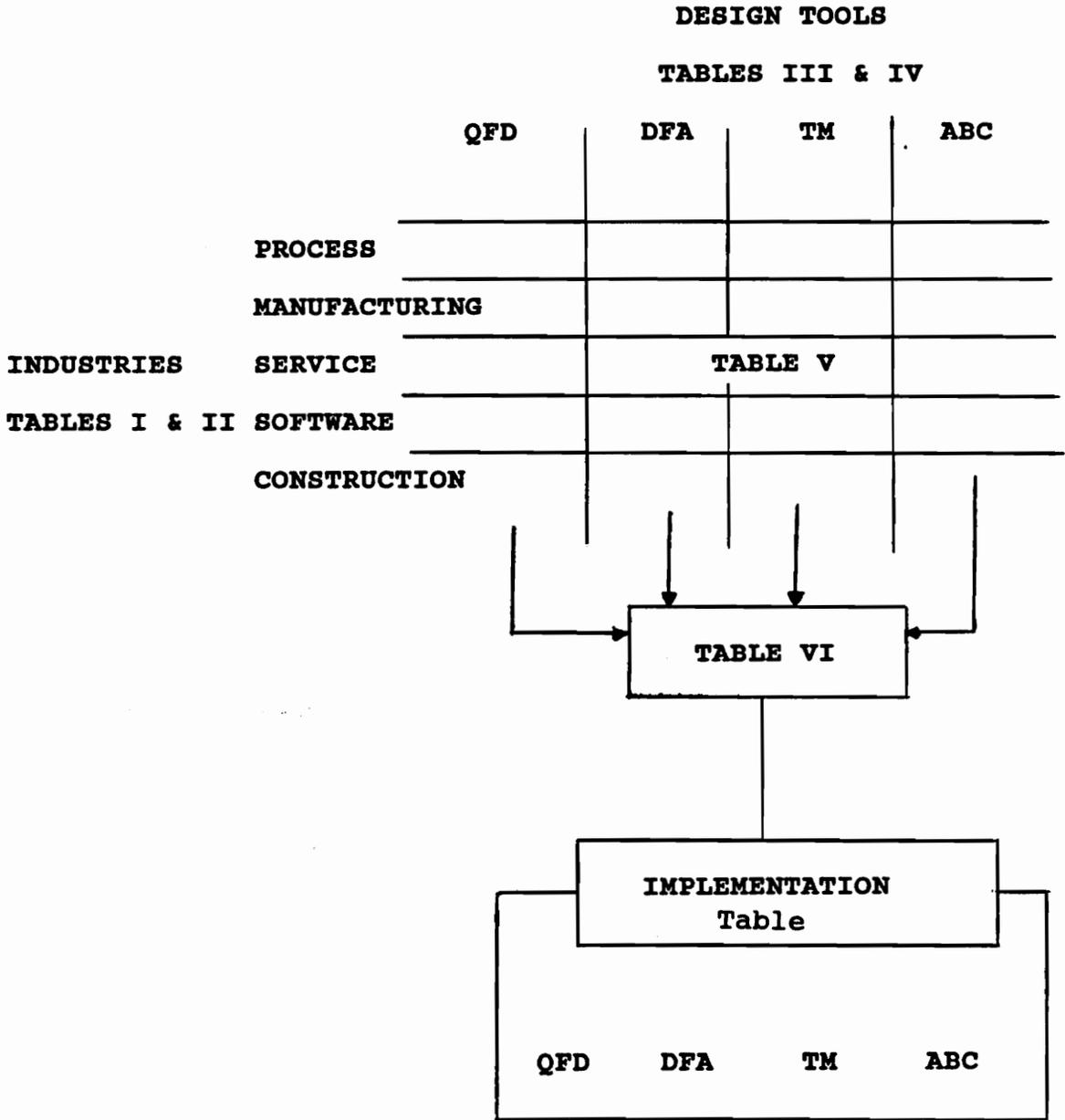


Figure 5 A Complex View of the Taxonomy

The taxonomy can be thought of as being composed of two parts. Part one includes Tables 1-6 and is addressed in the chapter Taxonomy. This first part answers the questions "when" and "what" of the 5W1H and gives all of this information in table form with an adequate explication of each one. The second part includes the Implementation Table (Table VII). Part two is composed of four chapters: Chapter 4, Quality Function Deployment; Chapter 5, Taguchi Methods; Chapter 6, Design for Assembly; and Chapter 7, Activity-Based Costing. The information in this part is given in text form and answers the questions "why", "who", "where" and especially "how" of the 5W1H.

It is recommended when reading this report that the reader keep an open mind regarding what can and cannot be generalized. The taxonomy has to be read with the idea of understanding new ways of design thinking and what the real possibilities are for the different tools available. After understanding the tools and their application possibilities, the reader must use association and imagination to be successful in using the taxonomy.

## **2.0 LITERATURE REVIEW**

The literature review is divided into two sections: The first section is the study of the actual tools to support product design. The second section is the study of the management accounting systems, focusing on activity-based costing.

### **2.1 TOOLS TO SUPPORT DESIGN**

There are basically five different tools to support product design: 1) reliance on the engineering judgment of the design team members, 2) expert systems, 3) computer programs, 4) assembly-driven design for manufacturing, and 5) quality approaches (Ulrich, 1989). A brief description of each of these different tools to support product design will follow.

#### **2.1.1 Reliance on the experienced engineers' judgement**

Small and medium sized firms commonly uses this approach to design products or processes. In this approach the experienced members of the design team use their collective experience to influence design choices. The obscurity of the approach comes from the way it is applied. Trade-offs between designs are very difficult to evaluate, previous detailed support information regarding the decisions offered is difficult to obtain, and specific past experiences may have been misleading (Ulrich, 1989). [Further references: Daetz, 1987; Grager, 1986; Trucks, 1987]

### **2.1.2 Expert systems**

An expert system is a computer program where the basic software is a group of IF ... THEN rules, based on experience or data obtained from manuals, etc. An example of this tool is an existent expert system produced by Cognition Inc., which projects probable production costs for various part or assembly configurations and provides guidance as to their manufacturability. [Further references: Matthews, 1983; Winchell, 1989]

### **2.1.3 Computer programs**

The internal report of The Charles Stark Draper Laboratory Inc.<sup>1</sup> (1990) states that, "at present, most computer tools for aiding design are directed at the creation of geometry or representation of geometry, together with some analytical capability for functional performance such as finite element analysis. Even these tools do not provide any guidance or advice to help improve the design. Little has been done to link geometric models to cost analyses, process planning for fabrication or assembly, tolerance analysis, quality analysis, or other aspects of product design and manufacture. Furthermore, there are few or no computerized tools to aid these analyses." [Further references: Boothroyd 1988, Quinalan 1988]

#### **2.14 Assembly-driven design for manufacturing**

The most widely published methodologies are Design for Assembly, Design for Manufacture and Design for Flexibility. Design for Assembly (DFA) involves reducing the number of separate parts to a minimum and making the remaining parts as easy as possible to assemble. Design for Assembly, developed by Boothroyd and Dewhurst, is probably the best known and most widely used technique. The technique was developed during their research at the University of Massachusetts, where they published "Product Design for Assembly Handbook" in 1983.

In the 1970's, a methodology and database was developed at Hitachi Ltd., and called the Assembly Evaluation Method (AEM). DFA and AEM are the only two quantitative assembly analysis procedures developed as a result of independent empirical and analytical work. All others are derivations of these.

Design for Manufacture (DFM) is the integration of product design and process planning into one common activity. Stoll<sup>2</sup> (1988) states that, "the objectives are to identify product concepts that are inherently easy to manufacture, to focus on component design for ease of manufacture and assembly, and to integrate manufacturing process design and product design to ensure the best matching of needs and requirements." Stoll (1988) gives a selected list of DFM methodologies as design axioms, DFM guidelines, toolkit, etc., indicating also where

they might fit into the proposed DFM process.

Design for Flexibility (DFF) can be seen as an extension of Design for Assembly. The flexibility of an assembly system is primarily its ability to tolerate a range of product variations. The demand for flexibility changes the conditions of DFA; thus, it has to be considered more than a product, more than one system, and more than one assembly (Andreasen & Ahm, 1987).

#### **2.1.5 Quality approaches**

Quality approaches to support product design can be seen as tools for DFM, but this approach will be discussed separately because of its importance in the product design. The most common approaches to consider quality in the product design are: Quality Function Deployment (QFD) and Taguchi Methods.

##### **2.1.5.A Quality Function Deployment**

The concept of Quality Function Deployment was introduced in Japan by Professors Akao and Mizuno in 1967, but it did not emerge as a viable methodology until 1972 when it was applied in Mitsubishi Heavy Industries, marking the beginning of the movement in Japan.

Quality Function Deployment was introduced to the United States in 1983 by Yoji Akao, who has introduced it in Japan 16

years before. Yoji Akao published a short article in Quality Progress which gave rise, less than seven years later, to the major force in total quality effort in the US.

Sullivan (1986) describes the methodology based on Macabe's approach, in which the QFD system concept is based on four key documents: Planning Matrix, Deployment Matrix, Process Plan, and Operating Instructions (or Production Planning). Y. Akao offers a more detailed framework for QFD. He mentions in his book (Akao 1990) that a comprehensive QFD system must reflect technology, reliability, and cost considerations. Akao defines four steps to implement QFD, as Aswad (1989) summarizes them as: Step I- Quality Deployment; Step II- Technology Deployment; Step III- Cost Deployment; Step IV- Reliability Deployment.

#### **2.1.5.B Taguchi Methods**

During the 1950s and early 1960s Dr. Genichi Taguchi developed the foundations of Robust Design. Phadke (1989) defines Robust Design as "an engineering methodology for improving productivity during research and development so that high-quality products can be produced quickly and at low cost".

In 1957 he published the first edition of Design of Experimental Method, which concentrated on the process of laying out calculations through orthogonal arrays, but the

content was no more than an amplification of the theory of R.A. Fisher of Great Britain and the application of this theory to technical areas.

In 1962 G. Taguchi published the second edition, which was an extensive revision of the first edition. After doing research in Bell Telephone Laboratories, and teaching at a university in Japan, in 1967 he published the third edition of Design of Experimental Method, in which he introduced the expressions of dynamic characteristics by signal noise ratio and applications to instrumentation error.

Since then, the Taguchi methods have become one of the leading quality tools used in Japan. In 1980 Dr. Taguchi's concepts and methods were introduced into the United States. Throughout these ten years, Taguchi's concepts and methods have attracted much attention.

Pignatiello<sup>3</sup> (1988) differentiates Taguchi Methods into Taguchi's strategy and Taguchi's tactics. He states that, "the Taguchi strategy is a systematic application of the design and analysis of experiments for the purpose of designing and improving product and process quality. The strategy involves the empirical minimization of an expected loss function over an uncontrollable noise space."

Taguchi's tactics draws on many ideas from statistical experimental design, for e.g. orthogonal arrays, for obtaining dependable information about variables involved in making the engineering decisions. For further information in experimental design check: Myers, 1972; John & Quenouille, 1977; Box & Draper, 1969.

## **2.2 MANAGEMENT ACCOUNTING SYSTEMS**

The traditional cost methodology has its foundations from the scientific management movement (Kaplan, 1989), which promoted the standardization and simplification of the production processes in order to use direct labor, direct material or machine hours for costing.

The traditional accounting system distributes the overhead cost to products according to weights that vary directly with volume of outputs (direct labor, materials dollars, machine hours). This type of overhead distribution results in an inaccurate product cost. The inaccuracy occurs when the quantity of volume-related input consumed by a product does not vary in direct proportion to the quantity of volume-unrelated consumed.

One of the first papers published in the American literature, where the previous problems are addressed and emphasis is given to activity-based costing is the paper written by R.

Kaplan (1983). As in Turney (1989) is said activity-based costing is based on the fact that activities consume resources and products consume activities. Products incur costs by the activities required for design, manufacture, sale, delivery and service. In ABC the product cost is determined by the activities the product demands during the production process. ABC traces costs to products through activities and not as traditional allocation, which based its allocation in the measure of attributes of the individual product item (e.g. the number of direct labor hours consumed). (Cooper 1989 d)

Buttler (1990) expressed that another aspect in management accounting systems that has to be taken into account, together with ABC is life-cycle costing. Life-cycle costing (LCC) is an idea that all costs arising from an investment decision are relevant to that decision.

It is important to link ABC with LCC during the design stage, and this has already been accomplished by, e.g., Institute of Competitive Design, which produced a Predictive Cost Modeling (PCM) which enables companies to predict the total life-cycle costs from many design alternatives. Through PCM, the design team builds a comprehensive product cost model to determine how manufacturability, quality, materials, and field service, as well as other costs, can best be eliminated (Arpino, 1988).

### 3.0 TAXONOMY

The taxonomy can be approached as a whole as explained in the Introduction, or in sections depending which information is required.

- . If information about the general characteristics of the is wanted, read Table III on page 24
- . If information on which tool is applicable to a certain industry is wanted, read Table V on page 40.
- . If information about benefits, challenges, or software availability is wanted, read Table VI on page 43. In particular:

QFD on page 44

DFA on page 49

Taguchi Methods on page 47

ABC on page 52

- . If detailed information on each tool is wanted, read the Implementation Table on page . In particular:

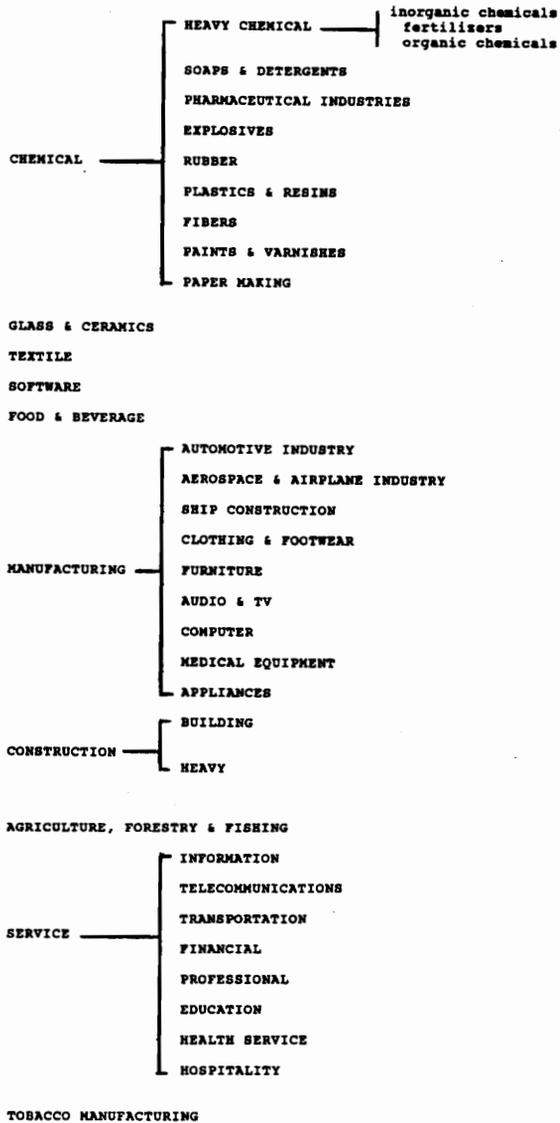
QFD Appendix A on page 62

Taguchi Methods Appendix B on page 97

DFA Appendix C on page 135

ABC Appendix D on page 169

**TABLE I**  
**TYPES OF INDUSTRIES**



Given the fact that in the twenty century more than 450 separate industries were identified in the United States, only the following industries are consider in the project: Process Industries, Manufacturing Industries, Software Industries, Service Industries, and Construction Industries.

The previous table is just the industries consider to be most important among those 450 industries existent in the United States.

TABLE II

GENERAL CHARACTERISTICS OF THE SELECTED INDUSTRIES

	GENERAL CHARACTERISTICS
PROCESS	<ul style="list-style-type: none"> <li>. product is produced in a continuous way</li> <li>. capital intensive</li> <li>. production batches are generally governed by the machines</li> <li>. on site quality control may be difficult</li> <li>. change overs are not always easy</li> <li>. materials used in the process must be always available in the production site</li> </ul>
MANUFACTURING	<ul style="list-style-type: none"> <li>. has four basic processes: forming, treating, finishing, and assembly</li> <li>. can be fully automated</li> <li>. product is produced in an intermittent or repetitive way</li> <li>. rework of defect product is possible</li> <li>. the production process can be stopped for product failure</li> <li>. not as rigorous material control as process industries</li> </ul>
SERVICE	<ul style="list-style-type: none"> <li>. there is high customer contact through the service process</li> <li>. the customer participates in the process of providing the service</li> <li>. skills are sold directly to the customer</li> <li>. services cannot be mass-produced</li> <li>. high personnel judgement is employed by individuals performing the service</li> <li>. are labor intensive</li> <li>. quality control is primarily limited to process control</li> <li>. pricing options are more elaborate</li> <li>. a service is perishable; i.e. it cannot be carried in inventory, but is consumed in production</li> </ul> <p>(Murdick, Render &amp; Russell 1990)</p>
SOFTWARE	<ul style="list-style-type: none"> <li>. three phases of software development:               <ul style="list-style-type: none"> <li>- setting design baseline (derivation of data processing requirements and preliminary design)</li> <li>- production (detail design, code and debug)</li> <li>- test</li> </ul> </li> <li>. team effort is usually needed in developing software</li> <li>. can be mass-produced</li> <li>. individual initiative and creativity are very important</li> <li>. there exists a high dependency in software and hardware in microprocessors</li> <li>. building of large software systems is like building a large scale industrial effort</li> <li>. labor intensive</li> </ul>
CONSTRUCTION	<ul style="list-style-type: none"> <li>. must move workforce and equipment to the site</li> <li>. is under government control</li> <li>. needs safety programs</li> <li>. the product generally is produced after a contract is obtained</li> <li>. bidding and contract award are one of the principal activities</li> <li>. can be mass-produced</li> <li>. cannot be fully automated</li> <li>. is highly customer oriented</li> </ul>

TABLE III

TABLE OF GENERAL CHARACTERISTICS OF THE FOUR DESIGN TOOLS

	QFD	DFA	TM	ABC
ACCURACY	good	good	depends on case	depends on case
TRAINING	medium	medium	high	medium
SOFTWARE NEEDED	no, but it will help	no, but it will help	no, but it will help	yes
QUALITY IMPROVEMENT	not really	yes	yes	no
COST REDUCTION	yes	yes	yes	yes
IMPLEMENTATION TIME	long	medium	medium	medium
KNOWLEDGE	no	no	yes	no
CREATIVITY	no	yes	no	no
TEAM	yes	yes	yes	yes
HOW LONG TO SEE RESULTS	after some time	immediately	after some time	after some time
ENHANCES RELIABILITY	yes	possibly	possibly	no

\* See Glossary on next page.

\* See Explanation on page 28

### 3.1 GLOSSARY

**Accuracy** Accuracy reflects how close are the results obtained from the application of the tool are to the proclaimed ones. The accuracy of the tool will depend on whether the tool uses hypotheses during its application to obtain the aimed at results. For example, Taguchi uses the hypothesis of additivity in his model, and Activity-Based Costing uses the hypothesis of the aggregation of activities. These hypotheses can or cannot be valid for every scenario. If they are true for every scenario, then the application of the tool is similar to that one which does not uses hypotheses. In both cases the application of the tool will deliver the aimed at results and the accuracy will be considered good. If the hypotheses are not true for every scenario, then the accuracy of the tool is diminished, since the attainment of the aimed at results will depend on certain hypotheses whose validity depend on the particular application case. Three different levels were considered: 1) good = the results obtained by the application of the tool are very close to the aimed at results. Good accuracy does not mean that all the aimed at results will be obtained if the tool is applied, even though it is possible. Good accuracy means that either the tool does not use hypotheses or that the hypotheses are true in every scenario. Thus, if the tool is applied to obtain the aimed at result X, it is probable that this result will be obtained. 2) depends on case = the accuracy will depend on the

particular case or scenario in which the tool is applied. Precaution and care are recommended to assure that the results are accurate. For example, the tool can be based on a certain hypothesis that is not true for every scenario. When this tool is applied, precaution and care must be taken in order to assure that the hypothesis is true, or as close to true as possible. For example, Taguchi uses additivity to perform the experimental design. The additivity of the model will depend on the particular scenario of its application and on the parameters chosen by the experimenter. Thus, whether or not the aimed at results are obtained depends on the particular case of application and on the carefulness of the experimenter in correctly choosing the parameters in order to obtain the additivity of the model. 3) poor = the results need careful analysis, given that the tool uses hypotheses that are valid only in certain conditions.

**Training** indicates how intensive the training must be. Three levels were considered: 1) high = the training involves great effort by the trainee to understand the tool. For example, the trainee must study subjects difficult for him (i.e. in Taguchi Methods, the trainee must study statistics and experimental design). 2) medium = training is not very hard. The tool can be understood without any difficulty, thus the training is very easy-going for the trainee. 3) none = no or almost no training is required. In this case, the trainee possesses all

or almost all of the knowledge required for the tool's application.

**Software** indicates whether software is necessary for the tool's application. Three levels were considered: yes, no but it will help, and no. No but it will help means that the software carries certain benefits, i.e. quick interaction, easy control, quick data analysis, etc.

**Quality improvement** indicates whether the simple application of the tool will improve the quality of the product. Three levels were selected: yes, not really, and no. Not really means that it can improve quality in the broadest sense of the word.

**Cost reduction** indicates whether the application of the tool will reduce cost. Three levels were selected: yes, probably, and no.

**Implementation time** indicates how long it takes for the full implementation of the tool. Three levels were selected: long = generally more than two years; medium = generally less than two year; immediately = generally less than six months.

**Knowledge** indicates whether more knowledge than the average manager or engineer possesses is required for the application of the tool. Two levels were selected: yes or no.

**Creativity** indicates if creativity is needed for a better application of the tool. Two levels were selected: yes or no.

**Team** indicates if a team is needed for the tool's

application. Two levels were selected: yes or no.

**How long to see results** indicates how much time, after starting the application of the tool, must elapse in order to see the results. Two levels were selected: 1) after some time = the results are not shown as the tool is being applied. Some time must elapse in order to see results. 2) immediately = the results or future benefits can be seen or perceived as the tool is being applied.

**Enhances reliability** indicates if the application of the tool enhances reliability. Three levels were selected: yes, possibly, and no.

### **3.2 EXPLANATION OF TABLE III**

#### **3.21 General Quality Function Deployment Characteristics**

**Accuracy** QFD is a structural methodology for planning which helps prevent errors in design and production activities. The outcomes obtained by this methodology are considered to be accurate with respect to the proclaimed results since QFD does not use any particular hypothesis.

**Training** The training needed is considered to be medium since the application of the tool does not usually require any special knowledge not commonly used in industry. Additionally the tool can be understood very easy.

**Software need** There is no need for any special software for

a successfully application of QFD, but it will help.

**Quality improvement** As Eureka & Ryan<sup>4</sup> (1988) state, "Taken literally, the term Quality Function Deployment may seem a bit misleading. QFD isn't a quality tool, although it can certainly improve quality in the broadest sense of the word. Rather, it's a visually powerful planning tool".

**Cost reduction** QFD will achieve reductions in: redesign, rework, inspection errors, unnecessary activities, etc. with a consequent cost reduction. For example, Toyota Auto Body Co., Ltd Kariya Japan reported a cumulative cost reduction of 61% after using QFD. (Hauser & Clausing 1988)

**Implementation time** In general, the implementation time of QFD is long, usually more than two years. As King<sup>5</sup> (1989) mentions, "Introducing QFD will mean a fundamental change for many organizations...Most companies go through two phases. The first phase is individual projects using one or more charts. The second phase, which usually starts after three years, is changing the design system... all U.S. companies are still in phase one...."

**Knowledge** QFD's application usually does not require more knowledge than that possessed by the average U.S. manager.

**Creativity** Creativity is not a requirement for a successful application of QFD, given that all necessary QFD steps can be derived in a systematic way without any need of creativity from part of the manager.

**Team** Given the different disciplines involved in the application of QFD, a team approach is needed for its successful application (Akao 1990, King 1989, Eureka & Ryan 1988).

**How long to see results** Commonly, QFD requires a long time for full implementation, thus the benefits or results derived are not perceived immediately. The time will vary depending on each particular case.

**Enhances reliability** QFD enhances reliability, since, it is considered during its application (Akao 1990, King 1989).

### **3.22 General Design For Assembly Characteristics**

**Accuracy** No special construction hypotheses are used in the application of DFA. DFA is the systematic application of a method, using mainly creativity, by which parts are discarded from the product. Thus, the outcome is considered to be accurate with respect to the one proclaimed by the tool.

**Training** The DFA method is very easy to understand, and to apply. No special knowledge is needed for its application.

**Software need** Software is not needed for a successful application of DFA, but it will help.

**Quality improvement** DFA improves quality. For example, by the reduction of parts, less causes of possible breakdown or malfunctions exist (Lewis & Connelly 1990).

**Cost reduction** DFA will reduce part count, labor content,

design time, inventory, etc., thus reducing costs.

**Implementation time** The time needed for team forming and training is usually not long. The greatest time is spent in designing or redesigning the assembly system. The implementation time will depend greatly on the particular case; for example, it can take years as in the construction of the IBM ProPrinter Charlotte factory, or as Lewis<sup>6</sup> (1990 I) states, "... The second project that adhered to the new methodology was finished in 18 weeks, including the hard-tooling cycle".

**Knowledge** Generally, there is no need of special knowledge for a successful application of DFA.

**Creativity** Creativity plays a big role in the successful application of DFA; thus, generally, creativity tools are taught during training (Lewis & Connelly 1990).

**Team** A team approach is needed for the successful application of DFA, given the different disciplines involved in the design or redesign of a product.

**How long to see results** DFA shows results immediately. As the tool is being applied, the design team can perceive the achievements obtained (Stoll 1988). For example, a team can perceived the benefits that are going to be achieved when they have reduced by five parts the product.

**Enhances reliability** It is possible that with the application of DFA, reliability is enhanced since the reduction of parts

can result in fewer breakdown (Lewis & Connelly 1990).

### **3.23 General Taguchi Methods Characteristics**

**Accuracy** In his study Taguchi uses the hypothesis of additivity. It will not always be possible to satisfy this requirement; thus, the results obtained are going to be biased with respect to the optimum result. To obtain accurate results, certain precautions must be taken to achieve additivity. Additionally, Taguchi uses a signal-to-noise ratio (S/N) to estimate the effects of the causes of variability in the quality characteristic. This S/N must be carefully selected in order to assure a successful application of the Taguchi Methods.

**Training** Knowledge of statistics and design of experiments is needed in order to perform Taguchi Methods, but usually this knowledge is not well established among engineers in manufacturing industry, thus a high level of training is needed. (Input obtained from "Product Design for Assembly" workshop, SME Feb. 1991)

**Software needed** There is no need for software for a successfully application of Taguchi Methods, but it will help.

**Quality improvement** Given the reduction of the variability of the product's function/functions, the quality of the product is improved.

**Cost reduction** Cost reduction is obtained by the reduction of

defects, the increase in customer satisfaction, the decrease in service, etc..

**Implementation time** The implementation time will depend on the particular case and the existent knowledge of the particular industry. The implementation time chosen is medium, given that, generally, statistical knowledge can be acquired and the necessary experiments run in less than two years.

**Knowledge** Additional knowledge is needed than that possessed by the average engineer. This knowledge is needed mainly in the area of experimental design.

**Creativity** Creativity is not necessary for the successful application of Taguchi Methods, given that the application of the design of experiments is methodical.

**Team** A team approach is recommended for the successful application of the Taguchi Methods due to the different disciplines involved in the product's design.

**How long to see results** Since the experiments can take several weeks or months, a lag time exists between the beginning of the tool application and the final analysis of results.

**Enhances reliability** Even though reliability is not explicitly introduced in the design of experiments, reliability is possible enhance by the application of Taguchi Methods. As Phadke<sup>7</sup> (1989) states, "Finding an appropriate continuous quality characteristic and reducing its

sensitivity to noise factors is the best way of improving reliability."

### **3.24 General Activity Based Costing Characteristics**

**Accuracy** Aggregation of activities is needed for the calculation of the product's cost. Of course, not all activities vary in direct proportion with the cost driver used to allocate the cost of these activities to the products. Thus, the accuracy of the product's cost will depend in each particular case on how well the cost driver reflects the consumption of resources by the different activities.

**Training** ABC is easy to understand and does not necessitate any special knowledge in its application.

**Software need** ABC does need a software package for its successful application in industry.

**Quality improvement** ABC is mainly an accounting procedure. It does not enhance quality improvement in its application.

**Cost reduction** With the application of ABC, cost reduction can be obtained by the elimination of unnecessary activities, the achievement of good product sourcing, and adequate operational control.

**Implementation time** The implementation is the time needed to design a cost system, which depends on the availability of the information needed for an ABC and on the existent interdepartmental communications, management involvement, etc.

The implementation time is greatly related to the complexity of the system in which ABC is going to be applied. A medium time of less than two years is selected. For example, Bailey (1991) studied 10 companies in the UK where the total implementation time varied between 20 weeks and 52 weeks.

**Knowledge** There is no need of any special knowledge for the successful application of ABC.

**Creativity** ABC can be approached in a methodical way; thus, there is no need for creativity for its successful application.

**Team** ABC will involve different departments; consequently, a team approach is needed for its successful application.

**How long to see results** ABC has a long-term resource consumption orientation. There is some lag time between the start of ABC's application and the perception of its results. For example, Cooper<sup>8</sup> (1990) says, "a resource-consumption orientation captures the drop in demand for fixed overhead when a single product is dropped, even though this drop might not result in an immediate reduction in spending."

**Enhances reliability** Given the nature of ABC, it does not enhance reliability.

TABLE IV

INTERACTION TABLE BETWEEN THE FOUR TOOLS

B \ A	QFD	DFA	TM	ABC
QFD		O	O	X
DFA	X		X	X
TM	X	O		X
ABC	O	O	O	

X = DIRECT INFLUENCE

Meaning that if design tool A is applied after design tool B, the results obtained from the application of design tool A would directly influence on the results obtained by the application of design tool B.

O = INDIRECT INFLUENCE

Meaning that if design tool A is applied after design tool B, the results obtained from the application of design tool A would not directly influence on the results obtained by the application of design tool B.

\* See explanation of TABLE IV in next page.

### 3.3 EXPLANATION OF TABLE IV

Direct influence means that, by the application of a tool, the principal results (which are given by the basic aims of the tool) obtained by the previous tool are affected. For example, in DFA the basic aim is to reduce part count. Another tool will directly affect the results of DFA if, by its application, the reduced parts are modified (i.e. an extra part is discarded or a part is introduced).

Indirect influence means that, by the application of a tool, the secondary results obtained by the previously applied tool are affected. For example, in the application of DFA, the secondary results include a reduction in inventory cost, an elimination of suppliers, and an increase in product reliability. The application of another tool will indirectly affect DFA if it does not affect the number of parts obtained by DFA, but does affect, for example, the inventory cost introduced by DFA.

The explanations are given for each  $B_i$   $i=1..4$  for all  $A_j$   $j=1..4$  .

.  $B_1A_2$  (QFD - DFA) direct influence

QFD is a planning tool which takes into account the parts/components of the product and all related activities. If DFA is applied, parts are usually going to be discarded thus affecting the different matrices where these parts, or related

activities, are considered. Consequently, the planning results obtained by the application of QFD are affected.

.  $B_1A_3$  (QFD - TM) direct influence

During the application of Taguchi Methods, generally, parts are discarded, materials changed, or processes modified in order to decrease the causes of variation affecting the product. Any of these changes will generally affect the matrix in which the part/material/process is considered. Consequently, the planning results obtained by the application of QFD are affected.

.  $B_1A_4$  (QFD - ABC) indirect influence

By the application of ABC, product cost can change or products can be eliminated from production. If a product is eliminated from production, the QFD of that product is also eliminated. Now, if the product cost is changed, then some costs have to be changed in the different matrices of QFD. But the planning results are not affected in the sense that the matrices and tables previously obtained are still valid.

.  $B_2A_1$  (DFA - QFD) indirect influence

By the application of QFD, a better plan of how to produce the product is obtained, but this will not directly affect the minimization of parts introduced by DFA.

.  $B_2A_3$  (DFA - TM) indirect influence

Taguchi Methods can affect the composition of the materials, the number of parts, the process characteristics, etc. Generally, it will not further minimize the number of parts

taken by DFA, since DFA is a technique used for the minimization of parts and the Taguchi Methods is not. The indirect influence is due to the fact that, for example, Taguchi Methods can influence the composition of a certain material, thus changing the previous assembly cost introduced by DFA.

.  $B_2A_4$  (DFA - ABC) indirect influence

ABC will not influence the parts count, but it can influence, for example, an inventory cost introduced by a change in product cost.

.  $B_3A_1$  (TM - QFD) indirect influence

QFD will not introduce variability in the product, so it will not affect the minimization of variability obtained by Taguchi Methods. However it can affect, for example the production control points, because of more accurate planning.

.  $B_3A_2$  (TM - DFA) direct influence

The simplification of a part affects the product for which the experimental design was designed thus directly affecting the results obtained.

.  $B_3A_4$  (TM - ABC) indirect influence

ABC has no influence on the variability of the product, but it will influence TM's secondary results, such as product cost.

.  $B_4A_i$   $i=1..3$  (ABC - QFD, DFA, TM) direct influence

The application of QFD, DFA, or TM will usually, change the product or activities performed on the manufacturing floor, thus changing product cost.

TABLE V

TABLE SHOWING WHICH TOOL IS MOST APPLICABLE IN  
WHICH INDUSTRY

	QFD	DFA	TM	ABC
PROCESS	X		X	O
MANUFACTURING	X	X	X	X
SERVICE	X		O	X
SOFTWARE	X	Y	O	X
CONSTRUCTION	X	Y	O	X

X = TOOL CAN BE APPLIED IN INDUSTRY

Y = TOOL CAN BE APPLIED WITH CERTAIN MODIFICATIONS WHICH  
DEPEND ON THE PARTICULAR INDUSTRY

O = TOOL CAN BE APPLIED BUT CARE MUST BE TAKEN SINCE THE  
BENEFITS MAY NOT BE WORTH THE IMPLEMENTATION COST

\* See the explanation of TABLE V on the next page.

### 3.4 EXPLANATION OF TABLE V

. QFD is a planning tool by which customer requirements, product's functions, and engineering characteristics are deployed by means of matrices from the design table to the shop floor. It does not require any particular industrial environment for its successful application; therefore, it can be applied in any industry.

. DFA was developed for the manufacturing industry, where assembly operations are possible. In the case of the process industry, assembly operations generally are not carried out; therefore, DFA cannot be applied. However, in particular process industries, such as certain food industries (i.e. beverage), the DFA principles are applicable. With respect to the software and construction industries, DFA principles can be applied with the necessary modifications for each case. In a software industry, the actions taken to put together different subroutines, commands, files, etc. can be thought of as assembly operations. In the construction industry, the actions taken to build a house can be thought of as assembly operations.

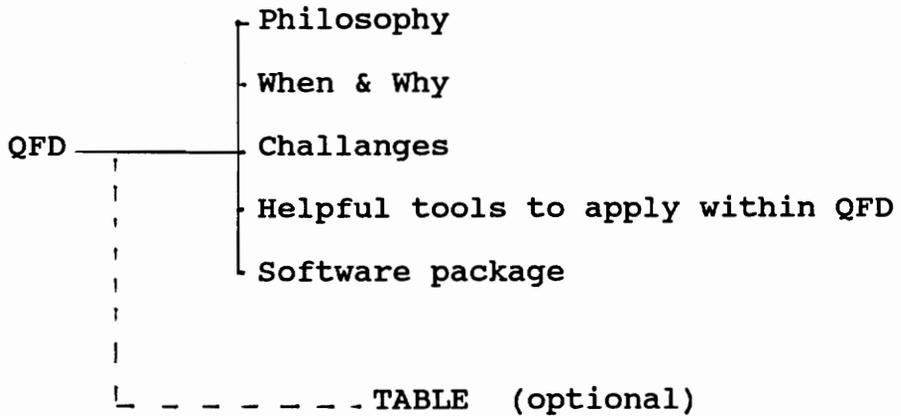
. The process and manufacturing industries are appropriate for TM application, because all the necessary conditions to run Taguchi Methods are relatively easy to meet. In the case of service, software, and construction industries, care must be taken since, the run of the experiment is usually not as easy

as in the manufacturing and process industries, and it can also be too expensive. For example, in an airport, TM can be applied to reduce the variability in departure time affected by the traffic jams in the runway. In this case, a simulation program must be created, and the cost of creating it may surpass the possible benefits.

. ABC can be applied in any type of industry. Its application is generally recommended in industries where the direct labor is low, where there is great product diversity, or where competition is fierce. But these are not rules, since some companies apply ABC just for its behavioral effect, for example. In the case of process industries, care must be taken since the cost of designing an ABC can be much more than the possible attainable benefits. For example, some process industries have homogenous outputs, and can rely on cost per ton or per gallon.

**TABLE VI**

The majority of the points included in this table were obtained from the specialized bibliography. However, some points were obtained from questionnaires sent to the following people: Dr. G. Boothroyd, Professor. & Chairman, Industrial & Manufacturing Eng. Dept., University of Rhode Island; J. McHugh, Manager of Quality Function Deployment, American Supplier Institute; A. Wu, Manager of Taguchi Methods, American Supplier Institute. The following picture shows a schematic view of Table VI.



DFA — . . .

TM — . . .

ABC — . . .

TABLE VI \_ QUALITY FUNCTION DEPLOYMENT

P H I L O S O P H Y	<ul style="list-style-type: none"> <li>. translates customer requirements into appropriate technical requirements</li> <li>. identify the key systems, sub-systems, parts and manufacturing controls that will lead to significant improvements in market share</li> <li>. structural method for planning (product or organizational)</li> </ul>
	<ul style="list-style-type: none"> <li>. increase productivity</li> <li>. increase quality (in broadest sense of the word)</li> <li>. decrease lead time</li> <li>. reduce number of engineering changes during production development</li> </ul>
	<ul style="list-style-type: none"> <li>. reduce total development cost</li> <li>. reduce quality defects attributed to product design</li> </ul>
Q F D	
W H E N	<ul style="list-style-type: none"> <li>. increase supplier involvement</li> </ul>
&	
W H Y	<ul style="list-style-type: none"> <li>. reduce development time</li> <li>. enhance design reliability</li> <li>. increase customer satisfaction</li> <li>. provides a basis for improvement planning</li> <li>. allows clear targets to be define early based on market/business demands</li> <li>. allows simultaneous focus in product and process technologies</li> <li>. communication and team work are enhanced</li> <li>. increase the possibility of product to provide a competitive edge</li> <li>. increase the product fitness to customer needs</li> </ul>

CONT. TABLE VI \_ QUALITY FUNCTION DEPLOYMENT

FIG  
D

C  
H  
A  
L  
L  
A  
N  
G  
E  
S

- . good system for collecting and disseminating information/data
- . decrease warranty costs
- . increase market share
  
- . needs time to implement and see results
- . needs patience and discipline
- . no noticeable immediate savings
- . requires a multi-functional team
- . team building skills must be acquire
- . information overload
- . initial effort results in higher product development costs
- . quality chart can become to big
- . demanded quality is hard to understand
- . user information is hard to collect
- . full implementation can take a good number of years
- . implementation will generally imply organizational changes
- . needs complete management involvement
- . it is a difficult process which requires greater efforts at the earlier stages of production development
- . inconsistencies in quantifying expert judgement
- . training must be available
- . management needs to provide adequate time for project efforts

CONT. TABLE VI \_ QUALITY FUNCTION DEPLOYMENT

Q F D	<p>. an effective QFD project will require an average of one third of an individual time</p>	
	<p>TOOLS HELPFUL TO APPLY WITHIN QFD</p>	<ul style="list-style-type: none"> <li>. Value Analysis</li> <li>. Design For Assembly</li> <li>. quality tools (e.g. affinity diagram)</li>   <li>. Taguchi Methods</li>   <li>. Activity-Based Costing</li>   <li>. Software Packages (e.g. CAD)</li> </ul>
	<p>SOFTWARE PACKAGE</p>	<ul style="list-style-type: none"> <li>. QFD Designer (Version 1.02)            U\$ 975</li> <li>. QFD Designer (Version 2.0)            U\$ 975</li> </ul> <p style="text-align: center;">by American Supplier Institute Dearborn, MI 48120</p>

Reference: Akao 1990, King 1989, Eureka & Ryan 1988, Aswad 1988  
Sullivan 1986.

TABLE VI \_ TAGUCHI METHODS

P H I L O S O P H Y		. improve the quality of a product by minimizing the effect of the causes of variation without eliminating the causes	
		. an engineering methodology for improving productivity during research and development so that high-quality products can be produced quickly and at low cost	
		. the quality of product is measured in terms of the total loss to society due to functional variation and harmful side effects	
T A G U C H I M E T H O S		. increase quality	
		. increase supplier involvement	
		. increase customer satisfaction	
		. increase quality without increasing manufacturing cost	
		W H E N & W H Y	. increase product reliability
		. improves interdepartmental communication	
		. reduction of quality defects	
		. reduction of operating cost	
		. reduction of labor and material cost for rework and scrap	
		. allowance of product to provide a competitive edge	
. allowance of low grade material and components usage			
. allowance of economical product and process design from both manufacturing and customer's viewpoints			
. enhance employee involvement in activities to improve quality and productivity			
. information overload			

CONT. TABLE VI \_ TAGUCHI METHODS

T  
A  
G  
U  
C  
H  
I  
  
M  
E  
T  
H  
O  
D  
S

C  
H  
A  
L  
L  
A  
N  
G  
E  
S

- . technical experience together with experiments through prototype hardware models or computer simulation are needed
- . good system for collecting and disseminating information/data
- . adequate communication between departments
- . be aware that TM are not going to work every time
- . training must be available
- . must not be used in isolation (it is an integral part of the whole quality control program)
- . a change in thinking by the engineers related to the idea that staying in-spec implies product quality must be implemented
- . product design, manufacturing, field-support, and marketing should be pursued concurrently by an interfunctional team
- . complete management involvement
- . change idea that quality is responsibility of only few quality control people
- . requires the appropriate use of statistical design and analysis methods

HELPFUL  
TOOLS TO  
APPLY WITHIN  
TM

- . Quality Function Deployment
- . Software Packages (e.g. CAD)

S  
O P  
F A  
T C  
W K  
A A  
R G  
E E

- . ANOVA-TM 2.2 Software U\$ 795
- . STN PLUS Software U\$ 795
- . CAPD-TM U\$ 795
- . Taguchi Consultant U\$ 495  
by American Supplier Institute  
Dearborn, MI 48120
- . Qualitek-3, Version 3.1 by Nutek, Inc.  
(313) 643-5460
- . Taguchi Consultant and Taguchi Analyst by  
Texas Instruments (615) 461-2000

Reference: Phadke 1989, Kackar 1986, King 1989, Pignatiello1988, Gunter 1987, Taguchi & Clausing 1990.

TABLE VI \_ DESIGN FOR ASSEMBLY

P  
H  
I  
L  
O  
S  
O  
P  
H  
Y

- . technique which minimize the total product cost by targeting assembly time, part cost, and the assembly process at the design stage of the product development stage
- . involves reducing the number of separate parts to a minimum and making the remaining parts easy as possible to assemble
- . improve time to market
- . improve product quality
- . improve material and production flow
- . increase standardization
- . simplifies manual assembly
- . reduce manufacturing overhead
- . reduce total material cost
- . reduce assembly time

D  
F  
A

W  
H  
E  
N

CONT. TABLE VI \_ DESIGN FOR ASSEMBLY

&  
W  
H  
Y

- . reduce recording keeping
- . reduce production-control costs
- . reduce total design time
- . reduce inventory
- . achieve a good work environment
- . desire to automate production
- . desire to increase productivity
- . desire fewer tools, devices, etc.
- . simplify material handling
- . be able to understand and tackle the problems early
- . most successful when implemented by a multi-functional team
- . will increase preliminary design time
- . better if there is early supplier involvement
- . management involvement and commitment are essential
- . needs adequate training
- . complete system design changes needs time to be implemented
- . needs training in creative procedures
- . needs commitment and understanding by all members of the product development team
- . be aware of the cost of making the cost and time to be spent in the effort
- . needs a freely manufacturing cost information

C  
H  
A  
L  
L  
E  
N  
G  
E  
S

D  
F  
A

CONT. TABLE VI \_ DESIGN FOR ASSEMBLY

- . must be supported by techniques that will allow the design team to make early estimates of material, processing and tool costing
- . be aware of possible changes that will require retraining for other jobs, grow market share, and increase communication
- . be aware that possible changes will require the commitment of expending resources (e.g. better handling systems)
- . needs an information system
- . be aware that initial assembly projects can be unprofitable
- . requires expert knowledge (e.g. in joining methods)

HELPFUL TOOLS  
TO APPLY WITHIN  
DFA

- . Value Analysis
- . Creativity Procedures
- . Software Packages (e.g. CAD)

SOFTWARE  
PACKAGE

- . Complete DFA Toolkit (Version 4.1)  
U\$ 12500
- by Boothroyd Dewhurst, INC.  
Wakefield, RI 02879

Reference of DFA Table: Lewis & Connelly 1990, Boothroyd & Dewhurst 1989, Boothroyd 1988, Andreasen 1988 II, Boothroyd & Dewhurst 1988, Daetz 1987.

TABLE VI \_ ACTIVITY-BASED COSTING

P H I L O S O P H Y		.	identify the activities performed by each support and operating department and then compute the unit cost of performing these activities
			assume that activities consume resources and products consume activities
			resource-consuming activities cause costs; products incur costs by the activities that require for design, engineering, sale, delivery, and service
			report more accurate product cost
			make more accurate product-related decisions
			make better capital investment decisions
			make more accurate budgeting decisions
			when new products are introduced
			when adopting new marketing process
			when improving production process
A C T I V I T Y - B A S E D  C O S T I N G		.	if measurement costs are low
			if competition is fierce
			if product diversity is high
			if more accurate knowledge on what design parameters create demands on the organization's indirect and support resources is needed
			to improve the information useful for manager's planning and control decisions
			if the company is striving to achieve world-class standards
			when
			when
			when
			&
W H E N  W H Y		.	if measurement costs are low
if competition is fierce			
if product diversity is high			
if more accurate knowledge on what design parameters create demands on the organization's indirect and support resources is needed			
to improve the information useful for manager's planning and control decisions			
if the company is striving to achieve world-class standards			
when			
when			
when			
&			

CONT. TABLE VI \_ ACTIVITY-BASED COSTING

W N E N & W H Y	<ul style="list-style-type: none"> <li>. more accurate cost information for strategic and design purpose</li> <li>. achieve manufacturing excellence</li> <li>. elimination of waste activities</li> <li>. more accurate information for continuous improvement in manufacturing</li> <li>. better understanding the impact of sourcing decisions</li> <li>. better understanding the impact of new process technologies</li> <li>. better understanding the impact of different designs on product cost and flexibility</li> <li>. reduction of activity times (e.g. order lead time)</li> <li>. better understanding and elimination of complexity</li> <li>. prevention of product design and marketing from placing unreasonable demands on productions</li> <li>. more accurate product life-cycle cost estimations</li> <li>. improvement in investment management</li> <li>. improvement in profitability</li> <li>. elimination of cross-subsidization of products</li> </ul>
	C H A L L E N G E S

A  
C  
T  
I  
V  
I  
T  
Y  
-  
B  
A  
S  
E  
D  
  
C  
O  
S  
T  
I  
N  
G

CONT. TABLE VI \_ ACTIVITY-BASED COSTING

C  
H  
A  
L  
L  
E  
N  
G  
E  
S  
  
A  
C  
T  
I  
V  
I  
T  
Y  
  
B  
A  
S  
E  
D  
  
C  
O  
S  
T  
I  
N  
G

- . attention must be paid to data entry to avoid poor data quality
- . employee involvement
- . requires design training and maintenance resources
- . a complex manufacturing organization will require a system that is sufficient detailed to capture the patterns of activity performed and consumption
- . carefulness in not motivating the wrong behavior must exist
- . top management must understand the value and effort of implementing the ABCS
- . top management must prepare for how changes must affect them and their employees
- . awareness must exist in the fact that an ABC system differs-form an operational control system

HELPFUL TOOLS TO APPLY WITHIN ABC

- . computer software
- . quality tools

SOFTWARE PACKAGE

- . each company can develop a software package for its particular environment

Reference: Cooper 1988 a & b, 1989 c & d, Kaplan 1988, 1990, Turney 1989, Johnson 1988, Cooper & Kaplan 1988, Berliner & Brimson 1988, Ostrenga 1990, Koons 1990.

CONT. TABLE VI \_ ACTIVITY-BASED COSTING

ABC	
PROCESS	<p>. Companies with continuous-flow production that yield homogeneous outputs can rely on measurement of product costs in units, like cost per ton or cost per gallon. Thus, the implementation of an ABCS must be study carefully since the cost of implementation may be higher than the obtainable benefits.</p>
CONSTRUCTION & MANUFACTURING	<p>. Product costing for large projects like major constructions, ship buildings or design and manufacture of large machine is rather simple; thus ABCS may not be necessary.</p> <p>. When product diversity is high, though, especially in production of unique items or with multiperiod production process (e.g. major constructions) operational control systems will be difficult to develop.</p>
SOFTWARE	<p>. Useful to determine more accurate life-cycle cost.</p>
SERVICE	<p>. Helps understand impact of sourcing decisions.</p> <p>. Increase the awareness in management into eliminating activities or improving the efficiency of activity performance.</p> <p>. The complexity of products in the manufacturing industry is analogous to the complexity of services offer by the service company.</p>

### **3.5 EXPLANATION OF TABLE VI**

The table is based on information obtained from the references cited on pg. 43 and at the end of each section of TABLE VI. Some of TABLE VI points are analyzed as follows:

#### **. with respect to QFD**

\_ An increment in productivity and reductions in lead time, development time, and development cost are all obtained because unnecessary parts, processes, inspection, etc. are discarded during the planning. Additionally, the production process is planned in an orderly way; consequently, a reduction in the time spent in determining what to do, or how and who must do it, is achieved.

\_ An increase in customer satisfaction since their requirements of the product are fulfilled.

\_ There is an increase in supplier involvement, given that for an adequate consideration of technology, material availability, and future supply, early supplier involvement is required.

\_ QFD has certain drawbacks or challenges, such as the large amount of time needed for complete implementation. Also user information is hard to collect or correctly interpret, because of the general ambiguity of the customers' requirements.

#### **. with respect to Taguchi Methods**

\_ There is an increase in the product's quality and reliability, since the methods reduce the product's variability introduced by environmental factors, such as

temperature, working load, etc.

\_ There is an increase in interdepartmental communications, since an interfunctional team is needed for a successful tool application.

\_ A good system for collecting and disseminating information/data is needed for an accurate analysis of the experimental results.

\_ Information overload can occur if the experiments are not accurately designed and monitored.

**. with respect to DFA**

\_ By the reduction of part count, there are improvements in product quality, and material and production flow as well as reductions in assembly time, inventory, and recording keeping, among others.

\_ There is increased standardization since it is recommended by DFA.

\_ There will be an increase in the preliminary design time, since more time will be spent at this stage in order to design a product which is easy to assemble.

\_ Needs easily available manufacturing cost information to make possible the evaluation of alternatives.

**. with respect to ABC**

\_ There is an elimination of the cross-subsidization of products due to the accurate allocation of resource consumption by each product.

\_ There is an ability to make better capital investment

decisions, budgeting decisions, and product-related decisions, since ABC provides an accurate knowledge of the location of the resource consumption.

\_ There is an elimination of wasteful activities. During the accounting procedure, activities are analyzed to determine if they are value-added or non-value added.

\_ An optimal cost system is not the most accurate, since an optimal cost system is one in which the cost of measurement equals the cost of error.

\_ Requires design training and maintenance resources. Every cost system must be maintained and modified as time goes by.

#### **4.0 SUMMARY**

This project discusses and provides alternative approaches used in concurrent engineering, these include: Quality Function Deployment, Taguchi Methods, Design For Assembly, and Activity-Based Costing.

Objectives of this report were to identify when and why the tools are needed, to make these techniques easily understandable, and to create a mind-set for applying proven design rules. Quality Function Deployment, Taguchi Methods, Design for Assembly were analyzed and compared as to their characteristics, interactions, and benefits/challenges.

Detailed description and examples for each product design tool were also discussed.

This report provides fundamental knowledge of each of the above methodologies in order to understand how they can be used independently or in conjunction with each other. Specifically, we attempted to understand how Quality Function Deployment (QFD) can be used for translation of customer and engineering requirements for product design. How Taguchi Methods (TM) improves the quality of the product by minimizing the effect of the causes of variation without eliminating the causes. How, Design for Assembly (DFA) minimizes the total product cost by targeting assembly time, part cost, and the assembly process at the design stage, and how Activity-Based Costing (ABC) is used to identify the activities performed by each support and operating departments and to compute the unit cost of performing these activities.

With information developed in this report, it can be understood how these tools can work concurrently. QFD is used as a unifying tool for the other approaches. Within application of QFD, DFA can be used to decrease part count. Afterwards Taguchi Methods can be used to minimize the performance variation of these parts with respect to noise factors and finally Activity-Based Costing is ideal for calculating all the necessary cost involved in QFD. In

addition, the interaction between any two particular design tools: e.g., after the application of DFA, Taguchi's Methods can be applied in order to make the product robust. The application of the two techniques will optimize the product's design since the application of DFA achieves a simplified product with respect to parts and materials, giving rise to a higher product reliability and maintainability. Additionally, applying Taguchi's Methods results of a reduction in the variability of the product's principal functions. Hence, results show that the two techniques are compatible and their simultaneous application brings large savings, among others benefits, to the overall life-cycle cost.

The different tools were compared as to accuracy, cost reduction, implementation time, and time duration until final results are achieved in addition to several other parameters (Table III). Additionally, interactions among the different four tools were provided in Table IV. With this information, the manager/designer is able form an impression of the usability of each tool.

Even though there are many different design tools or methodologies, the four tools covered in this project have great potential. Additionally, research is needed in order to determine the true potentials of each tool. However, even in their few years of industrial application, they have exhibited

great power in designing a good product, creating good product performance, and expecting a low product life-cycle cost.

The contribution of the project is that it addressed one of the most important aspects of the manufacturing process: "the product design." Given the competitiveness of today marketplace, a company must design a product or provide a service in the most effective and efficient way. This can only be achieved if the necessary tools are provided to the manager/designer in early stages of product development.

## **5.0 APPENDIXES**

The appendixes contain the Implementation Table:

Appendix A - QUALITY FUNCTION DEPLOYMENT

Appendix B - TAGUCHI METHODS

Appendix C - DESIGN FOR ASSEMBLY

Appendix D - ACTIVITY-BASED COSTING

### **5.1 APPENDIX A - QUALITY FUNCTION DEPLOYMENT**

Quality function deployment (QFD) is a planning tool which enables companies to prioritize customer demands, develop innovative responses and involve all departments for its successful implementation.

As Eureka & Ryan<sup>9</sup> (1988) state, " QFD is not a quality tool, although it can certainly improve quality in the broadest sense of the word. Rather, QFD is a structured method for planning. QFD allows product planners to begin the planning process with a structured list of customer needs and to evaluate each proposed product feature and function according to the impact it has in meeting the customer's needs."

In this chapter, two approaches of QFD will be studied: Macabe's and Akao's approach.

It has to be pointed out that QFD charts and systems should

not be copied. Once the principles are understood, the charts need to be customized to each individual operation. Here, the philosophy behind these two QFD approaches will be explained in order to learn the principles of QFD.

#### **5.1.1 MACABE'S APPROACH OF QFD**

Eureka & Ryan<sup>10</sup> (1988) explain that, "Quality function deployment translates customer requirements into appropriate design requirements, part characteristics, manufacturing operations, and production requirements." Eureka and Ryan summarization of the QFD approach is shown in Figure 6.

The deployment of customer requirements and related technical requirements is accomplished via a series of matrices and charts. The deployment is performed from product planning and product design to process planning and the shop floor.

The Macabe's QFD system concept is based on the following four key documents: Product Planning, Parts Planning, Process Planning and Production Planning.

As Eureka & Ryan<sup>11</sup> (1988) say, " for practical purpose, QFD can be thought of as a four-part process: phases one and two address product planning and product design and phases three and four address process planning and shop-floor activities ". This methodology is illustrated on Figure 7.

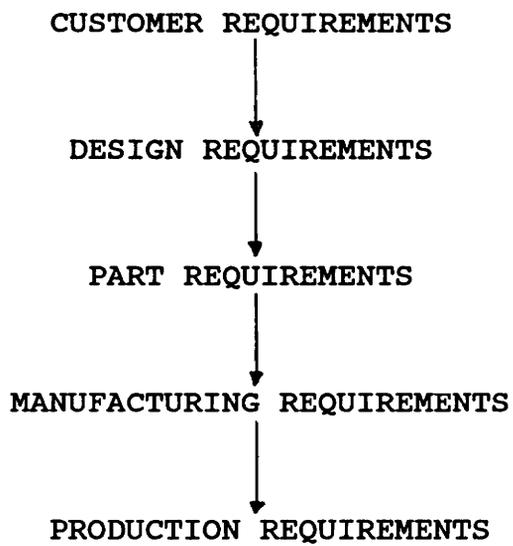
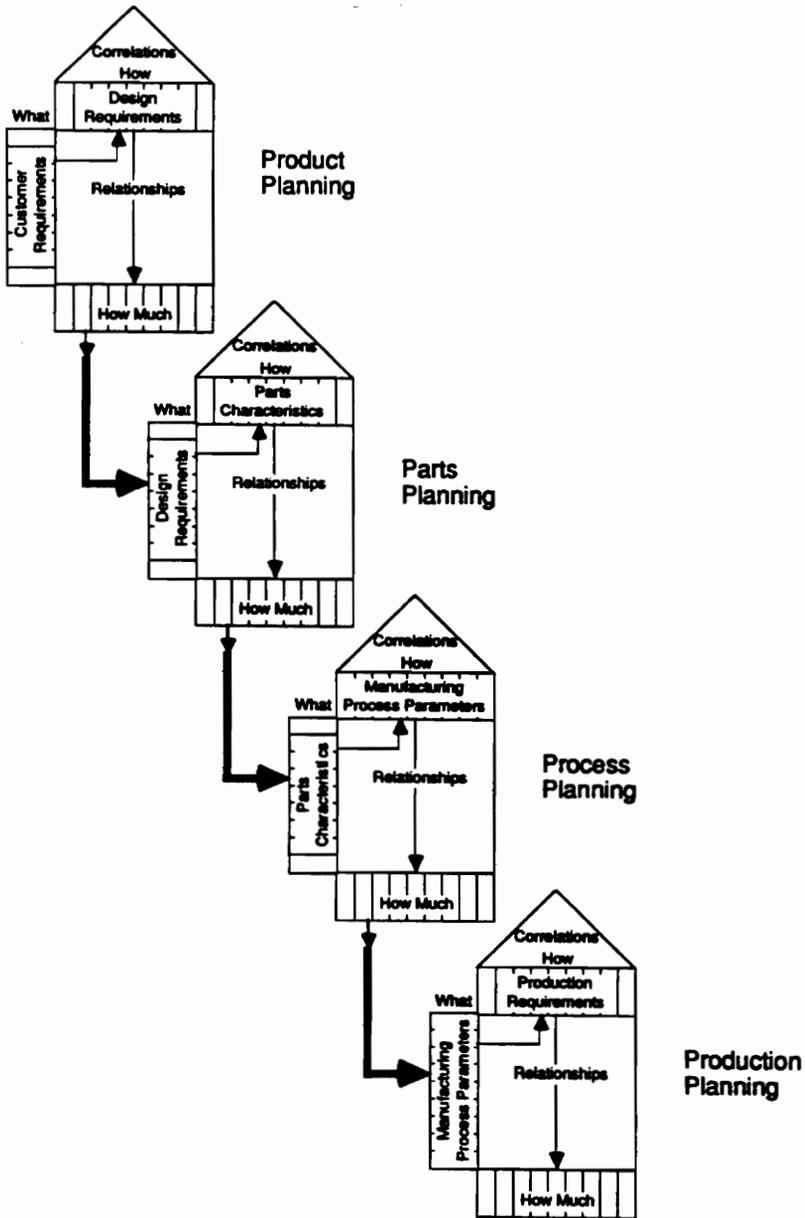


Figure 6 QFD Approach  
(Eureka & Ryan, 1988)



Figure\_7 QFD Methodology  
(Aswad, 1989)

In the following section of the chapter a detail examination of the previous matrices is given.

#### **5.1.1.1 Product Planning**

Product planning translates the voice of the customer into counterpart control characteristics. It is a kind of conceptual map that provides the means for interfunctional planning and communications and it is also known as the House of Quality. Figure 8 shows a typical house of quality.

The construction of the house of quality involves eight steps (Akao 1990, Sullivan 1986, King 1989, Aswad 1989, Eureka & Ryan 1988):

##### **Step 1**

The QFD begins with a list of the "whats", called customer attributes. The customers attributes or requirements are phrases customers use to describe products and product characteristics. The determination of customers requirements are defined by detailed consultation, survey, feedback mechanisms, and market research. Figure 9 shows the customers requirements in the House of Quality.

##### **Step 2**

The design team must specify some engineering or quality characteristics that describe the product in measurable terms. These engineering characteristics are the product control characteristics that assure the achievement of customer product requirements.

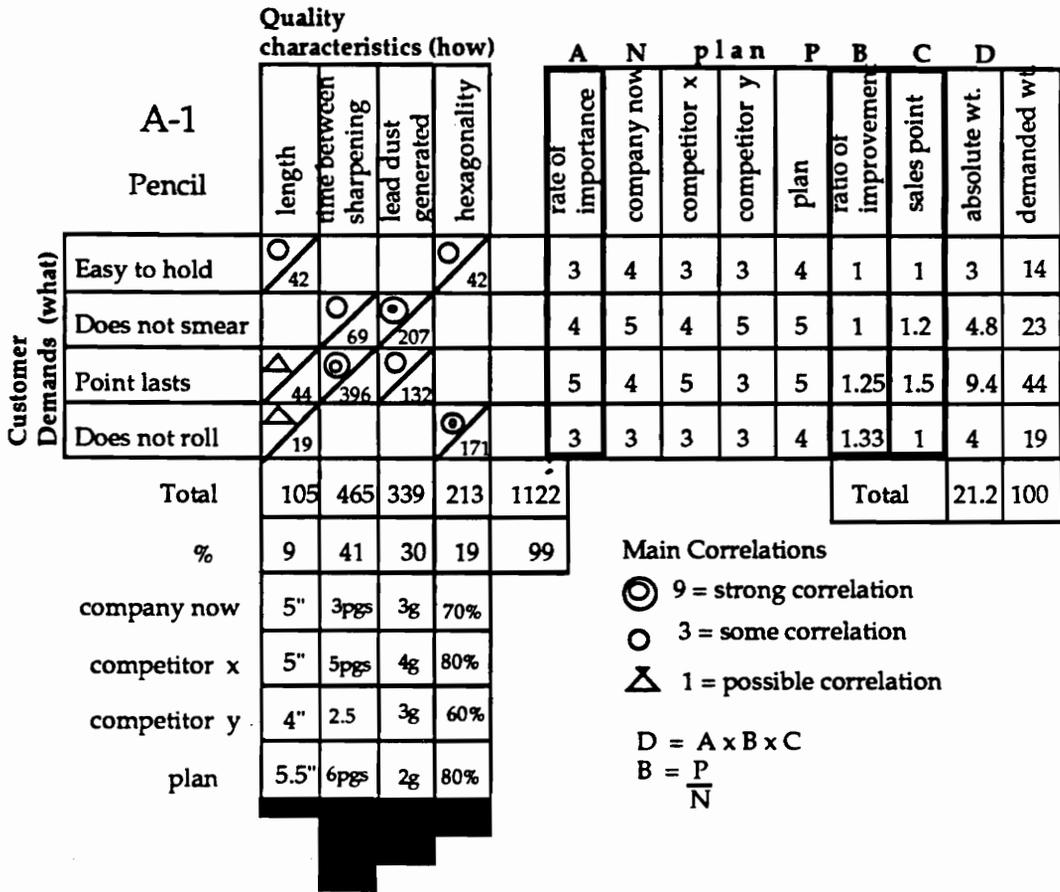


Figure 8 Typical House of Quality  
(King, 1988)

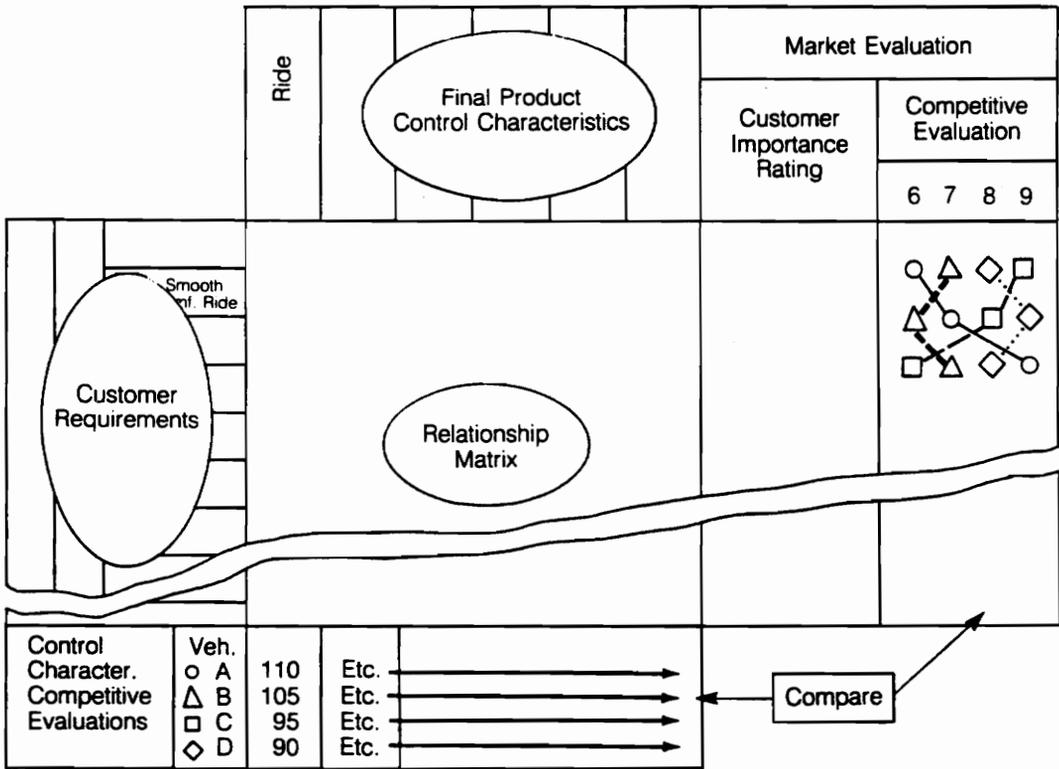


Figure 9 Customer Requirements in the House of Quality (Sullivan, 1986)

Quality elements are design elements that can be measured when the quality is evaluated. Thus, design or engineering characteristics are the measurable aspects of quality elements. For example, if a "what" of a customer is "hot" that a cup of coffee must be, an engineering characteristic can be "serving temperature". The engineering characteristics are also expanded into secondary and tertiary requirements. These characteristics are listed across the top row of the House of Quality.

### **Step 3**

Each customer requirement is related to the engineering characteristics. In this step, a relationship matrix between the customer requirements and engineering product characteristics is developed. A set of symbols is used to identify the significance of the relationships

strong relationship      medium relationship      weak relationship

Generally the values 9-3-1 are assigned to strong, medium and weak relationships, respectively. These values are used for deploying weighting of customer requirements and engineering characteristics.

The absence of symbols or a majority of weak relationships signs should be taken into account. If this happens, some engineering characteristics must be changed to address these particular customer requirements. Figure 10 shows a relationship matrix.

<div style="display: flex; justify-content: space-between;"> <div style="width: 45%; text-align: center;"> <b>quality element deployment chart</b> </div> <div style="width: 10%; text-align: center;">           quality elements            1st level            2nd level            3rd level         </div> <div style="width: 45%; text-align: center;"> <b>characteristics target values</b> </div> </div>			maneuverability			electrical function						
						portability (6)		TRS characteristics (7)			IS characteristics	
						measurement	shape	weight	electrical consumption	electric temperature characteristics	operating range voltage	frequency
			1st level	2nd level	3rd level							
1 easy to maneuver	11 easy to hold	111 easy to carry around	⊙	⊙	⊙							
		(1) 112 easy to hold because it is small	○	○								
		113 easy to hold because it is light	⊙	⊙	⊙							
		114 stable when held	⊙	⊙	⊙							
		115 stable when it is put down	○	○	○							
	12 I do not get tired while maneuvering	(2) 121 has an appropriate weight										
		122 has an appropriate size										
	13 easy to understand how to maneuver	(3) 131 easy to understand how to use								○		
		132 easy to maneuver even for beginners								○		
	14 easy to maneuver	(4) 141 easy to maneuver even if it is small		○	○	○						
		142 easy to read the indicator								○		

**Figure 10 Relationship Matrix**  
(Akao, 1990)

#### **Step 4**

In this step customers express importance ratings for their listed requirements. Usually the scale 1-5 is used to rate the importance of each demanded item, 5 being very good. If needed, the terms expressed in % can be placed near this list. Additionally, customers evaluate the customer attributes of the product with respect to the competition using the same scale. In this way, the strengths and weaknesses of the product compared to the products in the marketplace are shown.

#### **Step 5**

After the market evaluation, decisions can be made on where the company would like to be in the future, with respect to each of the customer requirements. An improvement ratio can be determined for each customer requirement.

$$\text{improvement ratio} = \frac{\text{where the company plans to be}}{\text{where the company is today}}$$

Additionally, sales points can be determined. These selling points are advertisable characteristics to be emphasized in a particular market segment and are determined according to the company's product strategy.

The qualities of the product to be developed will not only depend on the customer requirements, but also in the company's policy. To address this point, an absolute weight (AQW) is

calculated for each of the customer requirements.

$$\text{AQW} = \frac{(\text{customer rate of importance})(\text{improvement ratio})}{(\text{sales point})}$$

#### **Step 6**

The next step is to multiply each symbol in the relationship matrix by the corresponding absolute quality weight, and to place the value in the same square of the correlation symbol.

Each column of the relationship matrix corresponds to one quality characteristic. By adding the values in each column and placing the resulting sum in a bottom row, a total weight for each quality characteristic is obtained. The values can also be converted to percentage.

#### **Step 7**

A competitive assessment graph is created. In this graph the comparisons of the customer requirements, as well as the engineering characteristics between a company's product and similar competitive products, are performed. If this data is objective, it is expressed in measurable terms. If the data is subjective, it is translated to numerical performance rating.

Step 4 and 7 are beneficial when they are used to detect errors in engineering judgment. Strongly related customer requirements and engineering characteristics should exhibit a

similar competitive assessment relationship. After the quality characteristic competitive evaluation is made, the targets for each of the final product control characteristics are established.

#### **Step 8**

In this last step, a triangle matrix (called the roof of the House of Quality) is formed on top of the engineering characteristics. This matrix is used to show the relationships between the engineering characteristics. Symbols are used to show strong positive, medium positive, medium negative and strong negative relationships.

The House of Quality can be built in many phases and forms to meet almost any need. Some additional elements that can be included are level of technical difficulty, technical standards, quality standards and estimate cost percentage.

When constructing the House of Quality it should be taken into consideration that the customers do not specify in their demands the product or service functions that they assume are expected. These functions have to be addressed by the designer. Figure 11 shows a complete House of Quality.

#### **5.1.1.2 Parts Planning**

From the House of Quality, the design requirements or engineering characteristics are deployed to the parts planning

PRODUCT PLANNING MATRIX

- ⊙ STRONG RELATIONSHIP = 5
- MEDIUM RELATIONSHIP = 3
- △ SMALL RELATIONSHIP = 1

- ⊙ STRONG POSITIVE RELATIONSHIP
- POSITIVE RELATIONSHIP
- × NEGATIVE RELATIONSHIP
- \* STRONG NEGATIVE RELATIONSHIP

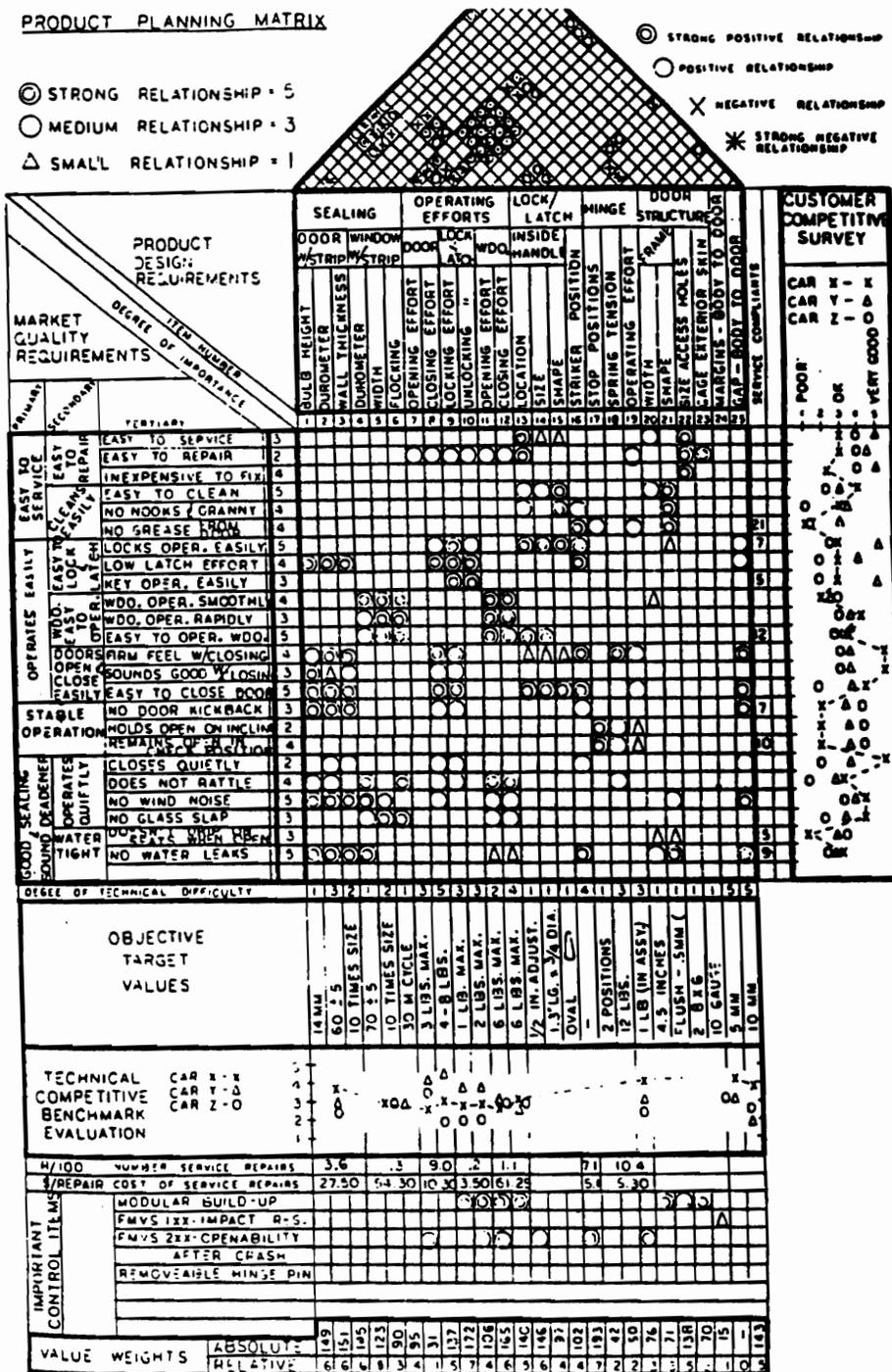


Figure 11 Complete House of Quality

(Akao, 1987)

matrix. Not all of the design requirements need to be deployed, only high-risk, new, difficult, or important. Consequently, the subsystem and components are specified and a similar matrix to the House of Quality is formed. The relationships between components and engineering characteristics are determined, and symbols as 0 or O, O, are placed to show the different types of these relationships.

Using the new relationship matrix and the quality characteristic weights deployed from the House of Quality, weights for each part, component or subsystem can be determined. This is done by multiplying the respective relationship value of each part, component or subsystem and the respective weight of the quality characteristic. Adding all values in each column, the total weight for each part, component or subsystem is obtained. From the total weights, critical parts for the execution of the engineering characteristics can be identified. These critical part characteristics are deployed further to the process planning matrix. Figure 12 shows an example of a parts planning matrix.

Supporting activities such as value analysis, Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FEMA), design optimization, cost analysis, and parts selection for reliability assurance are utilized.

Quality Chart III

Part characteristic	Quality characteristics	Charac- teristics	Target value		Difference	Runout of surface	Adhesion strength	Torsional strength	Part characteristics	Deg. of import
			A	B						
Components	Part characteristics item	Critical item	○	○			>20	C		
Outer sleeve	I.D.		↘	→			↗	→	øD 0.1	5
	Surface roughness after grit		→	→			↗	→	≤ E	5
Rubber	Rubber hardness		↗	→			↘	↗	H <sub>s</sub> 2	5
	Sheet thickness		↗	→			↘	→	t6 4	5

Figure 12 Parts Planning Matrix  
(Akao, 1990)

### 5.1.1.3 Process Planning

This matrix represents the transition from design to manufacturing operations, from development to execution. From the parts planning matrix, the components and the critical component part characteristics are obtained. Subsequently, the information about the processes needed to produce these different components is also obtained.

These critical component part characteristics are placed in the top part of the table, and the process or manufacturing operations are placed vertically. A relationship matrix is created, and again, symbols are used to highlight strong/weak relationships.

When a critical product component parameter is created, or directly affected in a given step of a process, that parameter is identified as a control point. For example, in the component spring, a critical part characteristic is "wire length". The process "cut wire" will affect directly wire length. Thus, a control point in this process is length (Sullivan, 1986).

Each process has certain parameters, e.g., time, temperature, etc., that have to be monitored to assure the component parameters are achieved. These parameters are named check points. A list of these check points is placed near the

control points. From this matrix table, a process plan and control chart can be derived. This chart includes process flow, control points, control method, sample size frequency, check method, etc. Figure 13 shows a process planning table.

#### **5.1.1.4 Product Planning**

This matrix transfers the information generated in the subsequent phases to the factory floor. Many variations of this matrix can be anticipated based on individual process situations. In this document, a series of tables and charts is used to relate the check points and control points to the operator.

The basic information that this phase has to transmit to each operator is: what parts are involved, how many he/she should check, what is the tool to use for inspection, how to make the checking, where/how to print information and what to do, to whom report in case of failure and all the other necessary information that it is believed to be necessary in order to facilitate production and inspection (Sullivan 1986).

#### **5.1.2 AKAO'S APPROACH TO QFD**

Akao<sup>12</sup> (1990) affirms " a comprehensive quality function deployment system must reflect technology, reliability, and

No.	Process	Critical Comp. Part Characteristics						Control Points	Process Monitoring Plan		
		Wire Dia.	Wire Lgh.	Hardness	Etc.	Etc.	Etc.		Check Points	Monitoring Method	Frequency
1	Draw Wire	●		○		○		<ul style="list-style-type: none"> <li>• O.D.</li> <li>• Includ.</li> <li>• Cracks</li> <li>• Etc.</li> </ul>	<ul style="list-style-type: none"> <li>• Mat. Temp.</li> <li>• Die Temp.</li> <li>• Speed</li> </ul>	<ul style="list-style-type: none"> <li>• Check Sheet</li> <li>• X &amp; R</li> <li>• Etc.</li> </ul>	<ul style="list-style-type: none"> <li>• 1 Hr.</li> <li>• 3 Cks./ Hour-5 Min. Apart</li> </ul>
2	Cut Wire		●				○	• Length			
3	Roll Spring				○						

Figure 13 Process Planning Table  
(Sullivan, 1986)

cost considerations. " Akao's approach separates quality deployment into four sections represented in his QFD diagram by four columns: one for quality function deployment, one for technology deployment, one for reliability deployment and the last one for cost deployment. Akao's methodology is illustrated on Figure 14.

In the next pages, an analysis of Akao's four sections/phases or columns is given.

#### **5.1.2.1 Phase I Quality Deployment**

This phase of QFD is composed of four charts:

- 1) customers requirements and quality characteristics are related in the chart (1-I)
- 2) quality characteristics are related to the various functions of design and/or process in the chart (2-I)
- 3) customer requirements are related to the various functions in the chart (2'-I)
- 4) quality characteristics are related to subassemblies and parts in the chart (3-I)

Chart (1-I), called "quality chart" by Akao, is the House of Quality in Macabe's QFD approach. Thus, the Akao's methodology starts in the same way as the Macabe's methodology. First consumer information is gather by different methods. Next, the information provided by consumers about the qualities they

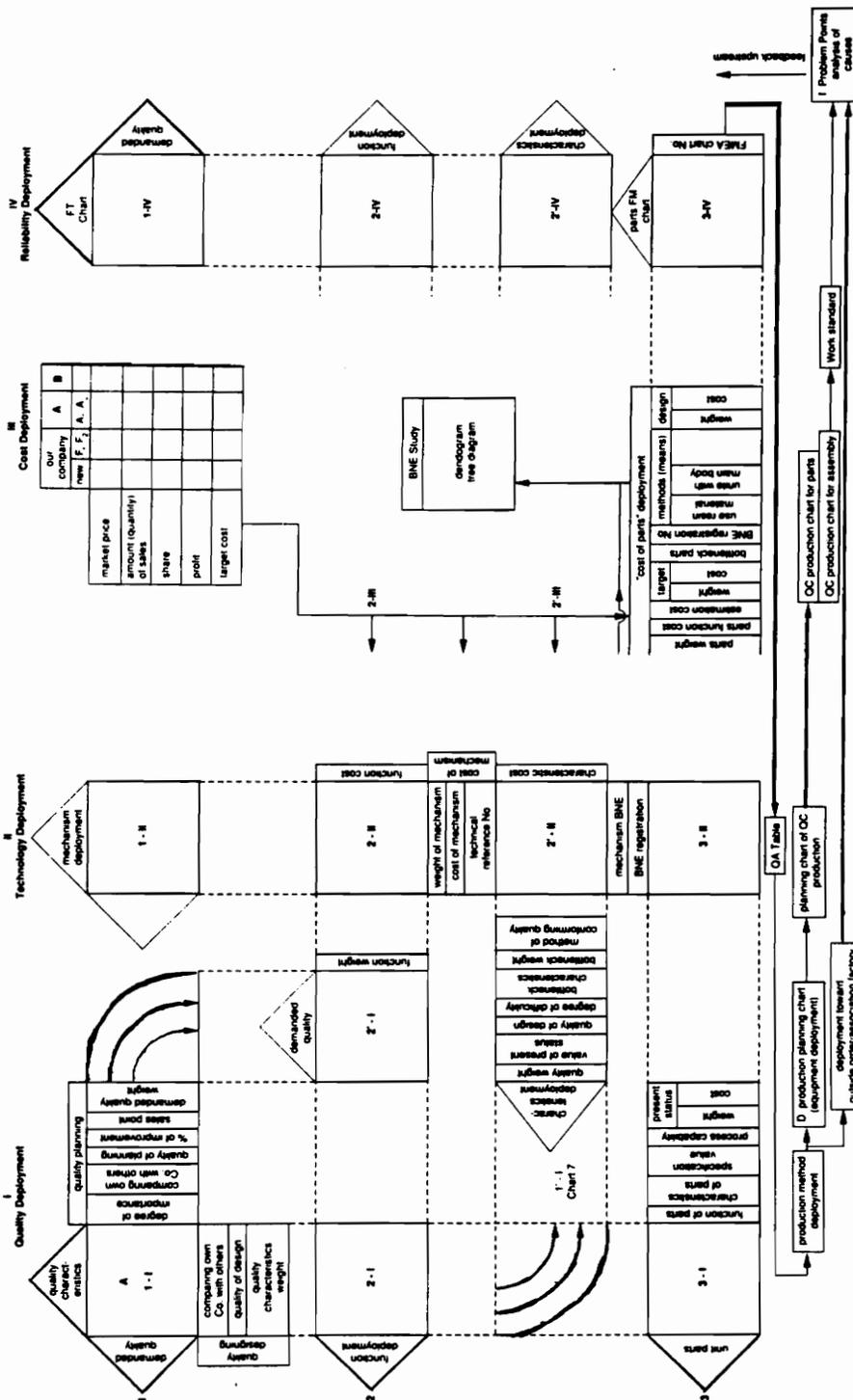


Figure 14 Akao's QFD Methodology (Akao, 1990)

want in a product must be systematically analyzed, in order to make it useful for product deployment. After this analysis, questionnaires can be distributed regarding the degree of importance of various demands (Akao, 1990).

Chart (1-I) has the same format as Macabe's House of Quality. On the left side, the demanded qualities at their different levels; at the top, the quality characteristics; and, at the right side the quality planning. The quality plan can contain the following points:

- . degree of importance (of the demand quality by the customer)
- . competitive analysis (our company, other companies)
- . plan quality plan (what is the quality to achieve),  
rate of improvement, sales point
- . weight absolute and demanded quality

Figure 15 shows a basic quality chart.

Mitsufuji<sup>13</sup> (Akao, 1990) states " the fundamental purpose of the quality chart is to convert each quality demanded by customers into quality characteristics expressed in the engineering language used by one's company." Both demand quality and quality characteristics should be deployed to approximately third levels of detail.

One of the most difficult points in the preparation of the

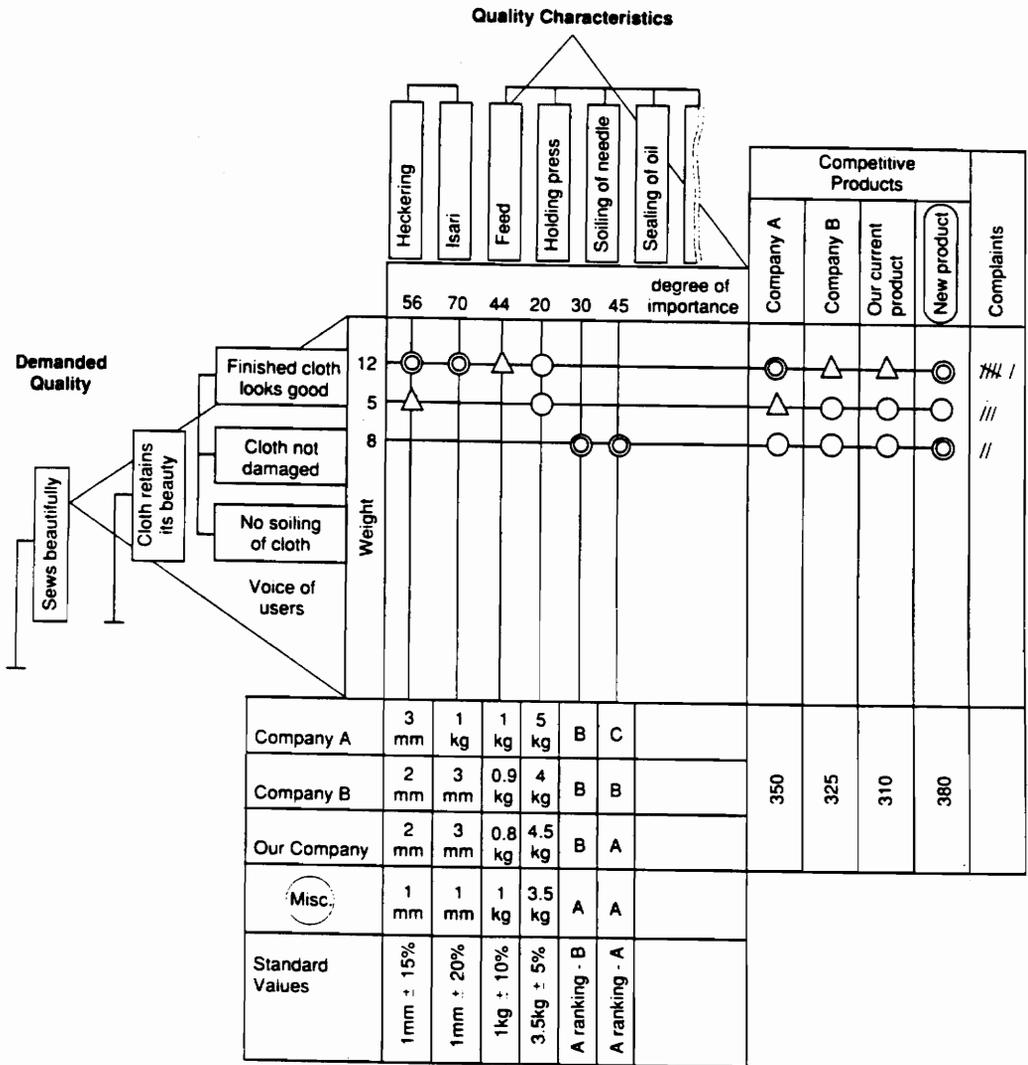


Figure 15 Quality Chart  
(Akao, 1990)

quality chart is to determine the relationships between demanded quality and quality characteristics. These relationships should be based on knowing and controlling facts; however, often is based on experience and/or intuition (Akao, 1990).

After the relationships are determined, the quality characteristics for further deployment have to be selected. This selection is accomplished by converting the importance of demanded quality items into the importance of counterpart characteristic.

quality charact. =  $\sum_j$  (strength of the match)<sub>ij</sub> (the weight evaluation score of the demanded quality to be correlated)<sub>j</sub>

For example, suppose a quality demanded by the customers deployed at third level is "wide set space". The evaluation point given by the customers is equal to 15. Suppose the designer specifies a quality characteristic "roominess length" which has a strong relationship with "wide set space", with a value of 5. The weight of the particular intersection is equal to 5\*15=75. The vertical sum of all scores in the column roominess length will give the overall score of such a quality characteristic (Akao, 1990).

Each quality characteristic must be expressed by product

functions as well as mechanisms. These mechanisms enable the realization of the product's functions. These functions and mechanisms must be determined in order to specify the needed technology to accomplish the quality characteristics. Given that the basic functions of the product are not between customers demands, a function deployment must be the starting point for the technology deployment. The function deployment chart (2-I) is produced in order to take this point into account. The need of this chart can be summarized by the following statement: if the basic function or functions are not fulfilled in the design it is worthless to market the product (Akao, 1990).

A function can be specified by a verb plus an object. To construct the chart, the main function or functions are specified. These functions, however, have nothing to do with the user. This chart focuses on the voice of the engineer. For example, suppose the product is a remote control. The user is satisfied as long as he/she can communicate hand movements to the distant object and will not care whether a laser or some other system is used instead of radio waves to achieve this objective. But this difference in technology is crucial for the engineer since it represents a totally different design of the remote control product (Akao, 1990).

In chart (2'-I) the functions are related to the customers

requirements. The demanded quality and their demanded weights are deployed from the quality chart, and the functions are deployed from the chart (2-I). The correlations are identified in the matrix using the same symbols and values as in the previous matrices. The function weights are determined by the addition in each row of the multiplication of each demanded weight with the corresponding correlation value. These function weights are then converted into percentage to identify the relative value of each function.

In chart (3-I) the quality characteristics are related to the subsystem-part of the product or system in consideration. The purpose of this matrix is to determine which parts or subsystems are more related to the quality characteristics. The quality characteristics that are deployed in this chart are the most critical ones.

Additional information can be introduced in a table form, next to chart (3-I), to identify critical items of each part: its function, its critical quality characteristic, the target value, the variation as measured by the process capability (Cpk) and the current cost of making the parts (also, the weights can be added if wanted). This information is obtained as follows: from chart (3-I) critical parts can be determined. Once these critical parts are listed, their functions can be specified. From the relationship matrix of chart (3-I), the

quality characteristics related to each of these critical parts can be obtained. From the actual process, the current capability (measured by Cpk) of the critical parts in meeting their target values can be determined. Finally, for each critical part, the actual cost, weights and target values can be listed.

#### **5.1.2.2 Phase II Technology Deployment**

As Akao<sup>14</sup> (1990) mentions, " even when the design quality has been determined by converting each demanded quality into quality characteristics, it is still difficult to immediately create a link with the technology needed to achieve these qualities. First, the product functions that express these quality characteristics must be determined jointly with what mechanisms will be required to realize them. When all of these steps are taken together, the activity is called technology deployment."

The phase II-Technology Deployment begins with the creation of the chart (1-II). In this chart the product mechanisms are identified. For example, a radio controlled product is composed of the following mechanisms: transmitting, auxiliary, signal receiving and servo. The transmitter can be further divided into a control, a signal generation, and a radio wave transmission mechanisms.

The chart (1-II) begins by considering the seed technology. These seed technologies are new materials, new mechanism or new technology. Relationships between the mechanisms and the seed technologies are established on the attempt to determine which of the new technologies should be considered in developing the new product and/or to suggest new directions for the product (King, 1989). Figure 16 shows an example of the chart (1-II).

The product functions must be converted into mechanisms for their realization. The chart (2-II) is used to identify which mechanisms are most related to the key functions and to check that the mechanisms can support the functions that will be performed (King, 1989). The mechanisms are deployed from chart (1-II) and the functions are deployed from chart (2-I). The correlations are identified using the same symbols and values as in the other matrices.

In this chart the mechanism weights can be obtained given that we have the function weights and the type of correlation. Additionally, the mechanism costs can be calculated. The calculation is the following: from the cost deployment, the actual and plan costs can be obtained for the product, subsystems and general functions. The function costs are determined by distributing the cost according to the functions weights. Once the function costs are determined, the mechanism

First Level of Detail  
Mechanisms

		writing mechanism	erasing mechanism	lead holding mechanism	chewing mechanism
new technology	molded plastics	○	○		
	polymer technology	⊙	⊙		△
	plastic erasers		⊙		
	new assembly methods	△			
	new kinds of wood			⊙	

Figure 16      Chart (1-II)  
(King, 1989)

costs can be determined based on the relationship matrix.

A table can be created (table 1'-I) in order to determine the degree of difficulty of achieving a quality characteristic and bottleneck characteristic. During the process of evaluating and determining quality values, the state of "engineering bottleneck (BNE)" can be reached. Professor Furukawa<sup>15</sup> (Akao, 1990) explains what is BNE, "when the product quality plan and quality design are developed from a quality chart, and a quality target value is set at a higher level than the previous standard, and this level is difficult to achieve, we have what we call an engineering bottleneck." King (1989) explains what is the information included in the table (1'-I):

- a) The key quality characteristics are deployed in their third level as the first columns of the table.
- b) Next to them the current values and the target values are specified.
- c) Finally, the degree of difficulty to obtain these new target values are listed.

Figure 17 shows an example of the table (1'-I).

If the achievement of the required function with the company's special technology capability is likely to be very difficult, this situation should be designated as an engineering bottleneck. A common way to deal with engineering bottleneck is PDPC (Process Decision Program Chart). The PDPC is a method

### Quality Characteristics

3rd level    4th level

	factors	present value	target value	degree of difficulty	project #
time between sharpening	wood hardness	20 psi to break	20 psi to break	1	101
	lead hardness	#2	#2		
	lead composition	traditional	lead polymers	3	102
	darkness of line	20 color spectrom.	30 color spectrom.	2	103
lead dust generated	size of dust	10 microns	8 microns	2	104
	amount of dust	10 part./line	6 part./line	3	105

Figure 17      Table (1'-I)  
(King, 1989)

by which the bottleneck is resolved by asking questions and giving the respective answers, until a satisfactory answer is obtained. Figure 18 shows a PDPC.

In chart (2'-II) the mechanism are related to the key quality characteristics and to all information of table (1'-I).

Finally, in chart (3-II) the critical parts deployed from chart (3-I) are related to the mechanisms.

#### **5.1.2.3 Phase III Cost Deployment**

As Maekawa<sup>16</sup> (Akao, 1990) states, "the purpose of cost deployment is to build into the engineering process a systematic way to reduce product cost while maintaining balance with quality."

The cost deployment starts by creating a table which identifies market price, sales volume, market share, and targeted manufacturing cost as they relate to the current products, the competitor's product, and the plan for future product (King, 1989).

Once we have the target cost for the product, the cost of each demand quality can be obtained by ( relative evaluation \* target cost \* 100 ).

This conversion or deployment can continue to the quality

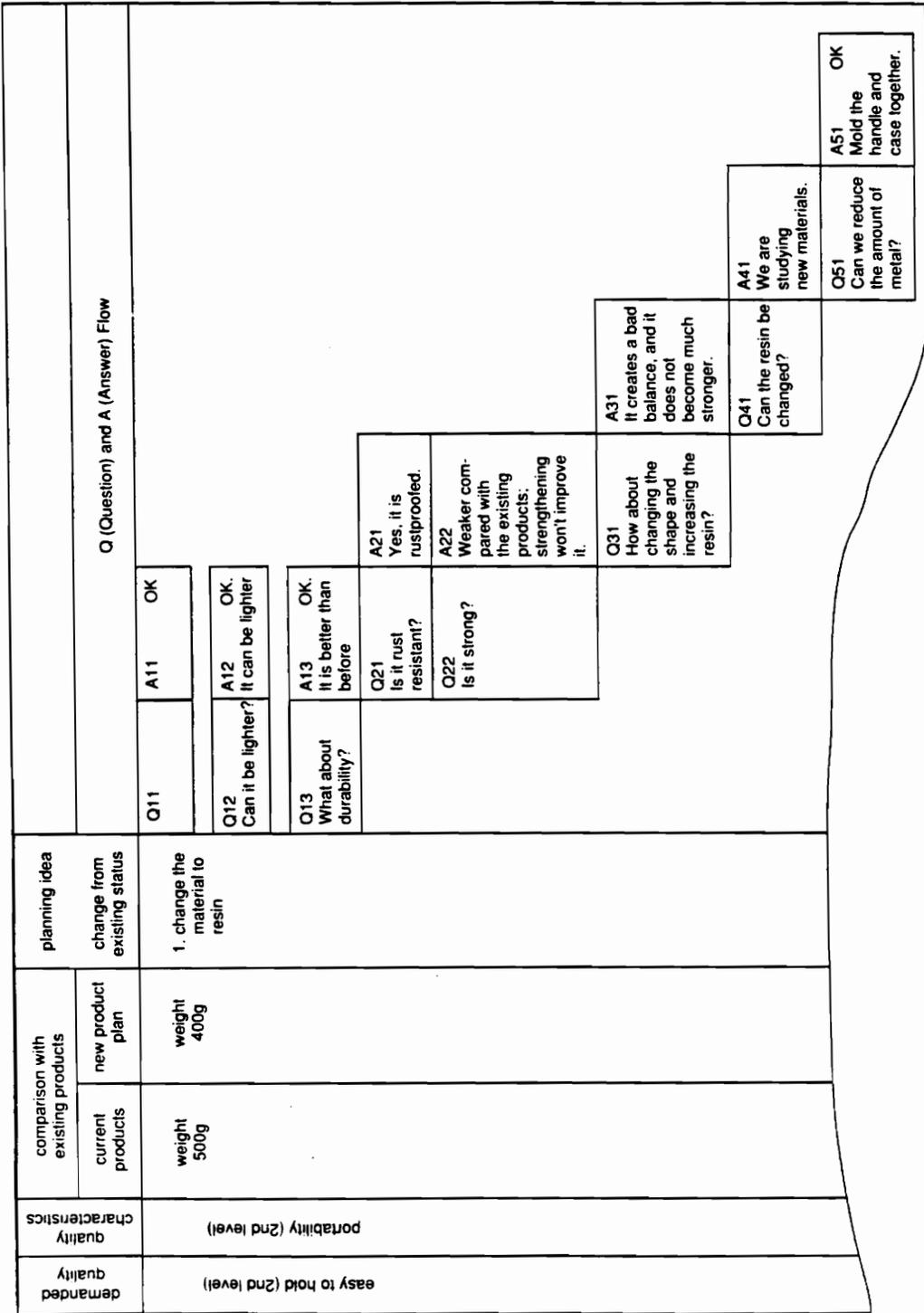


Figure 18 Process Decision Program Chart (PDPC)  
Akao 1990

characteristic, the function cost, mechanism cost and part cost. For example, suppose a demanded quality X with a target cost of Y. This cost Y will be distributed in a proportional way among the quality characteristics that are related to X, depending on their type of relationship. Then, all the different costs for quality characteristic Y can be added and multiply the sum of costs by the total importance scores to obtained the quality characteristic cost. This cost is related to the functions. The quality characteristic Y will be related to some functions by certain relationships (strong, weak, etc). Thus, the cost will be distributed among these functions in a proportional way. The functions are related to mechanism, then, the cost can be deployed in the same way to the different mechanism. These mechanisms are related in a chart with unit parts, thus, parts cost can be obtained according to the match between mechanisms and parts.

#### **5.1.2.4 Phase IV Reliability Deployment**

Reliability deployment guarantees that the basic functional quality features of a product will last over a certain time period. In reliability deployment, characteristics whose performance values could be difficult to maintain over the desired timespan are determined. For this purpose Fault Tree Analysis and Failure Mode Effect Analysis are useful.

Chart (1-IV) is formed: in the top by product failure modes

which are generated by a Fault Tree Analysis and on one side by the demanded qualities with their respective demanded weights. The matrix shows the correlation between the different product modes effects and the customers demands. The prioritization of product failure mode is obtained as follows: first multiplying the demanded weights and the respective correlation value; then, adding the products in each column. The results obtained are the raw weights for each failure mode. Finally, these values can be converted to percentage values (King, 1989).

Chart (2-IV) relates the product failure modes to the functions. Chart (2'-IV) relates the product failure modes to the quality characteristics.

All these three previous charts are to prioritize product failure modes, since products need to be reliable and engineers need to focus on key issues. In each of the previous charts a review must be made for any failure mode where there are no correlations, to determine if any function, quality characteristic, etc. is missing.

Chart (3-IV) relates parts failure modes and the critical parts. The purpose of this chart is to prioritize FMEA studies. This is done as follows: parts failure modes are obtained by applying the brainstorm method. Affinity and tree

diagrams are utilized to take these failure modes to the third level of detail. The critical parts and their weights are deployed from chart (3-1). The failure modes are correlated with the critical parts. Each part weight is multiplied by the respective correlated value. Subsequently, the weights are added for each critical part and the results are converted to percentage (King, 1989).

Takamura<sup>17</sup> (Akao, 1990) states, " the aim of QFD at the preproduction stage is to achieve mass production of a product with assured quality, with ease of manufacturing, and a minimum cost." To fulfill this requirement, the design department's ideas must be communicated to the production department. This communication is achieved through Quality Assurance tables, equipment deployment, process planning charts, FTA, FMEA and quality control charts. King (1989) explains each of these tools:

- . Quality assurance charts identify the control items that must be incorporated in the process design to implement the quality characteristic being deployed. The QA table lists the various parts, degree of importance, quality characteristics, design specifications, problems to appear if quality is not satisfied and remarks and comments.

- . The equipment deployment chart lists the various production options and compares each supplier in-house or out in terms of

cost and quality.

. Quality control planning chart: each process is identified, from raw material to final product, the process condition and equipment are determined for each process. Then each process is related with the parts characteristics, and the process control points are determine.

These control points are transferred to the QC process chart where part name, flow chart (raw material & processes), process name, work instructions, control items, control instructions and control methods are specified.

. The FTA and FMEA are useful to specify the different way that the process can fail, and to identify corrective actions.

## **5.2 APPENDIX B - TAGUCHI METHODS**

This section is divided into five parts, they are:

- 1) Introduction to Robust Design methodology.
- 2) Definition of all the different terminology and tools used by Taguchi.
- 3) Taguchi's methodology and tactics.
- 4) Drawbacks of Taguchi's Methods.
- 5) QFD with Taguchi's Methods.

The Taguchi methods discussed here concern his approach to off-line quality control, which include technical aids for

quality and cost control in product and the process design. They are used to improve product quality and manufacturability, and to reduce product development, manufacturing and lifetime costs. In contrast, on-line quality control methods are technical aids for quality and cost control in manufacturing.

### 5.2.1 INTRODUCTION

Taguchi's popularity testifies to the merit of his quality philosophy. Taguchi's quality definition invokes a new concept in quality " Quality is the loss imparted to the society from the time a product is shipped". For example, failure to meet the ideal performance. This failure brings consumer dissatisfaction, added warranty cost to the producer and a loss in market-share due. Thus, the quality of the product is responsible for all societal losses due to the poor performance of the product.

Baker<sup>18</sup> (1986) explains that while the American Society for Quality Control "has defined quality as "the totality of features and characteristics of a product or service that bear on its ability to satisfy given needs", Taguchi on the other hand distinguishes between quality and features, arguing that adding features is not a way of improving the quality of a given product."

Every product or process has a certain number of quality characteristics which are appropriate response variables for measuring quality. The primary quality characteristics are called performance characteristics, which are the final performance in satisfying a user's need. The ideal value of a performance characteristic is called the target value.

The ideal quality a customer can expect from a product or process is that through their lives they deliver the target performance (each performance characteristic at their respective target value) each time they are used, considering all possible operating conditions without harmful side effects (Phadke, 1989). The variation of a performance characteristic about its target value is referred to as performance variation. The smaller the performance variation about the target value, the better the quality. In this sense, Taguchi states that quality losses must be defined as deviation from target, not conformance to arbitrary specifications.

If quality is specified in terms of interval specifications, this is implying, as Kackar<sup>19</sup> (1986) explains, " that the quality level remains the same for all values of the performance characteristic in the specification interval and then suddenly deteriorates the moment performance value slips out of the specification interval." Figure 19 show these two different ideas of quality thinking.

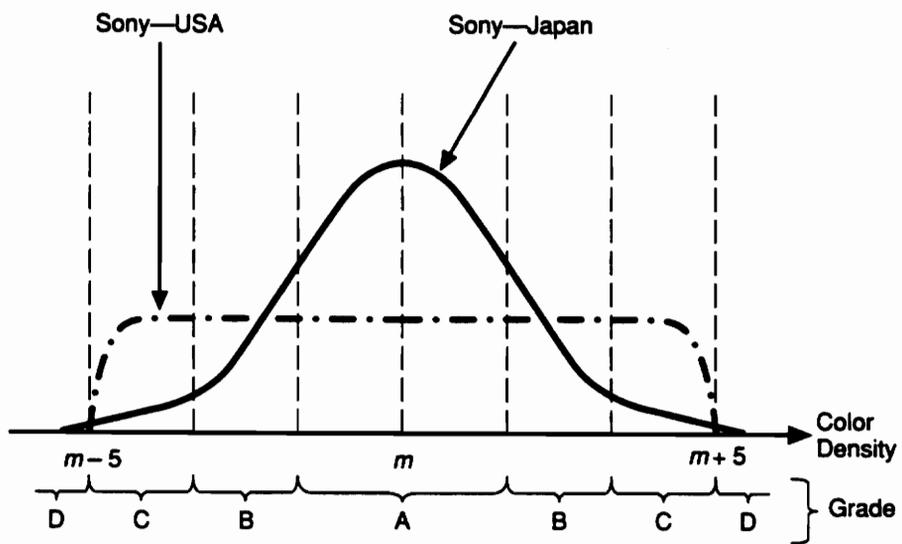


Figure 19 Defects Distribution  
(Phadke, 1989)

With the traditional interval specifications quality thinking, the USA process distribution will be considered better than the Japanese since it meets specs and has zero defects. But merely meeting specifications is a poor measure of quality. The Japanese process distribution has defect units since the tails of the process distribution are outside specs, but as its distribution is more uniformly distributed around the target, it will have more perfect products than the US factory. Thus, the loss due to customer dissatisfaction will be less than for the US products (Baker, 1986). As Gunter<sup>20</sup> (1987) states, "there is no abrupt change from perfect to useless as some arbitrary boundary is crossed. What really happens is that performance gradually deteriorates as the quality measure deviates farther and farther from the intended target." The primary causes of a product's performance variations or deterioration are: environment variables (e.g. temperature, humidity), product deterioration (e.g. increase in electrical resistance of a resistor), and manufacturing imperfections.

Aware of all this, Taguchi developed the foundations of Robust Design. Phadke<sup>21</sup> (1989) indicates that the fundamental principle behind Robust Design is "to improve the quality of a product by minimizing the effect of the cause of variation without eliminating the causes." Taguchi outlined a three-step approach in order to achieve Robust Design: system design

(application of scientific and engineering knowledge to configure the basic product or process design), parameter design (identification of parameter levels which minimize the performance variation), and tolerance design (determination of tolerances that minimize the product costs) (Kackar, 1985).

In order to identify optimal parameter settings, Taguchi specifies a criterion that is to be optimized "loss function" or "quality loss function". This loss function gives the quality loss due to performance variation. Taguchi states that loss increases by the square of deviation from the target value, giving the loss function equal to  $L = C * D^2$ , where  $C = \text{constant}$ .

Taguchi Methods can be differentiate between Taguchi's tactics and Taguchi's strategy. Taguchi's strategy is explained by Pignatiello<sup>22</sup> (1988), " Taguchi strategy is a systematic application of the design and analysis of experiments. The strategy involves the empirical minimization of the loss function to determine the best product design." Taguchi's tactics involve the use of certain statistical tools, such as: orthogonal array to perform the experiments; signal to noise ratios to determine the best product design; analysis of variance as a qualitative tool to determine effects of different design factors among other statistical considerations. Figure 20 illustrates Taguchi's off-line and

on-line quality control process.

## **5.2.2 TAGUCHI'S TERMINOLOGY AND TOOLS**

The following terminologies and tools will be addressed:

5.2.2.1\_ loss function

5.2.2.2\_ parameter classification

5.2.2.3\_ Taguchi's stages in product development

5.2.2.4\_ signal to noise ratios

5.2.2.5\_ orthogonal arrays

5.2.2.6\_ interaction

5.2.2.7\_ additivity

5.2.2.8\_ design and noise matrices

5.2.2.9\_ analysis of variance

### **5.2.2.1 Loss Function**

Taguchi has defined the quality level of a product to be the total loss incurred by society due to the departure of the product performance from its target value. Taguchi emphasizes the importance to quantify this loss, by a quality loss function, so that the impact on customers of alternative product and processes designs can be evaluated. This loss function specifies that the loss associated with a product is proportional to the square of the difference between the target value and the observed quality characteristic value of the product (Pignatiello, 1988).

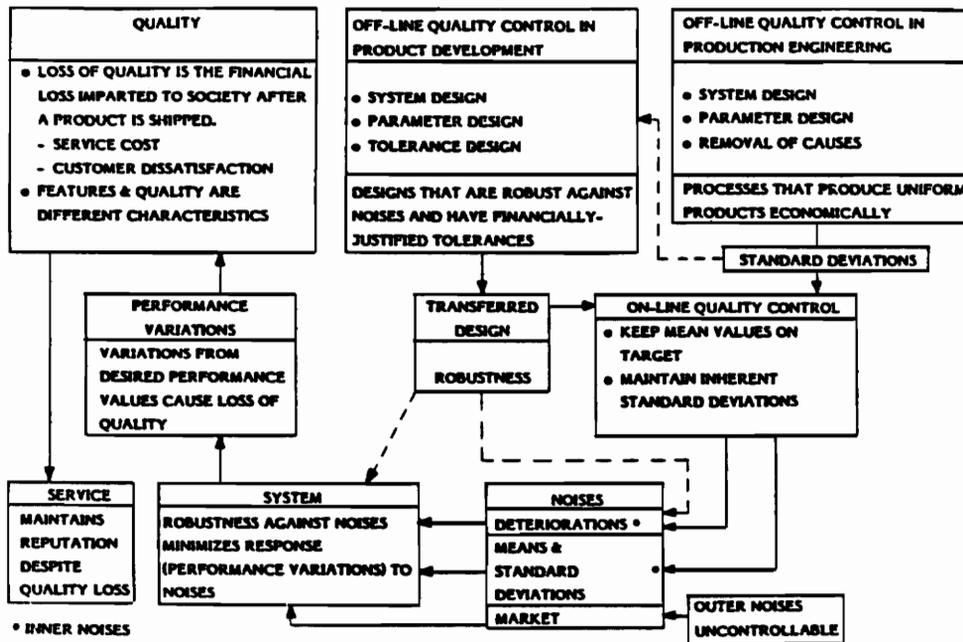


Figure 20 Taguchi's Off-Line & On-Line Quality Control Process (Baker, 1986)

The loss function is defined as  $L(y) = k * (y - m)^2$

where,  $y$  = quality characteristic

$m$  = target value for  $y$

$k$  = constant called quality loss coefficient

$L(y)$  = loss in terms of dollars suffered by the customer due to the deviation of  $y$  from  $m$ .

To determine the constant  $k$ , assume  $\pm T$  is the customer's tolerance interval around  $m$  and the cost of the customer of repairing or discarding the product is  $A$  dollars. Then the value of  $k$  is given by  $k = A / T^2$ .

The loss function or quadratic loss function can be divided into four commonly occurring situations. The loss function given previously is applicable whenever the quality characteristic has a finite target value, usually non-zero, and the quality loss is symmetric around the target value. This type of quality characteristic is called "nominal the best type". Figure 21 shows the quality loss function for the case "nominal the best type".

Another common type of quality characteristics are "smaller the best type" characteristics. These characteristics have a target value of 0. As the quality characteristics increases, their performance become progressively worse. For example, pollution from an automobile. The quality loss in this

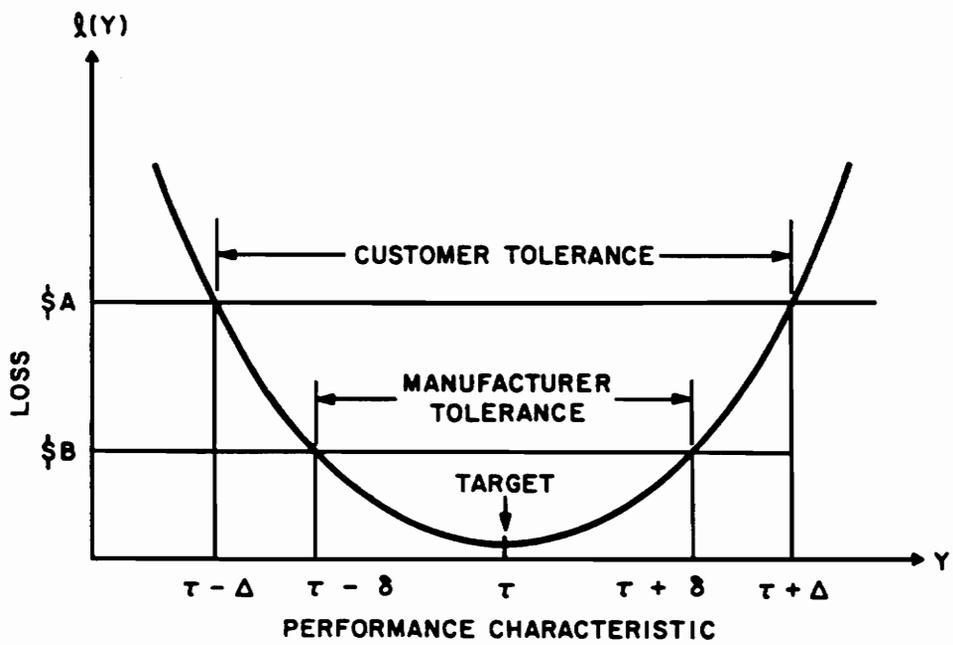


Figure 21 Quality Loss Function  
(Kackar, 1985)

situation can be expressed as  $L(y) = k * y^2$  .

The third common type are the "larger the better type" characteristics and are those quality characteristics which have a target value of infinity. For example, strength of a certain material. The quality loss in this situation is given by  $L(y) = k ( 1/y^2)$  .

The last most common situation is the asymmetric loss function. In some situations the variation of the quality characteristic from the target value  $m$  in one direction is worst than in the other direction. For example, some electric circuits are more sensible to increments of temperature than to decrements. The quality loss function can be approximated by

$$L(y) = \begin{matrix} k_1 * ( y - m )^2 & y > m \\ k_2 * ( y - m )^2 & y \leq m . \end{matrix}$$

#### **5.2.2.2 Parameter Classification**

When planning an experiment one considers a variety of variables, or factors. These factors are certain parameters that can influence the response of the product. Taguchi classifies these factors in the following three main classes (Phadke, 1989):

- I) noise factors**
- II) signal factors**
- III) control factors**

## **I) NOISE FACTORS**

The noise factors are those factors that cause variations in the performance of the product and belong to the uncontrollable noise space. The noise factors can be divided into three general classes:

- a) **external noise** Environmental conditions and the working load are two primary noise factors, these include, temperature, human operator skill level, supply voltage, etc.
- b) **unit-to-unit variation** Variation between products caused by the manufacturing process
- c) **deterioration** As time passes components deteriorate leading to performance variations.

## **II) SIGNAL FACTORS**

Are parameters that can be set by the product user to obtain an expected response value. For example, the truck driver who choose the steering angle  $s$  to make a turn of angle  $t$ .

## **III) CONTROL FACTORS**

Are those parameters that can be specified by the designer. Control factors, also called design parameters or factors, can take multiple values, called levels. For example, the value of the watts of a lamp, or the width in inches of the metal for a car's door.

### **5.2.2.3 Taguchi's Stages in Product Development**

Taguchi considers three stages of quality by design:

#### **A) System Design**

In this stage, engineering and scientific knowledge is used to configure the basic functional prototype design. In addition, examination of different architectures and technologies for achieving the desired function of the product is performed.

#### **B) Parameter Design**

Parameter design deals with the selection of control factors in order to minimize the sensitivity of the product's function in uncontrollable noise space and set the mean function on target.

#### **C) Tolerance Design**

Tolerance design determines the tolerances around the nominal settings identified by parameter design. Tolerance design involves a trade-off between reduction in the quality loss and increment in manufacturing cost due to the reduction of tolerance and higher grade materials. Tolerance design should be performed only after parameter design.

(Kackar, 1986; Phadke, 1989; Pignatiello, 1988)

#### **5.2.2.4 Signal to Noise Ratios ( S/N Ratios )**

Signal to noise ratios are the performance statistics used by Taguchi to estimate the effect of the noise factors on the quality characteristics. Taguchi has developed over 60 distinct signal to noise ratios. While many of these S/N ratios are unique to an industry or process, there are three S/N ratios that may be applied to a wide range of response variables.

Assume the quality characteristic is a continuous variable and is denoted by  $Y$ . Let  $y_1, y_2, \dots, y_n$  approximate a random sample from the distribution of  $Y$ .

**a) nominal the best type situation**

$$S/N = 10 \log ( y^2 / s^2 )$$

where

$$y = 1/n \sum_{i=1}^n y_i \quad \text{and} \quad s^2 = (1/ n-1) \sum_{i=1}^n ( y_i - y )^2$$

**b) smaller the better type situation**

$$S/N = - 10 \log [ 1/n \sum_{i=1}^n y_i^2 ]$$

**c) larger the better type situation**

$$S/N = - 10 \log [ 1/n \sum_{i=1}^n 1/y_i^2 ]$$

A simple explanation of why Taguchi uses these performance statistics to estimate the effect of noise factors on the quality characteristic will be given (Kackar, 1985; Pignatiello, 1988).

Suppose a quality characteristic has a target value of  $m$ . Let  $Y$  be the measured value of this quality characteristic. Let  $E(Y) = \mu$  be the expected value of the observed quality characteristic. Ideally, if there was no bias,  $E(Y) = \mu = m$ . Due to the noise factors  $Y$  has certain variability, this variability is given by  $\text{Var}(Y) = \sigma^2$ . The loss function used by Taguchi is given by  $L(Y) = k * ( y - m )^2$ .

Taking the expected value of the loss function we obtain

$E[L(Y)] = E[ k (y-m)^2 ] = k E[(y-m)^2] = \text{MSE}$ . If the bias is equal to  $(\mu - m)$ , then the  $\text{MSE} = \sigma^2 + (\mu - m)^2$ . Minimization of the loss function is equivalent to minimization of the expected average loss, thus minimization of the mean square error.

Suppose we are in the smaller the better scenario. In this case we want the target value to be zero,  $m = 0$ . If we substitute  $m=0$  in the expected loss function we have

$$\text{MSE} = E [( y - 0 )^2] = E [ y_2 ]$$

Taguchi recommends using for smaller the better situation the performance measure  $S/N = -10 \log \text{MSE} = -10 \log (1/n \sum_{i=1} y_i^2)$  by the method of moment estimation.

#### **5.2.2.5 Orthogonal Arrays**

Taguchi's tactics to obtain a robust design consists of using orthogonal arrays to run the experimental design. Taguchi utilizes matrix experiments to run the experiments and as Phadke<sup>23</sup> (1989) explains, " a matrix experiment consists of a set of experiments where the settings of the various products and process parameters to be studied are changed from one experiment to another." Figure 22 shows an orthogonal array.

Taguchi utilizes the columns to represent the design or control parameters. The rows are used to represent product designs or experiments. The numbers in the matrix represents

(a)  $L_8(2^7)$  orthogonal array

Expt. No.	Column						
	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2
	A	B	C	D	E	F	G
	Factor Assignment						

Figure 22 Orthogonal Array  
(Phadke, 1989)

the different levels of the design parameters. For example, suppose that it has been chosen a design parameter A to be the quantity of a certain additive. The current level of this design parameter is 1%. The new level of factor A which the designer wants to study is 5%. It can be assigned 5% to level 1 of factor A, and 1% to level 2. Thus, control factor A is a two level factor. If the column 1 is chosen to represent factor A, then the entries  $(i,1)$   $i=1,2$  represent different experiment levels. A1 and A2, respectively (Phadke, 1989).

Orthogonal arrays may offer many benefits, among others: the conclusions arrived at from such experiments are valid over the entire experimental region, there is a large savings in the experimental effort; data analysis

is very easy and departures from the additive model can be detected. There are different orthogonal arrays. Figure 23 shows the standard orthogonal arrays.

Terms Used in Matrix Experiments (Phadke, 1989)

**Experimental region** region formed by the factors being studied and their alternate levels

**Starting levels** levels of the different factors used before conducting the matrix experiment

**Overall mean** the mean of the value of the S/N ratios of the different experiments runs

Orthogonal Array*	Number of Rows	Maximum Number of Factors	Maximum Number of Columns at These Levels			
			2	3	4	5
$L_4$	4	3	3	-	-	-
$L_8$	8	7	7	-	-	-
$L_9$	9	4	-	4	-	-
$L_{12}$	12	11	11	-	-	-
$L_{16}$	16	15	15	-	-	-
$L'_{16}$	16	5	-	-	5	-
$L_{18}$	18	8	1	7	-	-
$L_{25}$	25	6	-	-	-	6
$L_{27}$	27	13	-	13	-	-
$L_{32}$	32	31	31	-	-	-
$L'_{32}$	32	10	1	-	9	-
$L_{36}$	36	23	11	12	-	-
$L'_{36}$	36	16	3	13	-	-
$L_{50}$	50	12	1	-	-	11
$L_{54}$	54	26	1	25	-	-
$L_{64}$	64	63	63	-	-	-
$L'_{64}$	64	21	-	-	21	-
$L_{81}$	81	40	-	40	-	-

\* 2-level arrays:  $L_4, L_8, L_{12}, L_{16}, L_{32}, L_{64}$ .

3-level arrays:  $L_9, L_{27}, L_{81}$ .

Mixed 2- and 3-level arrays:  $L_{18}, L_{36}, L'_{36}, L_{54}$ .

Figure 23 Standard Orthogonal Arrays  
(Phadke, 1989)

**Effect of a factor level** deviation from the overall mean caused by a factor set at a specific level

**Main effect** if a factor A has 3 levels, it would have three different effects of factor level. The mean of these different effects is the main effect of factor A

**Interaction** interaction appears if the effect of a factor depends on the level of another factor. These two factors are said to have an interaction.

#### 5.2.2.6 Interaction

Suppose that we have two factors A and B with three levels each. We draw a graph with the S/N ratio values for factor A for the settings B1, B2 and B3 of factor B as the ordinates, and the levels of factor A as the abscissa. There are going to be nine points, e.g. one of these points will be the value of the S/N ratio for factor A at level A1 and factor B at level B1, etc. Next, the three point which have level B1 are connected with lines. Same procedure is follow with points at B2 and B3. Thus, there are going to be three broken lines.

No interaction implies that these three broken lines are parallel. If they are parallel it implies that, if we change the level of factor A from A1 to A2 or A3, the corresponding change in the S/N ratio value is the same regardless of the level of factor B. Thus, it is said that between factors A and B there is no interaction.

Two basic types of interaction exist:

**Synergetic interaction\_** If the broken lines are not parallel but the direction of improvement does not change, it is said that factors A and B have a synergetic interaction.

**Antisynergetic interaction\_** If the broken lines are not parallel and the direction of improvement is not consistent, it is said that factors A and B have an antisynergetic interaction. (Phadke, 1989)

#### 5.2.2.7 Additivity

Additivity is a condition needed to assure that the effects of the control factors on performance and robustness follow the superposition principle. As Phadke & Taguchi<sup>24</sup> (1988) express, " if the effects of the control factors on performance and robustness are additive, that is, they follow the superposition principle, then we can predict the product's performance for any combination of settings of control factors by knowing only the main effects of the control factors."

Through the proper choice of the S/N ratio the interaction between factors can be reduced and the relationship between the S/N ratio and the design parameters can be approximated by:

$$S/N \text{ ratio } ( A_i, B_j, \dots, N_p ) = m + a_i + b_j + \dots + n_p + e$$

where

m = overall mean

A, B, ... N = design parameters

$A_i$  = factor A at level i ( same with other factors )

$a_i$  = deviation from the overall mean cause by setting factor A at level  $A_i$  ( same with other factors )

e = error of assuming the additive approximation plus the error in the repeatability of measuring the S/N ratio for a given experiment (Phadke, 1989)

#### **5.2.2.8 Control Orthogonal Array, or Inner Array, or Design Matrix**

The control matrix contains the control factors at their different levels as columns and the different experiments as rows. The inner array is used to determine experimental combinations of control factor settings.

#### **5.2.2.8.A Noise Orthogonal Array, or Outer Array, or Noise Matrix**

The noise matrix contains the noise factors at their selected levels. Its columns represent the noise factors and its rows the different combination of noise levels. The noise matrix is used in conjunction with the design matrix. The complete experiment consists of a combination of the design parameters and the noise factor matrix. For each row of the design matrix (representing a determine design given by the different levels of the control factors ), experiments are run for all rows of the noise matrix. Thus, if the design matrix has m rows ( m

test runs ) and the noise matrix has  $n$  rows, then the total number of experiments to be run are  $n*m$  (Kackar, 1985; 1986, Phadke, 1989; Pignatiello, 1988).

#### **5.2.2.9 Analysis of Variance ( ANOVA )**

The ANOVA is a useful technique for estimating error variance and for determining the relative importance of various factors. The ANOVA in Taguchi Methods is not used to make any probabilistic statement as is commonly done in statistics. Here, the ANOVA is used to determine the relative magnitude of the effects of each factor on the S/N ratio and to choose from among many alternatives the most appropriate quality characteristic.

#### **5.2.3 TAGUCHI'S METHODOLOGY AND TACTICS**

Taguchi's Robust Design is a methodology used for finding the optimum settings of the control factors to make the product insensitive to noise factors. Thus, robust products deliver a strong signal regardless of external noise and with a minimum of internal noise.

Taguchi's tactics includes the following eight steps:

5.2.3.1) system design

5.2.3.2) determination of noise factors

5.2.3.3) selection of the quality characteristics

- 5.2.3.4) selection of the S/N ratio
- 5.2.3.5) identification of control factors
- 5.2.3.6) construction of the design and the noise matrices
- 5.2.3.7) parameter design and evaluation
- 5.2.3.8) tolerance design

#### **5.2.3.1 System Design**

Taguchi's robust design technique begins with system design (also called conceptual design). During system design, the designer must determine those designs that can meet both cost and quality criteria determined by the market-place. In system design the engineers will examine the possible ways to achieve the desired function or functions of the product. In order to do this, the engineers have to specify the product's function and requirements to get a good insight of what he/she is dealing with. The engineer must specify the mission definition of the product, performance and physical parameters, use requirements, operational deployment or distribution, operational life cycle, effectiveness factors and the environment in which the product is expected to operate. Then a function analysis must be performed in order to identify the design requirements for each hierarchical level of the system.

With all these data, the designer examines a variety of architectures and technologies for achieving the desired function. It is possible that not only one architecture is

selected, but two or three.

In the case where a product is already in production, Taguchi's method can be applied for the reduction of defects. The main function of the product must be identified, as well as, side effects and failure modes. For example, in AT&T Bell Laboratories (Phadke, 1989) it was found that during the polysilicon deposition process of the manufacturing of VLSI circuits, two main problems occurred: (1) too many surface defects, and (2) too large a thickness variation existed. Taguchi Method was applied in order to make the circuits more robust, thus to make the circuits with less surface defects and a constant thickness.

Following system design, a prototype model of the product will be available for the case of a new product, or a list of imperfections to be eliminated for an old product.

#### **5.2.3.2 Determination of Noise Factors**

The next step is to determine the noise factors. The first area of concern is to determine those factors whose levels cannot be controlled during manufacturing, which are difficult to control, or expensive to control. After listing all potential noise factors, the most important factors are selected for the experiments. Subsequently the noise factor levels must be determined. Taguchi's guiding principle for

factor level selection is as follows (Kackar, 1985):

Suppose  $w_i$  is a noise factor with mean  $M_i$  and standard deviation  $S_i$

. if  $w_i$  is assumed to have a linear effect on the performance characteristic  $Y$ , the noise factor  $w_i$  should have two levels

$$( M_i - S_i ) \quad \text{and} \quad ( M_i + S_i )$$

. if  $w_i$  is assumed to have a quadratic effect on  $Y$ , then it should have three test levels

$$( M_i - \sqrt{3}/\sqrt{2} S_i ) , \quad M_i , \quad ( M_i + \sqrt{3}/\sqrt{2} S_i )$$

The set of all possible levels of the noise factors is called the noise space.

#### **5.2.3.3 Selection of the Quality Characteristics**

The next step in the Taguchi Method is to identify the quality characteristic to be observed. Additivity between control factors is desired, since it is possible the prediction of the product's performance by knowing only the main effects. To achieve additivity, the relative magnitude and importance of interactions must be reduced. This can be done through the proper choice of quality characteristics, signal to noise ratio and control factors (Phadke & Taguchi, 1987).

Tips for the selection of quality characteristic (Phadke, 1989)

\_ The quality characteristic should be directly related to the energy transfer associated with the basic mechanism of the product. For example, sagging is a common defect in spray painting. The size of the drops created is directly related to energy transfer. While, for e.g., the distance which the paint drop sag is not related to the energy transfer since it is controlled by gravity.

\_ try to select continuous variables as quality characteristics

\_ the quality characteristic should be monotonic. The effect of each control factor on the performance characteristic should be in a consistent direction, even when the settings of other control factors are changed.

\_ use quality characteristics easy to measure

\_ complex products should be divided into subsystems, optimized separately and then integrated together

#### **5.2.3.4 Selection of the S/N ratio**

In the search for a suitable S/N ratio for experimentation, the problem must be identified as a static or a dynamic problem. Static problems are those which the quality characteristic have a fixed target value. For example, the case of minimization of ceratin defect. In this case the target is zero and fixed. Dynamic problems are those problems in which the output and the target value depend on the signal factors. For example, a measuring instrument such as a spring

scale. Figure 24 shows the basic types of robust design problems and the associated Taguchi's S/N ratios.

#### **5.2.3.5 Identification of Control Factors**

After having selected a proper S/N ratio, the next step is to identify the design or control factors and their respective levels. The number of design factors to be selected differs from experiment to experiment, but for an effective application of design of experiment there should be at least six to eight (Taguchi, 1987).

During selection of design or control factors, special attention must be given to possible interactions. Existence of interactions means that the reliability of the experiment result is greatly lowered. Interactions always exist to a greater or lesser degree, but these must be minimized as much as possible. Reduction or even elimination of interactions can be obtained by the proper selection of the control factor levels.

The first thing to consider when choosing the levels, as Taguchi<sup>25</sup> (1987) mentions, "to choose levels so that the range which one wishes to learn about from the experiment will be included in the experiment, and any range which is known not to be actually usable is not included." For example, to identify curvature effects three levels for each control

Problem Type	Range for the Observations	Ideal Value	Adjustment	S/N Ratio and Comments
Smaller-the-better type	$0 \leq y < \infty$	0	None	$\eta = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^n y_i^2 \right]$
Nominal-the-best type	$0 \leq y < \infty$	Nonzero, finite	Scaling	$\eta = 10 \log_{10} \frac{\mu^2}{\sigma^2}$ $\mu = \frac{1}{n} \sum_{i=1}^n y_i$ $\sigma^2 = \frac{1}{n-1} \sum_{i=1}^n (y_i - \mu)^2$
Larger-the-better type	$0 \leq y < \infty$	$\infty$	None	$\eta = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right]$
Signed-target	$-\infty < y < \infty$	Finite, usually 0	Leveling	$\eta = -10 \log_{10} \sigma^2$ $\sigma^2 = \frac{1}{n-1} \sum_{i=1}^n (y_i - \mu)^2$
Fraction defective	$0 \leq p \leq 1$	0	None	$\eta = -10 \log_{10} \left[ \frac{p}{1-p} \right]$
Ordered categorical				Use accumulation analysis. See Section 5.5.
Curve or vector response				Divide the problem into several individual problems of the above types. See Chapter 6.

Figure 24 Taguchi's S/N Ratios  
(Phadke, 1989)

Problem Type	Input Range	Output Range	Ideal Function	Adjustment	S/N Ratio and Comments
Continuous-continuous (C-C)	$-\infty < M < \infty$	$-\infty < y < \infty$ ; $y = 0$ when $M = 0$	$y = M$	Scaling	$\eta = 10 \log_{10} \frac{\beta^2}{\sigma_c^2}$ $\beta = \frac{\sum_{i=1}^m \sum_{j=1}^n (y_{ij} M_i)}{\sum_{i=1}^m \sum_{j=1}^n (M_i^2)}$ $\sigma_c^2 = \frac{1}{(mn-1)} \sum_{i=1}^m \sum_{j=1}^n (y_{ij} - \beta M_i)^2$
Continuous-digital (C-D)	$-\infty < M < \infty$	Binary; ON, OFF			Divide the problem into two separate problems of C-C or nominal-the-best type for the ON and OFF functions. See Chapter 9.
Digital-continuous (D-C)	Binary; 0, 1	$-\infty < y < \infty$			Divide the problem into two nominal-the-best type problems.
Digital-digital (D-D)	Binary; 0, 1	Binary; 0, 1	$y = M$	Leveling	$\eta = 10 \log_{10} \left[ \frac{(1-2p')^2}{p'(1-p')} \right]$ $p' = \left[ 1 + \sqrt{\frac{1-p}{p} \cdot \frac{1-q}{q}} \right]^{-1} =$ <p>equalized error probability</p> <p><math>p</math> = error probability of output being 1 when input is 0</p> <p><math>q</math> = error probability of output being 0 input is 1</p>

Figure 24 Cont. Taguchi's S/N Ratios  
(Phadke, 1989)

factor are selected.

The sliding level technique is a common technique of forming levels of factors by considering interrelations among various factors (Taguchi, 1987; Phadke, 1989). This technique enables one to avoid experiments in an unnecessary range in addition to eliminating interactions.

For example, suppose a mixture of 6 types of substances A, B, C, D, E and F. The levels of B and E depend on the levels of A. The levels of C depend on the levels of B. The levels of D depends on the levels of C and the levels of F depend on the levels of D. Suppose we wish to experiment in the range A1, A2, A3. Then for each level of A it is necessary to decide on the levels of B in which we wish to experiment based on theory or experience. Suppose that if A1 = 10% , A2 = 20%, A3 = 30%, then the levels of B are selected according to the desire knowledge we want to acquired as: for A1=10% 20 - 30% , for A2=20% 15-25% and for A3=30% 10-20%. This process will continue for the rest of the design factors.

#### **5.2.3.6 Construction of the Design and the Noise Matrices**

The next step in the Taguchi method is to construct the design and noise matrices and plan the parameter design experiment. At this stage we have a set of design factors and a set of noise factors. In order to perform the experiments, an

orthogonal array for the design factors and one for the noise factors must be selected. The first step in selecting an orthogonal array is to count the total degrees of freedom (dff). The degrees of freedom are determined as follows: 1) one degree of freedom is associated with the overall mean, 2) the degrees of freedom associated with a n-level factor is (n-1) degrees of freedom, for e.g., a 3-level factor counts for two degrees of freedom, and 3) an interaction between factors A and B counts for (dff A) \* (dff B) (Phadke, 1989).

For example, suppose factors A and B are 2-level factors C, D, and E are 3-level factors and we are interested in the interaction A\*C and D\*E

FACTORS	dff
overall mean	1
A and B	$2(2-1)=2$
C,D,E	$3(3-1)=6$
A*C	$(2-1)(3-1)=2$
D*E	$(3-1)(3-1)=4$
Total	15

The degrees of freedom will tell us the minimum number of experiments to be performed. In this case at least 15 experiments must be conducted to be able to estimate the effect of each factor and the desired interactions.

The number of rows of an orthogonal array represents the number of experiments. For this reason the number of rows must be at least equal to the total degrees of freedom. The number of columns of an orthogonal array represent the maximum number of factors that can be studied. The number of levels of the factors must matched the number of levels of the columns.

Three useful techniques for modifying orthogonal arrays are the dummy level technique, the compound factor method, and the column merging method.

. The dummy level technique allows the assignment of a factor with  $m$  levels to a column that has  $n$  levels, where  $n$  is grater than  $m$ . For example, suppose we have a two level factor  $A$  and we want to assign it to a 3-level column. From the 2 levels of  $A$ :  $A_1$  or  $A_2$  we choose the level we are more interesting in knowing information about it, suppose it is  $A_1$ . Then we just assign to the 3-level column  $A_1$ ,  $A_2$ , and  $A_3$  ( $A_3=A_1$ ).

. The compound factor method allows the study of more factors than the number of columns of the orthogonal array. For example,  $A$  and  $B$  are 2-level factors. We want to assign them to a 3-level factor column. Three levels were chosen as follows:  $(AB)_1 = A_1B_1$ ,  $(AB)_2 = A_1B_2$  and  $(AB)_3 = A_2B_1$ . Then factor  $AB$  can be assigned to the 3 level column. Thus, we are studying the effect of two factors with only one column (Taguchi, 1987).

. The column merging is a technique that creates a new column

by merging two columns and their interaction column. For example, column 1 and 2 are 2-level columns. By merging the two columns and their interaction column we create a 4-level column (Phadke, 1989).

The selection of the orthogonal array and the posterior modifications (if any) depends on the particular problem. Each problem has to be approached separately, and each technique must be applied after a detail study of the experiment requirements has been done.

Once the two matrices are defined, the number of experiments to be run, the different checkpoints, measures, etc. and the S/N ratio to be optimized are set.

#### **5.2.3.7 Parameter Design Experiment and Evaluation of S/N Ratio**

This step consists in conducting a parameter design experiment and evaluating the S/N ratio for each test run of the design matrix.

Let  $x$  = design factors

$w$  = noise factors

$Y$  = quality characteristic

Let  $x = (x_1, x_2, \dots, x_k)$  represent the design factors and  $w = (w_1, w_2, \dots, w_l)$  represent the noise factors included in the experiment. It is assumed that the quality characteristic

Y is a function of x and w;  $Y = f(x,w)$ . Taguchi's parameter design approach is to select the settings of x that maximize the S/N ratio, and then by using factors found to have no influence on the S/N ratio, set the expected value of the quality characteristic to the target value.

For each given x there is a distribution of Y. The expected value and the variance of the quality characteristic at x will be denoted as  $E(Y/x) = m$  and  $Var(Y/x) = E[ (Y/x) - m ]^2$ .

There is a distribution of the loss at Y given x. If the loss function is  $L(Y/x)$ , the expected loss is  $R(x) = E[L(Y/x)]$ . The objective is to find a product design, x, which minimize  $R(x)$  (Pignatiello 1988).

All these factors represent the noise parameter space. The noise factors that produce a variability in the response, will also produce an error of observation. Usually these error are assumed to be normally and independently distributed with mean zero and constant variance  $\sigma^2$ .

It is assumed that the controllable factors can be divided in

$$x = [ x_d \mid x_a \mid x_o ]$$

where

$x_d$  = vector of controllable factors which affect only the S/N ratio

$x_a$  = vector of controllable factors which affect only the  $E(Y)$

$x_0$  = are the remaining controllable factor which affect both  
or neither

The expected value and the variance of the quality characteristic can be expressed  $m(x) = f(x_a, x_0)$  and  $\sigma^2 = g(x_d, x_0)$ . Given the assumption of normality, the estimates of  $m$  and  $\sigma^2$  are  $\bar{y}$  and  $s^2$ . (Hunter 1985)

Given the design matrix  $D$  with  $n_1$  experiments to be run, and the noise matrix  $W$  with  $n_2$  rows, the entire data collection plan can be describe as  $D*W$ . Each product design in  $D$  is tested over each of the noise conditions in  $W$ , thus, the complete design contains  $N=(n_1)(n_2)$  experimental trials.

For each experimental trial we obtain a value of the quality characteristic  $Y$ ,  $y_{ij}$ . Then for each test run  $i$  of the matrix  $D$ , we will obtain  $y_{i1}, y_{i2}, \dots, y_{in_2}$  values of  $Y$ . For each of these test runs, the mean, variance, and S/N ratio are calculated.

The analysis proceeds as follows (Hunter, 1985):

First the S/N ratio is analyzed to determine  $x_d$ . Analysis of variance is carried out to determine those control factors which affect most the S/N ratio. Factors effect can be plotted. The plotting of factors effect is useful when there is more than one characteristic to be optimized. Different levels of the same factor could be optimum for different

characteristics. These plots help to visualize possible trade-offs, and which factor has greater effect on the quality characteristic.

From the  $x_d$  found, those control factors that maximize the S/N ratio are chosen for the design of the new product.

In order to identify the  $x_a$  factors, analysis of  $y$  is carried out. Taguchi calls these factors "adjustment factors", since these factors are going to be set at that levels that force  $E(Y)$  equal the target. ANOVA and plotting are carried out for this purpose. Once these factors are identified, their levels are set such that  $E(Y)$  is as nearest as possible to the target.

Thirdly, factors that affect only  $\sigma^2$  must be determined. Generally are not found. If any are found, they are used to decrease expected loss.

The last step is to identify factors which do not affect  $E(Y)$ , S/N and  $\sigma^2$ . These factors are studied in order to relax their tolerance and to set their levels so a decrement in cost is achieved.

The last step in parameter design is to verify that the optimum conditions suggested by the experiment do indeed give

the projected improvement. Experiments are conducted with optimum parameter settings and comparisons of the S/N obtained with the predicted one are done.

If the S/N ratio observed differs drastically with the one predicted, it is showing evidence of a strong interactions among the parameters. Thus the additive model is inadequate to describe the dependence of the S/N ratio on the various parameters. If this happens, corrective actions include finding a better quality characteristic, S/N ratio, different control factors or studying a few specific interactions among the control factors must be carried out.

#### **5.2.3.8 Tolerance Design**

Tolerance design is the final step in Taguchi's Method of Robust Design. Like tolerance design means spending money buying better grade materials, components, or machinery, tolerance design implies a trade-off between the benefits of the increment of reduction of variation and the increment of manufacturing costs. This study depends on the particular problem, so each problem must be approached using trade-off models created by the designer and use their knowledge to determine which tolerances are worthy of change.

#### **5.2.4 SOME DRAWBACKS OF THE TAGUCHI'S METHODS**

Critics of the Taguchi's Methods have focused on his tactics.

Statisticians such as Box (1988), Hunter (1987) and Leon, Schomaker and Kacker (1987) have criticized the Taguchi's S/N ratio and Taguchi's approach to deal with interactions. It is pointed out that some of these S/N ratios that Taguchi advises to use are not a good option to use in some situations. Hunter (1985) shows that for Latin Square type of design (orthogonal array), the presence of interactions can seriously bias the estimates of the linear and quadratic coefficients in a model as well as the estimate of the error variance. Other criticisms include: the complex ANOVA utilized by Taguchi, Taguchi's failure to take advantage of simple graphics and the large number of significant effects in the absence of data transformation.

But as Nair and Pregibon <sup>26</sup> (Box, 1988) mention, "there is an important lesson to be learned from Taguchi's success. He has identified well-defined classes of engineering problems and has proposed specific steps for solving them. Although Taguchi's recipe for solving the problems can indeed be improved, the salient message here is that we cannot expect to become expert in statistics and select the appropriate techniques to use."

#### **5.2.5 TAGUCHI'S METHODS AND QFD**

QFD is often used with Taguchi's Methods. In the system design QFD can be used to improve the quality and productivity of the

system design stage. QFD identifies the relationships between inputs (what customers want) and outputs (what the product must be in order to address the inputs), and points out conflicting inputs that must be balanced. Taguchi's Methods can be used to define the nature of those relationships and to optimize conflicting inputs.

If QFD is an effort to make sure customer requirements are met, then the loss function quantifies the cost impact of the deviations from those requirements. QFD can help identify key product or process concerns with respect to customer requirements. Taguchi's Methods can help identify what product or process relationships truly exist.

### **5.3 APPENDIX C - DESIGN FOR ASSEMBLY (DFA)**

Design for assembly is a technique which will minimize the total product cost by targeting assembly time, part cost, and the assembly process at the design stage of the product development. The basic philosophy behind DFA is to reduce the number of individual parts and then to ensure that the remaining parts are easy to manufacture and assemble. DFA has several secondary benefits, such as improve reliability and reduction in inventory and production-control costs. (Boothroyd & Dewhurst, 1988; Stoll, 1988)

DFA achieves (Lewis & Connelly, 1990):

- . Reduction of part count, which simplifies manual assembly, improves quality, lowers manufacturing overhead, reduces total material cost, and reduces assembly time.
- . Reduction of labor content, resulting from simplified material handling, and fewer and simpler assembly operations.
- . Shortening of product design time in the long run by fewer parts to design, encouraging simpler design, encouraging standardization when possible, and reducing expensive design changes.

In order to optimize the product's design by means of the application of DFA technique, two main points have to be considered:

- 1) application of design rules and procedures
- 2) usage of data base (or software packages) to calculate early manufacture (or assemble) costs

This section will only study point 1), given that:

- . Actually there is no software available that contains a general data base to calculate early assembly or manufacture cost for a general design.
- . Actual software packages are created for particular processes, e.g. Early Cost Estimation for Injection Molding by Boothroyd Dewhurst Inc.

- . The designer can select the particular software (or create one) for his particular design case, and calculate early cost with it.
- . The design principles can be applied in almost all design cases.

The following topics are going to be discussed in this section:

- 5.3.1 Why assemble?
- 5.3.2 Assembly parts and functions
- 5.3.3 Assembly systems
- 5.3.4 Guidelines for product design
- 5.3.5 Boothroyd Dewhurst DFA approach
- 5.3.6 DFA methodology approach

### **5.3.1 WHY ASSEMBLE?**

When designing a product the best possible design is a product made of only one part. However, as Andreasen (1988 II) states, there is a need to assemble given by the following points:

- 1. Degrees of freedom (movement):** realization of the required function demands certain movements between parts.
- 2. Material differentiation:** the product requires different materials to achieve its function.
- 3. Production considerations:** some systems are easier to

produce if they are divided into subsystems.

**4. Establishment considerations:** the product may be used in a fixed installation and have to be assembled in a separate process.

**5. Differentiation of functions:** the product has different functions.

**6. Particular functional conditions:** the need of maintenance, inspection, etc.

**7. Design considerations:** the product is designed in a particular way to attract customers.

#### **5.3.2 ASSEMBLY PARTS AND FUNCTIONS**

An assemble product generally consists of many parts which are put together in an exact sequence. Before the product is finally assembled, these parts are inspected, painted, reworked, shaped and adjusted. It is important to differentiate between the various objects which make part of the assembly process. For this purpose, Andreasen (1988) makes the following classification:

**machine part:** composed of a single material and is an individual part of the machine or product.

**component:** ranges from a machine part to a combination of parts which are included in the product.

**building block:** a composite part of the product which because of assembly requirements represents a sub-assembly.

**base components:** a (large) component onto which others are assembled.

**formless material:** e.g. viscose components such as glue, paint, liquids.

As Lewis & Connelly<sup>27</sup> (1990) state, "for both manual and automatic assembly, where automatic includes robotics or hard automation, the assembly process can be described as consisting of two separate operations: handling and insertion." They continue to define both, insertion and handling as:

#### **Insertion**

" Insertion involves placing the properly oriented part into the workfixture or partially assembled workpiece. The ease with which a part can be added is affected by factors such as:

- . is force required?
- . do chamfers exist to help align the part?
- . is there obstructed access?
- . can the assembler clearly see the mating location?
- . is holding down required?

#### **Handling**

For manual or automatic assembly, handling involves grasping the part from a bin, kit, or magazine, transporting it to the work area and orienting it to the correct position for

insertion. The following part attributes affect handling time, and can often be controlled in the design: geometry, symmetry; nesting and tangling; thickness; weight; size; flexible, sticky, oily, magnetic"

### **5.3.3 ASSEMBLY SYSTEMS**

Two kinds of situations can appear when DFA is applied:

- . a new product must be designed
- . a product must be redesigned

While the product is in the development stage, the designer needs to consider the assembly process. The various methods of implementing manual, partly or fully automated assembly systems are needed so the assembly process can be analyzed and planned in parallel with the product's design (Bassler & Schmaus, 1988).

Andreasen<sup>28</sup> (1988) states that, "assembly systems can be regarded as being composed of operator/assembler and machine/auxiliary equipment, regardless of the degree of mechanization and automation. An assembly system can be defined as an integrated structure of machines and operators which achieves construction of subsystems or finished products with specific characteristics, using components or if necessary, formless materials (glue, etc.). This integration is achieved by using a process where the necessary operation

are integrated in respect to material, energy and information."

The cost of assembling a product is related to both the design of the product and the assembly method used for its production. The lowest assembly cost can be achieved by designing the product so that it can be economically assembled by the most appropriated assembly method. A very broad spectrum of manual, machinized and automated assembly systems exists in industry today (Andreasen 1988 II):

**Manual assembly:** assembly is carried by an operator with help of auxiliary equipment

**Semi-automatic assembly:** the assembly is carried out by both, an automatic machine system and operators.

**Automatic assembly:** assembly is completely carried out by a machine system which follows a program.

**Flexible assembly:** the assembly system can assemble variants of a product.

**Adaptive assembly:** the system adapts itself automatically to product variations.

Another definition of the different assembly systems is given by Boothroyd and Dewhurst (1989) who defines three basic methods of assembly:

**1) manual assembly**

. bench or transfer-line assembly using only simple tools

## **2) special-purpose transfer machine assembly**

- . assemblies are transferred by an indexing transfer device
- . assemblies are transferred by a free-transfer device

## **3) robot assembly**

- . one general-purpose robot arm operates at a single work station
- . two general-purpose robot arms work hand-in-hand at a single station
- . a multi-station free-transfer machine with general-purpose robot arms

In practice, assembly systems can be a combination of one or more of these methods. Figure 25, shows the arrangement of assembly systems in a table according to complexity and degree of automation.

Boothroyd and Dewhurst (1989) created charts for the determination of the assembly system. These charts facilitate the determination of whether the product under consideration is a candidate for assembly using general-purpose assembly robots, special-purpose assembly equipment or whether it should be assembled manually. Boothroyd and Dewhurst created two charts (these two charts are not included here since they are exclusively work of Dr. Boothroyd and Dr. Dewhurst), one chart for products or assemblies which have only one style and

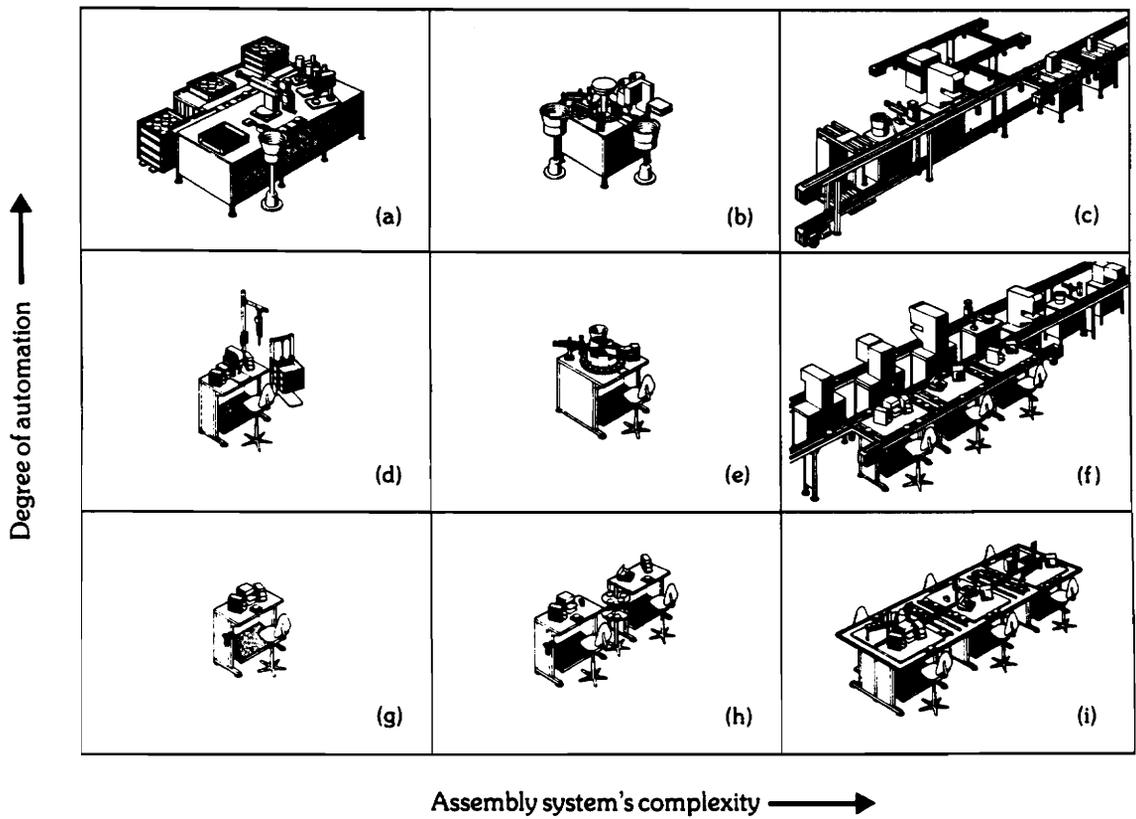


Figure 25

Arrangement of Assembly Systems  
(Andreasen, 1989)

one for products with many styles. Each of these charts are divided into three subcharts, each one representing a different equipment payback periods. The charts relates the annual production volume measured in thousands, the number of parts in the assembly (the average number of parts or subassemblies to be assembled on assembly system), and the total number of parts (the total number of parts or subassemblies form which various product styles can be assembled). A microcomputer program is available to allow the change of labor rates, equipment costs, and production parameters and to obtain detailed results for particular conditions.

#### **5.3.4 GUIDELINES FOR PRODUCT DESIGN**

The importance of these design rules is to make the designer aware of the right procedures for the product's design. This guidelines were obtained from the following references: Andreasen, 1987, 1988 I, 1988 II; Holbrook & Sackett, 1988; Huthwaite, 1990; Lewis & Connelly, 1990; Boothroyd & Dewhurst, 1989; Daetz, 1987.

##### **Minimize the number of parts**

The ideal design would be a one-piece product; however there are five main reasons why components should remain separate:

- 1) parts must move relative to each other
- 2) different materials are required to give different properties
- 3) for maintenance and replacement reasons
- 4) to enable assemble of other parts
- 5) manufacturing process constraints

One way to minimizing part count is to use multifunctional parts: parts that represent the combination of multiple parts or functions into a single part. Advantages Gained:

- . reduces administrative overhead
- . reduces number of vendors
- . simplifies assembly process
- . reduces inventory
- . simplifies factory layout

To know if a part is a candidate for elimination or combination with other parts, the following questions must be answered:

- . is this part required to move relative to all other parts already in the assembly?
- . must this part be made from a different material than all other parts already in the assembly?
- . do other assembly steps prevent this part being combined with another part?
- . will servicing require disassembly of this part from all

other parts in the assembly?

If the answer to each of the questions in NO, then it must be considered the possibility of combination of the function of the part with that of others in the product or eliminating the part altogether.

Some common ways to eliminate parts are:

- . Eliminate labels. Mold in laser or stamp information directly onto parts.
- . Eliminate welding operations. Integration of parts can achieve this point.
- . Use material properties, e.g. elastic properties of plastic can be used to take up tolerances within the assembly.

#### **Component standardization**

Standardize the use of components wherever possible, especially fasteners. These should be suited to the assembly techniques within the company to reduce the design variety placed upon manufacture. Standardize on electrical components, fasteners (if they must be used), materials and finishes.

- Advantages gained:
- . reduces material cost
  - . simplifies vendor selection
  - . reduces need for unique tooling
  - . enables automated assembly

#### **Design for handling**

Design parts that are easy to pick up. The factors that affect

handling are: a) geometry\_ simplify by employing regular shapes. b) stiffness\_ avoid soft or brittle materials  
c) weight\_ avoid heavy components.

### **Facilitate parts handling**

Design features to facilitate parts handling for automatic and hand operations. Parts should be designed so that they do not become tangled, stuck together, or require special handling prior to assembly. Flexible parts such as those with wiring or cables should also be avoided because they complicate automated assembly. When possible, parts should retain the same orientation from the point of manufacture to assemble.

Advantages gained:

- . enables automatic assembly
- . enables bowl and other automatic feeding techniques
- . simplifies assembly processes
- . reduces tangling and nesting
- . reduces assembly time

### **Design for insertion**

Provide chamfers and other location features; ensure product performance is not affected detrimentally. Enlarge clearances where possible for easier insertion.

### **Directions of insertion**

Design a product for minimum directions of insertion. This reduces the need to re-orientate a product during assembly.

### **Provide nesting features**

Parts should be designed with built-in self-locking features.

Parts that nest need no repositioning and can be held in place without additional clamping. Surface features should be added so that parts stay in place after initial assembly.

#### **Design parts with self-locating features**

Self-locating features on parts enable the assembly themselves and subsequent parts or modules to a precise location without adjustment. Advantages gained:

- . reduces assembly tooling
- . reduces operator training
- . simplifies assembly
- . reduces lifetime product cost
- . improves quality

#### **Design parts with self-fastening features**

Include features in each part that fastens it in the assembly without the use of discrete fasteners. Advantages gained:

- . encourages fixture-less assembly
- . reduces servicing cost
- . helps eliminate assembly adjustments
- . enables automatic assembly
- . reduces discrete hardware
- . improves quality
- . reduces assembly time

#### **Design parts to be self locating and aligning**

Parts should be designed so that mating surfaces fall into place. 1. Ensure that parts which are not self-securing are nevertheless fully located immediately on assembly. This avoids the need for holding-down which constrains subsequent

operations to be carried out with only one hand. 2. Provide parts with leads, lips, tapers, chambers, etc. so that alignment is built into the design. 3. Allow generous clearances if permissible in the design but avoid situations which may result in a tendency for parts to jam or hang-up during insertion. 4. Ensure that parts are located in the assembly before they must be released.

#### **Eliminate assembly adjustments**

Assemble modules or parts with no adjustments to achieve necessary system functions. Advantages gained:

- . reduces final assembly and testing operations
- . improves quality
- . reduces assembly time
- . reduces handling
- . reduces tools and fixtures

#### **Design parts that cannot be installed incorrectly**

Eliminate situations where a part can be installed in orientations which would not permit correct operation of the product. 1) provide obstructions that will not permit incorrect assembly. 2) make parts symmetrical so that assembly orientation is unimportant. 3) mark parts with the correct orientation.

#### **Design for orientation**

Design parts that can be oriented rapidly. This can be achieved by making parts completely symmetrical. If total symmetry is not possible, then design for obvious asymmetry to

avoid confusion.

In a product there are two types of symmetry: alpha and beta symmetry (Figure 26). Alpha symmetry is the rotational symmetry of a part about an axis perpendicular to the axis of insertion. Is the smallest number of degrees the part must be turned in order to repeat its orientation. Beta symmetry is the rotational symmetry of a part about its axis of insertion, or equivalent about an axis which is perpendicular to the surface on which the part is placed during assembly. The magnitude of rotationally symmetry is the smallest angle through which the part can be rotated and repeat its orientation. For a cylinder inserted into a circular hole, beta = 0. For a square sectioned part inserted into a square hole, beta = 90. In designing a product (  $\alpha + \beta$  ) must be minimized, since the larger this sum is the longer time for insertion and handling will require.

#### **Eliminate re-orientation**

A reorientation of the work-piece is required when there are multiple assembly processing surfaces. Advantages gained:

- . reduces assembly time
- . facilitates automatic assembly
- . simplifies assembly process

#### **Choose simple patterns of movement**

Uncomposed linear movements. One should avoid movements invarious directions and curved movements.

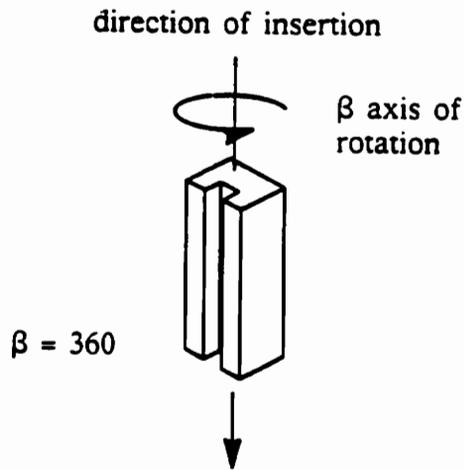
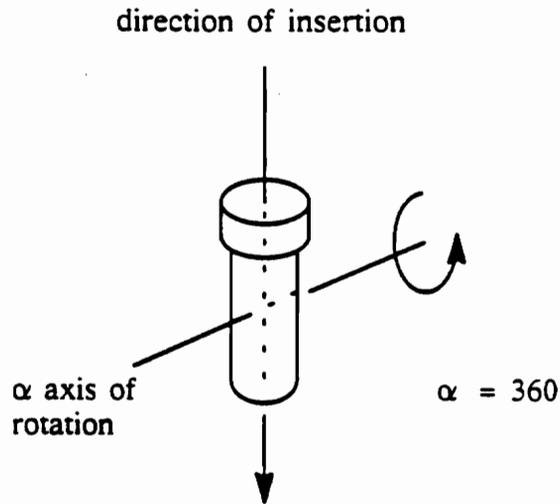


Figure 26      Alpha & Beta Symmetry  
(Lewis, 1990)

### **Design for stability**

Design parts for stability during assembly, this ensures time is not wasted in supporting sub-assemblies which tend to roll over. Provide features that enable parts to rest firmly in the correct orientation for assembly.

### **Weight reduction**

Minimize product weight, this helps to reduce component handling and insertion times.

### **Encourage modular assembly**

A module is a separate, self-contained unit or assembly with a defined set of inputs and outputs to monitor it's performance. The advantages gained are:

- . reduces final assembly time
- . simplifies inventory
- . simplifies build-to-order
- . facilitates automatic assembly
- . reduces post-assembly adjustments
- . improves serviceability

### **Design good basis components**

The base component is the first component to appear in the assembly process and onto/into which, the additional components are assembled. By doing so, a good basis for transport, fixing and force effects in joining process is achieved.

### **Construct the product on building blocks**

A building box system is a system of product which are

structured in such a way that all products can be constructed of a number of building stones. The building stone is a large, independent structured part of a product, which is a functional unit with simple relations to the rest of the product. By constructing the product on building blocks, parallel assembly can be applied and flexible assembly planning can be achieved.

#### **Sub-assembly grouping**

Where possible, components should be grouped into sub-assemblies. This provides greater flexibility in assembly scheduling.

#### **Stack assemblies**

Stackable assembly means building from the bottom up, where subsequent parts locate onto the previously assembled part.

Advantages gained:

- . promotes fixture-less assembly
- . enables automatic assembly
- . simplifies orientation
- . reduces reorientations
- . improves quality
- . helps prevent post-assembly adjustment

#### **Design a base component**

By base component is meant a larger component which comfortably allows itself to be transported from station to station.

\_ that the base component has many assembly surfaces common to

the other components

- \_ that the largest number of joinings possible can be conducted directly
- \_ that suitable attachment and support surface are available
- \_ that joining movements shall only be vertical or horizontal
- \_ that it is not necessary to turn the base component on the way

### **Eliminate cables**

Whenever possible use a direct connection between electrical assemblies. Advantages gained:

- . reduces cost significantly
- . improves quality
- . improves serviceability
- . enables automatic assembly
- . improves customer satisfaction

### **Minimize levels of assembly**

Each level of sub-assemblies that is introduced negatively impacts the assembly process. Advantages gained:

- . simplifies specification and paperwork
- . facilitates assembly process
- . simplifies factory layout

### **Reduce, simplify, and optimize manufacturing processes**

The number of manufacturing processes needed to assemble a product should be kept to a minimum. Processes that are difficult to control, such as welding, brazing, and those that require separate materials, should be eliminated. Similar operations should be done at the same time in the assembly

sequence.

**Work on a minimum number of surfaces**

A design requiring unnecessary assembly operations on more than one surface wastes motion and time. This is particularly true when all tasks on one surface are not completed at the same time.

**Assemble in the open**

Assembly operation should be carried out in clear view. This is important for manual assembly and, in most cases, essential for automated assembly.

**Do not fight gravity**

When laying out new designs, keep the manufacturing process in mind. Design products so that they can be assembled from the bottom up, in the Z-axis. This allows simple robots and insertion tools to use gravity to assist in the assembly process.

**Make merging unambiguous**

Avoid situations where various components or various details of one component must be placed simultaneously.

**Consider access and visibility for each operation**

Inadequate access or restricted vision can make a seemingly simple operation both time consuming and frustrating.

1. Ensure adequate clearance for hands, tools, testing and any subsequent processes such as welding or riveting.
2. Ensure that the assembly worker's vision of each operation is not restricted.

## **Design clearly**

This must be done so that the production and assembly processes can be clearly executed and eventual adjustments do not work against each other.

Boothroyd & Dewhurst<sup>29</sup> (1989) state that, " the important rules for design for automatic assembly differ from those for manual assembly. For manual assembly, assembly problems are most often associated with part insertion and securing operations. For automatic assembly, automatic handling of the parts is the principal concerns. Automation of the handling process is usually the most demanding part of an assembly automation task and the cost of automatic handling can change dramatically through small changes in part design."

The following rules were obtained from Boothroyd & Dewhurst (1989) :

- . Ensure that parts can be easily separated from bulk and conveyed along the track of a vibratory or hopper feeder. To achieve this avoid parts which are: nest or tangle in bulk, are flexible, are delicate or fragile, are sticky or magnetic, are smaller than 3 mm in the largest dimension.
- . Ensure that parts can be readily oriented in high speed feeding devices.
- . Make parts as symmetrical as possible, this will allow automatic orientation easier.

- . For non-symmetrical parts, ensure that the part features are not just slightly asymmetric.
- . For non-symmetrical parts, ensure that the asymmetry is not due to non-geometric features such as differences in surface coatings, lettering, differences in surface finish, etc.
- . For non-rotational parts, ensure that the three principal dimensions differ from each other by at least 10 percent.

All the previous rules can be applied to automatic insertion and robot assembly, but there are special assembly rules applicable to automatic insertion and robot assembly (Boothroyd & Dewhurst, 1989).

#### **5.3.4.1 Rules for automatic insertion**

- . Avoid the need for reorientation during assembly.
- . Ensure that parts, which are not secured immediately on insertion, are fully located and do not need to be held in place for transfer to the next workstation.
- . Include features such as leads, lips, tapers, chamfers, etc. in the design to ensure that parts are easy to align.
- . Avoid the need for high insertion forces.

#### **5.3.4.2 Rules for design for robot assembly**

In designing for robot assembly it is critically important to address the need for special-purpose tooling and equipment in

the assembly process.

- . Design parts so that they can all be gripped and inserted using the same robot gripper.
- . Design products so that they can be assembled in layer fashion from directly above.
- . Design parts which can be easily handled from bulk.
- . If parts are to be presented using automatic feeders, then ensure that they can be oriented using simple tooling.
- . If parts are to be presented in magazines or part trays, then ensure that they have a stable resting aspect from which they can be gripped and inserted without any manipulation by the robot.

#### **5.3.5 BOOTHROYD DEWHURST DFA APPROACH**

The Boothroyd Dewhurst DFA (B&D DFA) approach suggests that the best way to achieve assembly cost reduction is first to reduce the number of components that must be assembled and then to ensure that the remaining components are easy to assemble. The basic principle for component reduction is that combining two components into one will eliminate at least one operation in manual assembly, or an entire section of an assembly machine. The stages in the B&D DFA analysis are shown in Figure 27.

The first step in B&D DFA analysis is the selection of the

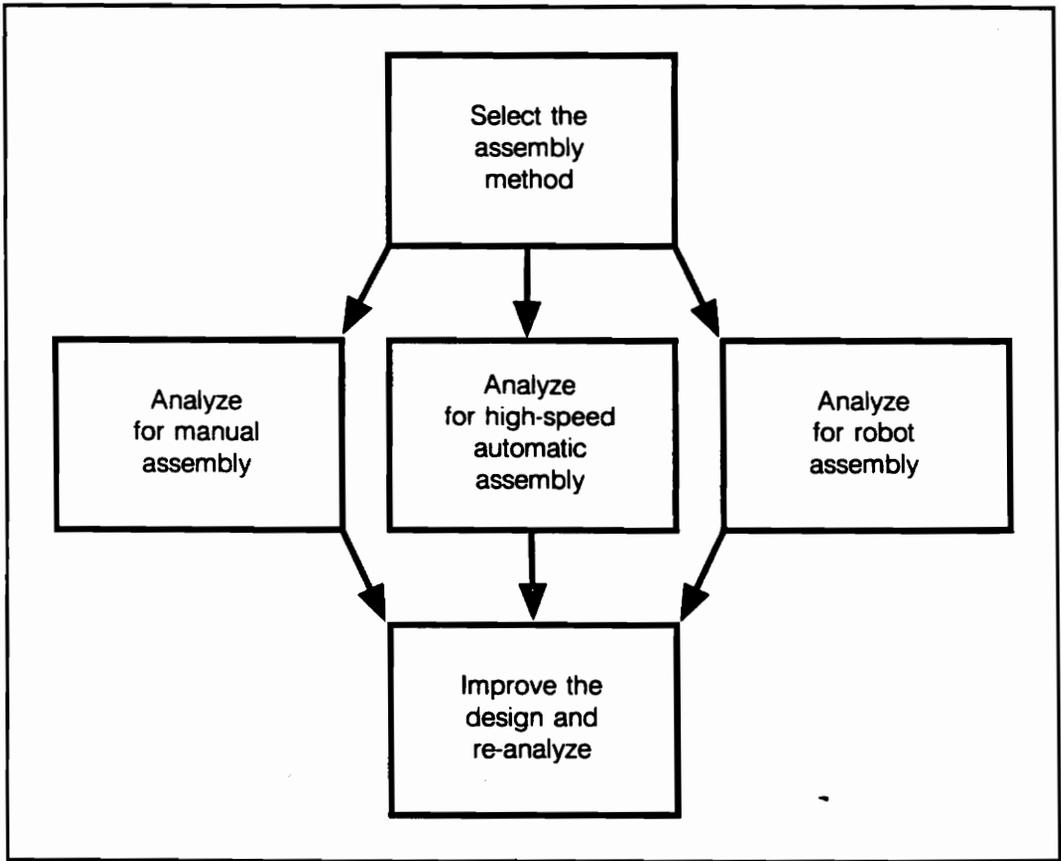


Figure 27 Boothroyd & Dewhurst DFA Stages  
(Boothroyd & Dewhurst, 1989)

appropriate assembly method. They separate the assembly systems into three main areas: manual, high-speed automatic and robot assembly. In their DFA Handbook they provide charts in order to select the appropriate assembly system.

After system selection, B&D divided the study into:

6.6.1 Design for manual assembly

6.6.2 Design for high-speed automatic assembly

6.6.3 Design for robot assembly

#### **5.3.5.1 Design For Manual Assembly**

As Boothroyd & Dewhurst<sup>30</sup> (1989) explain in their handbook, "the technique involves two important steps for each part in the assembly:

- 1) a decision as to whether the part can be considered a candidate for elimination or combination with other parts in the assembly
- 2) an estimation of the time taken to grasp, manipulate and insert the part"

For the identification of those components that are candidates for elimination or combination, Boothroyd and Dewhurst (1989) developed three simple questions.

- 1) During operation of the product, does the part move relative to all other parts already assembled? Only gross motion should be considered - small motions that can be

accommodate by elastic hinges, for example, are not sufficient for a positive answer.

2) Must the part be of a different material or be isolated from all other parts already assembled? Only fundamental reasons concerned with material properties are accepted.

3) Must the part be separate from all other parts already assembled because otherwise necessary assembly or disassembly of other parts would be impossible?.

Boothroyd and Dewhurst (1989) separate the analysis into the following steps.

Step 1 Obtain as much information as possible about the product or assembly.

Step 2 Start disassembling the product or imagine how it is done. Assign an identification number to each part or subassembly that is removed.

Step 3 Begin re-assembling the product. First assemble the part with the highest identification number.

Beginning at this step, B & D start using a worksheet (Figure 28) which includes the following information: part identification, handling time for each part, insertion time for each part, cost for each operation and the theoretical minimum number of parts for the assembly. Before each part is re-assembled, the need for each part as a separate part is tested by the application of the three questions given in page



160. If any answer is yes then the part is a candidate for elimination.

For the calculation of the handling and insertion times the B&D DFA Handbook is needed. Without the handbook, the quantification of the benefits to be obtained from the analysis cannot be calculate, but by following the different design steps these benefits will be as equally obtained.

Step 4. The calculated assembly time is summed up and a manual design assembly coefficient is calculated:

$$EM = 3 * NM / TM$$

where: EM = manual design efficiency

NM = theoretical minimum number of parts

TM = total manual assembly time

The assembly coefficient compares the assembly time of the product before any modification and the time needed to assemble the theoretical minimum number of parts, assuming for each of these parts an assembly time of 3 seconds.

Figure 29, shows an assembly with three possible design modifications that can be achieved by the application of DFA to design (a).

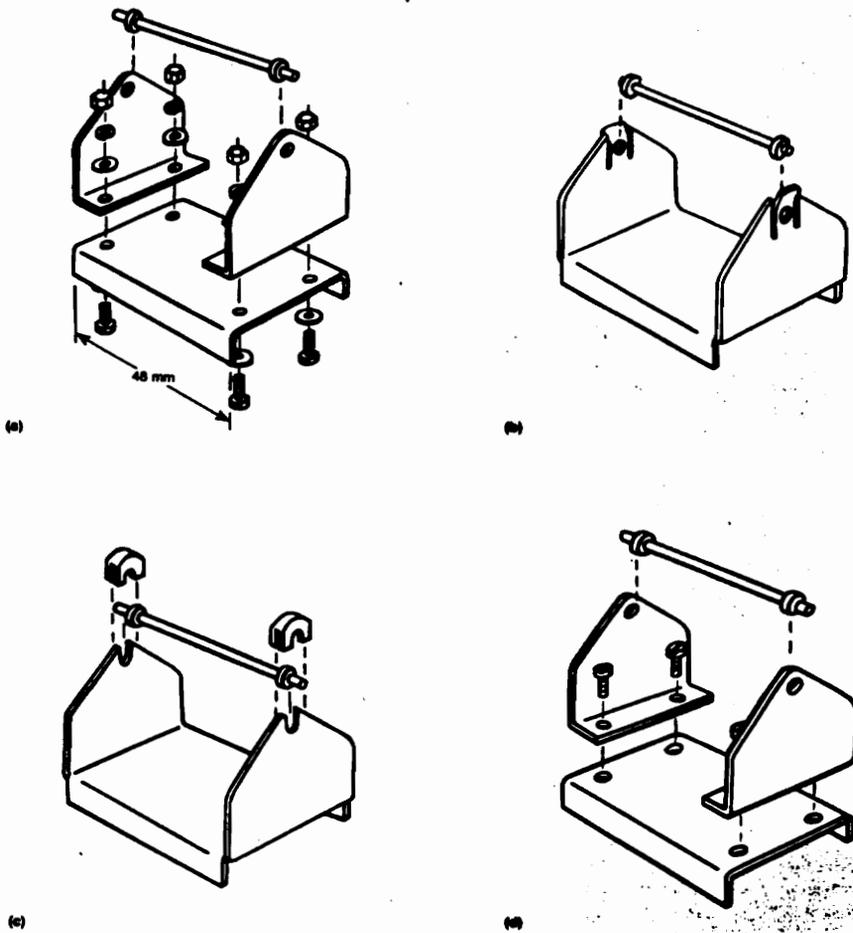


Figure 1. An assembly consisting of four major components and twenty fasteners (a). The ideal redesign (b) has two parts that snap together. In an alternative, four-part design (c), the spindle is held by plastic snap retainers. Even if the sheet-metal components remain separate, the number of fasteners can be reduced to four (d).

Figure 29 Assembly Simplification  
 (Boothroyd & Dewhurst, 1988)

### **5.3.5.2 Design For High-Speed Automatic Assembly**

The B&D design for high-speed automatic assembly basically has two purposes: estimate the full cost of automation, and identify areas for possible improvement through re-design. Boothroyd & Dewhurst<sup>31</sup> (1989) explains, "the method involves three important steps in the consideration of each part in the assembly: 1) an estimate of the cost of handling the part automatically in bulk and delivering it in the correct orientation for insertion on an automatic assembly machine 2) an estimate of the cost of inserting the part automatically into the assembly and the cost of any extra operations 3) a decision as to whether each part must be separate from all other parts in the assembly"

B & D provide a worksheet (see Fig.30) to conduct the analysis and a set of charts to calculate the relative feeder cost CR. The CR depends on the maximum feed rate, required feed rate, feeding and orienting efficiency, partial relative feeder cost and maximum dimensions of the part. The feeding and orienting efficiency and the partial relative feeder cost are obtained by the charts given in the B&D DFA handbook. The automatic assembly worksheet is presented in a similar form to the manual assembly worksheet. The procedure for redesigning the product for automatic assembly is similar to manual assembly. The only thing that changes are the charts used to calculate times and the costs.



In many circumstances the elimination of parts cannot be achieved because of other constraints, such as the economics of manufacture, the unavailability of the specialized equipment that might be needed to manufacture the combined parts.

#### **5.3.5.3 Design For Robot Assembly**

Boothroyd & Dewhurst<sup>32</sup> (1989) state that, "the basic procedure in this product or assembly analysis technique is to estimate the assembly cost using the most appropriate robot assembly system. In order to determine assembly costs, it is necessary to obtain estimates of the following:

- 1) the total cost of all the general-purpose equipment used in the system, including the cost of robots and any transfer devices and versatile grippers
- 2) the total cost of all the special-purpose equipment and tooling
- 3) the average assembly cycle time
- 4) the cost per assembly of the manual labor involved in machine supervision, loading feeders, etc."

#### **5.3.6 DFA METHODOLOGY APPROACH**

The different steps to approach the DFA technique are (Lewis & Connelly, 1990): . Develop a Multi-Functional Team. This team must support a creative climate.

. Establish product goals through a benchmarking process or by

creating a model.

- . Perform a Design for Assembly analysis of the product.
- . Segment the product into manageable modules or levels of assembly.
- . Apply Design for Assembly principles to these assembly modules.
- . Apply creativity tools such as brainstorming techniques to identify further design improvements.
- . Make material selections. Start early supplier involvement process to ensure economical production.
- . With the aid of cost models or competitive benchmarking, establish a target cost for every part in the new design.
- . Start the detailed design of the emerging product. Model, test & and evaluate the new design for fit, form and function.

#### **5.3.7 DFA, QFD AND TAGUCHI'S METHODS**

After the application of DFA, Taguchi's Methods can be applied in order to make the product robust. The application of the two techniques will optimize the product's design since the application of DFA achieves a simplified product in parts and materials, giving rise to a higher product reliability and maintainability. Additionally, applying the Taguchi Methods results of a reduction in the variability of the product's principal functions. Hence, the two techniques are compatible, and their simultaneous application will bring large savings,

among other benefits, to the product's life-cycle cost.

DFA can also be applied in conjunction with QFD. Given that with the application of QFD, the manufacturer tries to incorporate the customers requirements in the product, DFA is good for making the product as simple as possible, thus assuring that those requirements are fulfilled in the product's design.

#### **5.4 APPENDIX D - ACTIVITY-BASED COSTING**

This section of the project investigates deficiencies of today's costing systems and introduces activity based costing. The following topics are going to be studied:

- 5.4.1 Traditional Cost System
- 5.4.2 Introduction to Activity-Based Costing
- 5.4.3 Fixed VS. Variable Costs
- 5.4.4 Activity-Based Costing System Design
- 5.4.5 Operational Control (Performance Measurements)
- 5.4.6 Activity-Based Costing and Design
- 5.4.7 Activity-Based Costing and Life-cycle Cost

##### **5.4.1 TRADITIONAL COST SYSTEM**

As Berliner & Brimson<sup>33</sup> (1988) have observed, "management can

no longer accept an environment where cost accounting contributes to overhead costs rates so high as to obscure true product cost, where the impact of WIP on product cost is hidden in numerous cost categories and where other accounting practices hinder manufacturing."

In the past years, as Kaplan (1988) mentions, cost system designers have not realized the three different functions a cost system must address: individual product cost, operational control, and inventory valuation. It is a usual procedure that firms use only one cost system to collect and allocate costs to fulfill these three functions. What they have not realized is that the cost system that they are using seems to be designed primarily to perform inventory valuation and depreciation accounting. These cost systems have serious deficiencies to fulfill the other two functions; since, for operational control the data collected is too delayed and too aggregated, and for product costing is too aggregated.

An analysis of how product cost, operational control and inventory valuation is carried out with the traditional cost systems follows.

#### **5.4.1.1 Product Cost**

The current cost systems are built around standard labor times (originated during scientific management movement (Kaplan,

1990)). The definition of standard time is: is a unit-time value for the accomplishment of a work task as determined by the proper application of the appropriate work measurement techniques. For the general case, Berliner & Brimson<sup>34</sup> (1988) explain, "standards are predetermined measures that relate resources or costs to products, organizational units, or other cost objectives. Each standard is designed to yield a benchmark, a point of reference of measuring performance that reflects the expected relations between cost and objectives." In the case of a product's part, the standard time for each part is the sum of the theoretical times for each of the manufacturing operations required to produce the part (O'Guin, 1990).

These current cost systems, or traditional standard cost systems in manufacturing companies are designed to value inventory, but not to measure product costs accurately (Kaplan, 1988) (Inventory valuation is the monetary measurement of inventory quantities using specific unit costs. The most common approach is to establish a beginning inventory balance, and to accumulate the cost incurred in work-in-process to arrive to an ending inventory valuation and cost-of-sales (Berliner & Brimson, 1988)). This inaccuracy is due, in part, to the fact that the standard time does not contain purchasing, receiving, inspection or any of the overhead activities required. Thus, the standard cost used to calculate

product cost usually bear no relation to the resources consumed to design, produce, market, and deliver the product.

Another deficiency of the traditional cost systems is that products usually are costed by using a two-stage cost allocation system ( see Figure 31 ). In the first stage, costs are allocated to cost centers (this allocation is made even when the center has little or no control over those costs allocated to it). During this stage a great number of different allocation bases are used. This practice (of allocating cost to cost centers) evolved in order to value inventory, all factory costs must be allocated to products.

In the second stage of allocation, costs are allocated from the cost centers to the products. Despite the use of a great number of different allocation bases in the first stage, conventional cost systems use at most three second-stage allocation bases: direct labor hours, machine hours and material dollars (all of these three bases are volume-related).

Using volume-related allocation bases alone to trace costs to products during the second stage of allocation distorts reported product costs if some of the product-related activities are unrelated to volume. As Miller and Vollmann<sup>35</sup> (1985) stated, "existing cost accounting systems concentrate

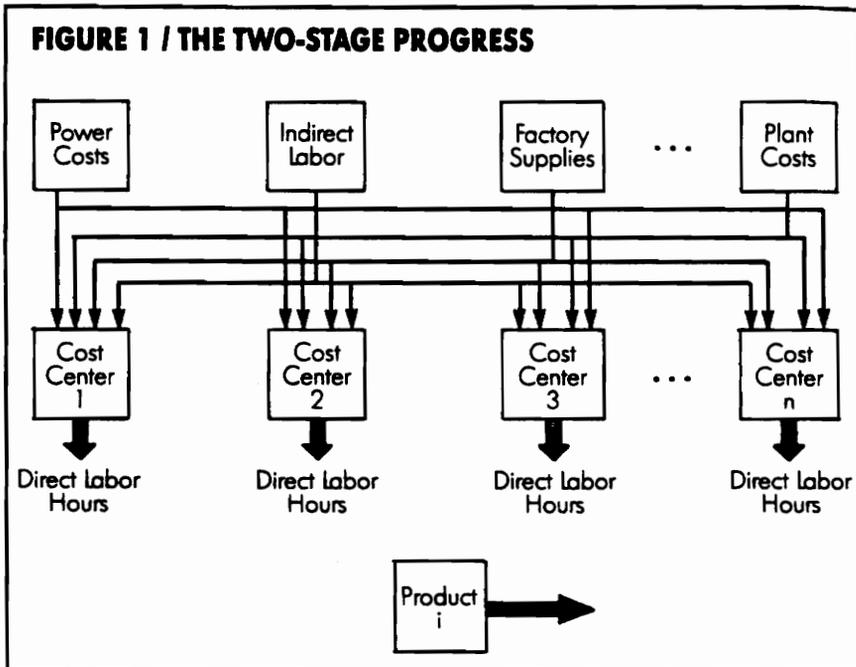


Figure 31 Two-Stage Progress  
(Bruns & Kaplan, 1987)

on direct labor and materials and hide the costs of overhead departments by simplistic allocations based on labor or materials." Cooper<sup>36</sup> (1988 a) clarifies this point remarking, "when the quantity of volume-related input that a product consumes does not vary in direct proportion to the quantity of volume-unrelated input consumed, volume-base cost systems will report distorted product costs."

The traditional cost systems may report accurate product costs where overhead activity is consumed in relation to production volume, but they fail to trace volume-unrelated activities. The result is that one product picks-up costs that belongs to another (Turney, 1989).

A volume-based cost system is what is in essence the traditional cost system. This system, generally, can not differentiate adequately between overhead consumed by high- and low-production volume products. The volume-based cost system will report accurate product costs if the ratio of items in the largest to the smallest batches is relatively small (say 5:1). But, as this ratio increases, the product cost becomes highly distorted (Cooper, 1988 b).

#### **5.4.1.2 Operational Control**

With respect to operational control as it relates to measuring cost performance, the traditional practice is to compare

actual to allowed expense using standard cost. The purpose of this comparison is to generate a variance. This variance is usually calculated at the production shop or factory level and it indicates only if the production shop is doing well or is doing poorly, but it does not reveal the source of the problem. The calculation of the variance does not give any indication to the engineer what products and batches caused the results; favorable or unfavorable (Koons, 1990).

An extra deficiency of traditional costing, with respect to operational control, is its frequency of reporting costs. As Kaplan<sup>37</sup> (1989) mentions, "U.S. managers increasingly began to run their companies "by the numbers". Annual budgeting processes emphasize performance in financial accounting terms—increased earnings per share and return of investment. The annual financial targets are further decomposed into monthly budgets, with monthly income expenses statements becoming the main instruments for motivation and control." Obviously, there is almost no use in receiving information every 22 or more days after the fact in order to control production. For example, it is not much help to get monthly cost reports for an operation that turns out many parts per second.

Finally, the allocation of overhead to products and departments, or to the computation of volume variances should not be part of a the operational control system because these

allocations hide the real information needed by the cost center managers to operate effectively.

#### **5.4.1.3 Inventory Valuation**

The traditional cost system seemed to be designed for this purpose, thus it does a good job valuating inventory.

#### **5.4.2 INTRODUCTION TO ACTIVITY-BASED COSTING**

The distortions in product cost can arise from a number of reasons, including the following:

- \_ production volume diversity
- \_ complexity diversity
- \_ size diversity
- \_ material diversity
- \_ setup diversity

The traditional volume-based cost system ignores these diversities when calculating product cost, consequently it reports distorted product cost. For this reason, a new cost system is becoming popular "activity-base costing or ABC", which traces costs to products according to the activities performed on them (Cooper, 1988 a).

For example, suppose two different products ( D , C ) require different levels of attention from engineering. Product C uses

a lot of direct labor. Product D is a new product designed to require very little direct labor. Product D still has production and quality problems that require a number of engineering changes. Traditional product costing allocates engineering costs using a volume-related allocation base such as direct-labor hours. Using this allocation approach, an equal amount of engineering cost is allocated to each direct labor hour. Thus, product C incorrectly picks up most of the engineering cost. In contrast, ABC traces cost of engineering change activities to the product (primarily D) that receives the benefit of this activity (Turney, 1989).

A basic assumption that establishes the philosophy by which ABC operates is that activities consume resources and products consume activities. For example, a product must be purchased. Purchasing is an activity. The product consumes the activity "purchasing". In order to purchase the product money, operator's time, etc. is needed. Thus, the activity "purchasing" needs resources in order to fulfill its purpose.

A more comprehensive definition of activities is the following:

- . A group of activities having a common objective within the business is called a function.

- . Functions can be decomposed into processes that represent the ongoing sets of activities.

. Activities are those actions needed to achieve the goals and objectives of the function. Activities are procedures or processes that cause work. These activities consume resources that are recorded as costs in the accounts. Activities can be decomposed into tasks, subtasks, and operations (Berliner & Brimson, 1988).

E.g. Function	purchasing
Activity	purchase machine
Task	write an order

Previous to defining ABC, it is necessary to define three common terminologies used in activity-based costing:

- . cost drivers
- . cost center
- . transaction

**cost driver** A driver is an activity or condition that has a direct influence on the operational performance and cost structure of an activity. Its occurrence creates cost. For example, number of set-ups, number of customers orders, quantity of material ordered, number of inspections, etc. are cost drivers. (Berliner & Brimson, 1988)

**cost center** The smallest unit of an organization from which budgeted or actual costs are collected and which has some common characteristics for measuring performance and assigning

responsibility. Another definition can be, an activity center is a segment of the production process for which management wants to report the cost of the activities performed separately. For example, the receiving department might be treated as the activity center "receiving". A cost center can consist of one or more work centers, work cells or workstations. (Berliner & Brimson, 1988; Cooper, 1989 d)

**transactions** Are physical (including electronic) documents associated with activities that impact information. For example, the order to purchase material is a transaction.

Transactions involving exchange of materials or exchange of information are the primary cost drivers for manufacturing overhead. Miller and Vollmann (Johnson & Kaplan, 1987) define four types of transactions that drive overhead cost:

- . logistical transactions: to order, execute and confirm material movements.

- . balancing transactions: to match the supply of material, labor and machines with demand.

- . quality transactions: to validate that production is in conformance with specifications.

- . change transactions: to update manufacturing information.

All factory personnel who are associated with activities related to any of the transactions categories previously

defined, perform the respective cost in that transaction category. In summary, a great deal of the manufacturing overhead is generated from the execution of transactions associated with the start or finish of production. For example, these transactions can be placing and paying for orders, receiving and inspecting purchased materials, setting up machines, moving inventory, etc.(Kaplan, 1988).

Given the previous definitions, activity-base costing can now be defined as,

"Activity-base costing is an information system that maintains and processes data on a firm's activities and products. It identifies the activities performed, it traces cost to these activities, and then uses various cost drivers to trace the cost of activities to the products. These cost drivers reflect the consumption of activities by the products. An activity-based costing system is used by management for a variety of purposes relating to both activities and products"

(Turney, 1990)<sup>38</sup>.

#### **5.4.3 FIXED VS. VARIABLE COSTS**

Disagreement exists concerning whether product costs should be measured by full or by variable cost. In a full or absorption cost system, all costs of production, both direct and

indirect, fixed and variable are allocated to the product. In a variable or direct cost system, only the variable costs of manufacturing are allocated to the product. In addition, fixed manufacturing overhead costs are not considered to be part of the manufacturing overhead rate; rather, they are considered with all non-manufacturing expenses (Heitger & Matulich, 1985).

The definition of variable cost used by academic accountants assumes that product decisions have a short-time horizon (the time period corresponding to the cycle of the firm's internal financial reporting system), typically a month or a quarter. This short-term focus for product costing has led almost all companies to view most of their manufacturing costs as fixed. However, these so called "fixed costs" are the most variable and rapidly increasing manufacturing costs. (Bruns & Kaplan, 1987).

The common scenario of the organizations in the past was that the different products did not demand a wide variety of requirements from the resources of production and marketing. But these conditions are no longer typical for many of today's organizations. Overhead is becoming a larger share of total manufacturing costs, and the production of diverse products cause quite different demands on equipment and support departments.

As Kaplan<sup>39</sup> (1988) states, "a company should base most of its important product decisions on estimates of the long-run, variable costs of individual products. Whether costs are fixed or variable, depends on the viewer's time horizon. In the short run virtually all costs are fixed... Over a long period, however, cost becomes variable... Product decisions have long-term consequences for the organization. Executives should therefore consider virtually all costs to be variable when measuring product costs."

Given this reality, ABC systems assume that almost all indirect and support costs are variable. Many indirect costs will not vary month to month with changes in the volume and/or mix of monthly production; that is, they appear to be fixed costs. However, these costs become variable each year (Kaplan, 1989).

#### **5.4.4 ACTIVITY-BASE COSTING SYSTEM DESIGN**

As Cooper (1990) specifies, five design steps should be taken in creating an ABC system:

- 5.4.4.1 aggregate actions into activities
- 5.4.4.2 report the cost of activities
- 5.4.4.3 identify activity centers
- 5.4.4.4 select first-stage cost drivers
- 5.4.4.5 select second-stage cost drivers

#### **5.4.4.1 Aggregate Actions Into Activities**

In a typical organization there are so many actions performed that it is economically unfeasible to use a different cost driver for each action. Therefore, many actions must be aggregated into each activity. This activity cost which is a summation of different actions costs is traced to the product by the application of a single driver. As more and more actions are aggregated into that activity, the ability of a single cost driver to accurately trace the resources consumed by products decreases.

#### **5.4.4.2 Report the Cost of Activities**

The next issue is the level of aggregation used in reporting the resources that each activity consumes. For example, the system might report set-up costs for a product including in the cost both set-up and material movement costs. Alternatively, the system might break the cost down and report a machine set-up cost and a material movement cost.

#### **5.4.4.3 Identify Activity Centers**

As Berliner & Brimson<sup>40</sup> (1988) explain, "cost centers should be established for organizational units and should consist of resources dedicated to similar activities... Cost center definition should use the following guidelines: segregate different processes... aggregate families of similar machines...isolate individual machines...base cost centers on

group technology...aggregate cost having drivers that move in the same relative proportion."

#### **5.4.4.4 Select First-Stage Cost Drivers**

The first stage allocates the costs into cost pools in each activity center. Each cost pool represents an activity performed in that center (Cooper, 1990). Generally, many different allocation bases are used in this first stage to allocate costs from plant overhead to cost centers.

#### **5.4.4.5 Select Second-Stage Cost Drivers**

From these five design steps, the one that distinguishes the ABC from traditional costs systems is this one. Selecting cost drivers calls for two separate but interrelated decisions:

1. how many cost drivers should be used
2. which cost drivers should be used

The type of cost drivers selected affects the number of drivers needed to achieve a desired level of accuracy.

Number of cost drivers required (Cooper, 1989 c):

The minimum number of cost drivers that an ABC system uses depends on: a) the desired accuracy of product costs

As the number of cost drivers increases, the accuracy of product cost also increases. b) the complexity of the product mix. Whether the costs of two activities can/cannot be aggregated and traced by means of a single cost driver.

Three factors determine if a single driver is acceptable

5.4.4.5.a product diversity

5.4.4.5.b the relative costs of the activities aggregated

5.4.4.5.c batch-size diversity

5.4.4.5.a Product diversity

Products are said to be diverse when the patterns of resources they consume are different. For example, two products are considered diverse if one of the products requires five inspection hours per 100 direct labor hours and the other product consumes only one inspection hour per 100 direct labor hours.

The degree of diversity between any two products with respect to two activities can be measured by:

1. calculating the ratio of the two activities consumed by each product.

e.g. Product A Inspection hrs/machine hrs

Product B Inspection hrs/machine hrs

2. dividing the higher ratio by the lower to measure the degree of diversity. For example,

product	batch-size per hour	machine/unit first unit	cost of activity	inspection hrs for
A	50	1 hr	1	10
B	50	1 hr	1	5

step 1\_ Product A = 10/50

Product B = 5/50

step 2\_ degree of diversity =  $(10/50)/(5/50) = 2$

Suppose machine hours is used as a cost driver to allocate inspection cost to product A and B

Inspect hrs allocated to            =            10 + 5            =    7.5 hrs  
each batch of both A and B            50 + 50

Now, product A, the high consumer of inspection cost, is undercosted. Product B, the low consumer of inspection cost, is overcosted. The ratio of actual to reported inspection cost for batch A is  $10/7.5 = 1.33$ , meaning that for the activity inspection, the cost required by product A is actually 1.33 times its reported cost. Product B will be 0.67 times its reported cost.

In general, the distortion produced by using only one cost driver to trace cost of different resources is proportional to the difference in how these products consume the resources.

5.4.4.5.b The relative costs of the activities aggregated

Cooper<sup>41</sup> (1990 I) explains that, "the relative cost of the various activities is a measure of how much each activity costs as a percentage of the total cost of the production process. In general, the higher the relative cost of an activity, the greater the distortion caused by using an imperfectly correlated cost driver to trace the costs of the

activity to products."

#### 5.4.4.5.c Batch-size diversity

Batch-size (volume) diversity occurs when products are manufactured in batches of different sizes. The volume diversity of two products is measured by dividing the batch size of the high-intensity product by the batch size of the low-intensity product.

For example, recall the previous example (in point 7.45a), but now a batch of product B contains 5 units instead of 50. Tracing the cost of the activity that is unaffected by volume (inspection) to products A & B using the volume-based cost driver, machine-hours, will cause product A to be overcosted and product B to be undercosted.

In practice, identifying how many cost drivers are needed calls for a mixture of judgement and analysis (Cooper 1989 c).

- a) Identify the inputs having large dollar values.
- b) Consider how diverse the products are and in what volumes they are produced.
- c) Identify which of the major inputs can be aggregated without introducing excessive distortion into reported costs.
- d) Analyze the smaller dollar-value inputs to see which of them can be aggregated with major inputs and which need to be traced separately.

Once the minimum number of required cost drivers is determined, three factors should be taken into account for the appropriate selection of the cost drivers.

1. Cost of Measurement: how easy is it to obtain the data required by the cost driver
2. Degree of Correlation: how does the actual consumption of the activity correlate with the consumption implied by the cost driver
3. Behavioral Effect: what behavior does the cost drive induce

#### 1. cost of measurement

An important technique for reducing measurement costs is to use cost drivers that capture the number of transactions generated by an activity instead of the duration of the activity. An important factor that has to be taken into account is that the measured cost associated with a cost driver depends on whether the data required by the driver is already available or has to be specially determined.

#### 2. degree of correlation

The cost of an activity is said to be directly traced when the cost driver measures the actual consumption of that activity and indirectly when it measures something else. For example, the costs of the activity "inspection" are directly traced by the cost driver "inspection hours" and indirectly traced by the cost drivers "number of inspections" and "machine hours" (Cooper, 1989 c).

Precaution must be used when transaction-based cost drivers are selected. These drivers are rarely correlated with the actual consumption of an activity. The selection of imperfectly correlated cost drivers can increase the cost drivers required to obtain a desired level of accuracy.

For example, the usage of number of orders processed can introduce distortions when it takes longer to order an item of raw material than a purchased part. This distortion can be reduced by using two cost drivers; number of raw material orders processed and number of purchased parts orders processed.

### 3. behavioral effect

Behavioral effects are the effects caused by the use of a particular cost driver on the behavior of individuals in the firm. The behavioral effects can be beneficial or harmful.

Beneficial behavior occurs when the behavior that results from use of a particular driver is desired. In this sense, the designer of an ABC system has the ability to choose cost drivers that are behaviorally consistent with the firm's manufacturing strategy, e.g., the designer may choose the number of vendors as a cost driver in order to emphasize the need to reduce the number of vendors; order lead time for components can be used as a driver to trace the cost of procurement activities to products (Turney, 1989). Or, if a

firm wants to reduce the number of unique parts it processes, the cost driver number of parts may be used.

Harmful behavior occurs when the behavior that results from the use of a particular driver is undesirable. For example, since an ABC system would show that the per-unit setup cost of low-volume products is quite high, some managers might increase lot sizes as a way to reduce the per-unit cost of these products.

#### **5.4.5 OPERATIONAL CONTROL (PERFORMANCE MEASUREMENTS)**

Johnson<sup>42</sup> (1988) explains that, "two types of activity-based information should form the backbone of world-class management accounting. One type is nonfinancial information about sources of competitive value (e.g. quality, flexibility, and cost) in a company's operating activities. The second type, strategic cost information, enables managers to assess the long-term profitability of a company's current mix of products and activities. Strategic cost information indicates if a company's activities are cost-effective in comparison to alternatives outside the company, and if the mix of products management has chosen to sell, uses activities in the most profitable way."

Therefore, a company requires both financial and nonfinancial information to measure performance. The objectives of

performance measurement are:

\_ to measure how well business activities are being performed in relation to specific goals and objectives developed in the strategic planning process

\_ to support elimination of waste

Elimination of waste is essential to achieve competitiveness. Given the fact that only those activities that consume resources have the power to add value, managers must remove those activities which do not add value, the non-value activities. The non-value activities are activities which cause delay (i.e. scrap), excess (i.e. inventory) and unevenness (i.e. overtime).

To make feasible the elimination of waste, first the activities in the manufacturing process have to be divided into value added and non-value added. A non-value added activity is an activity that can be eliminated with no deterioration of product attributes (function, quality, perceived value). Value is added to a product only when it is being processed (process time).

The time it takes a product to be produced is known as the lead time or throughput time. These times can be expressed as follows:

$$\text{Lead time} = \text{Process time} + \text{Inspection time} + \text{Move time} + \text{Wait time}$$

Move time, inspection time, and wait time represents non-value added time, since the product is not being processed.

**Lead time = Process time + Non-value-added time**

To measure the elimination of non-value-added time or waste, the performance measurement manufacturing cycle effectiveness (MCE) is used.

**MCE=processing time/(processing+inspection+wait+move) times**

Johnson (1988) states that there are four steps to managing waste in operating activities:

- . chart the flow of activities throughout the organization
- . identify sources of customer value in every activity, and eliminate any activities that contribute no identifiable value to customers
- . identify causes of delay, excess, and unevenness in all a activities
- . track indicators of waste

Finally, two comments about performance measurements. First, to be most useful, the frequency of reported information should follow the cycle of the production process being measured. Second, comprehensiveness of measures are represented by a balance between different categories such as (Ostrenega, 1990): Effectiveness- Are we doing the right things?; Efficiency- How well are we doing?; Productivity- How much output are we getting for a given input?; Utilization-

How are we using corporate resources such as inventory, asset turnover, etc.

#### **5.4.6 ACTIVITY-BASED COSTING AND DESIGN**

Traditional cost systems do not reward good product designs and do not penalize bad ones. They determine a new product's cost based on its direct material cost and its labor- and machine-time demands.

Instead activity-based costing:

- . Allows design engineers to understand the impact of different designs on product cost and flexibility. Product cost can be reduced and manufacturing flexibility improved by using designs that diminish the demand for high-cost activities and use many of the same activities (Turney, 1989).

- . Encourages product engineers to design products with fewer demands on support resources.

- . Provides important information in the bill of activities. The bill of activities may summarize activities consumed by a product into economic or functional groupings such as receiving, procurement, engineering changes, and quality.

- . Make visible the costs to support activities so that improvements in processes to reduce setup times, to improve materials layout, to focus the factory, or to reduce order processing costs to produce an immediate and direct benefit on

product cost (Kaplan, 1989).

. Relates activities to the events that create or drive the need for the activity and the resources consumed. Therefore, the cost drivers can be targeted for elimination or minimization if they relate to nonvalue added activities and optimization if they relate to value added activities. Thus it facilitates the cost reduction by a reduction in the drivers or cause of resource commitment and not by the direct reduction in activities (Ostrennga, 1990).

#### **5.4.7 ACTIVITY-BASED COSTING AND LIFE-CYCLE COST**

Life-cycle management focuses on those activities that occur prior to production to ensure the lowest total life-cycle cost. Studies show that about 80-85% of a product's life-cycle cost is determined by decisions made early in the cycle. Traditionally, product and process development activities are treated as period operating expenses communicating a wrong idea to the manager, given that these activities affect the long-term impact of the product cost and on a firm's total cost structure. ABC recommends that major activities should be viewed as capital investments and ultimately charged to products that benefit from these investments.

Product costs that arise during the development, production, and product logistics support phases must be linked to provide a long-term profitability picture and to support key

management decisions about product line, mix, and pricing. This becomes critical in environments where product life cycles are short, because prices ultimately must recover all cost plus profit.

The bill of activities can be used to determine all costs incurred during the product life cycle. Costs can be accumulated and assigned to the respective activities for posterior analysis. Additionally, activities can be used to determine life cycle costs during the design stage. Given the knowledge of possible activities to be performed by the product, the designer can apply analogy with similar products and determine possible costs to be incurred by the product. Thus, this approach makes possible the selection among alternative product designs during the early product's life-cycle stages.

Some of the steps to follow in order to achieve the previous statement are:

- . cost data should be accumulated across multiple years by product, function, activity, and cost element
- . project costs must be collected, compared to budgeted amounts
- . product costs must be monitored and compared to the target cost determined by the strategic plan and market evaluation
- . R & D can be split into two categories:

a) The cost of maintaining and improving existing products and product lines. This cost is traced directly to the item's benefiting from these efforts.

b) The cost for new products and processes. These costs should be isolated and charged to a project account, enabling the managers to compare the amount spent on each project and process development effort with the subsequent cash flow benefits. (Berliner & Brimson, 1988; Kaplan, 1990)

## 6.0 GLOSSARY

**Activity:** A combination of people, technology, raw materials, methods, and environment that produces a given product or service. Activities describe what an enterprise does.

**Activity Accounting:** The collection of financial and operational performance information about significant activities of an enterprise.

**Affinity Diagram:** Tool that gathers large amounts of language data and organizes them into groupings based on the natural relationship between each item.

**ANOVA:** An analysis of variance is a table of information that displays the contributions of each factor.

**Bottleneck Engineering (BNE):** Refers to the technological breakthroughs necessary to solve a design bottleneck and result in a competitive position.

**Controllable factor:** A design variable that is considered to influence the response and is included in the experiment. Its level can be controlled by the experimenters.

**Cost allocation:** The assignment and reassignment of a cost or group of costs to one or more cost objectives.

**Cost center:** The smallest unit of an organization for which budgeted or actual costs are collected and which has some common characteristics for measuring performance and assigning responsibility.

**Cost driver:** A factor whose occurrence creates cost.

**Design of experiment:** A systematic procedure to lay out the factors and conditions of an experiment. Taguchi employs specific partial factorial arrangements (orthogonal arrays) to determine the optimum design.

**Driver:** An activity or condition that has a direct influence on the operational performance and/or cost structure of other activities.

**Factorial Experiment:** A systematic procedure in which all controllable factors except one are held constant as the variable factor is altered discretely or continuously.

**Error:** The amount of variation in the response caused by factors other than controllable factors included in the experiment.

**Factory overhead:** All costs other than direct material costs and direct labor costs that are associated with the manufacturing process.

**Interaction:** Two factors are said to have interaction with each other if the influence of one on the response function is dependent on the value of the other.

**Life-cycle costing:** Accumulation of costs for activities that occur over the entire life cycle of a product, from inception to abandonment by the manufacturer and the consumer.

**Linear Graph:** A graphical representation of relative column locations of factors and their interactions. These were developed by Dr. Taguchi to assist in assigning different factors to columns of the orthogonal array.

**Loss Function:** A mathematical expression proposed by Dr. Taguchi to quantitatively determine the additional cost to society caused by the lack of quality in a product. This additional cost is viewed as a loss to society and is expressed as a direct function of the mean square deviation from the target value.

**Non-value added cost:** A cost or activity other than the minimum amount of equipment, materials, parts, space, and workers' time that is absolutely essential to add value to the enterprise.

**Noise Factors:** Noise factors are those factors that have an influence over a response but cannot be controlled in actual applications. They are of three kinds. **Outer Noise:** Consists of environmental conditions such as humidity, temperature, etc. **Inner Noise:** The deterioration of machines, tools and parts. **Between Product Noise:** The variation from piece to piece.

**Off-Line Quality Control:** Refers to the quality enhancement efforts in activities before production. These are activities such as upstream planning, R & D, systems design, parametric design, tolerance design and loss function, etc.

**Orthogonal Array:** A set of tables used to determine the least number of experiments and their conditions. The word orthogonal means balanced.

**Outer Array:** An orthogonal array used to define the conditions for the repetitions of the inner array design to measure the

effects of various noise factors. An experiment with outer arrays will reduce the product variability and sensitivity to the influence of noise factors.

**Parameter Design:** Parameter design is used to design a product by selecting the optimum condition of the parameter levels so that the product is least sensitive to noise factors.

**PDPC (Process Decision Program Chart):** PDPC is a method which maps out every conceivable event and contingency that can occur when moving from a problem statement to possible solutions. This tool is used to plan each possible chain of events that needs to occur when the problem or goal is an unfamiliar one.

**Quality Characteristics:** The yardstick which measures the performance of a product or a process under study. For a plastic molding process this could be the strength of the molded piece. For a cake, this could be a combination of taste, shape and moistness.

**Response:** A quantitative value of the measured quality characteristic. e.g, stiffness, weight, flatness.

**Robustness:** Describes a condition in which a product or process is least influenced by the variation of individual factors. To become robust is to become less sensitive to variations.

**S/N Ratio:** Stands for the signal to noise ration, i.e., the ratio of the power of a signal to the power of the noise (error). A high S/N ratio will mean that there is high

sensitivity with the least error of measurement. In Taguchi analysis using S/N ratios, a higher value is always desirable regardless of the quality characteristic.

**Signal Factor:** A factor that influences the average value, but not the variability in response.

**Standard Cost:** Normally, the annual process of calculating the anticipated cost of a specific product at a given level of volume and under an assumed set of circumstances.

**System Design:** The design of a product or a process using special Taguchi techniques.

**Taguchi Design:** A methodology to increase quality by optimizing system design, parameter design, and tolerance design.

**Target Cost:** A market-based cost that is calculated using a sales price necessary to capture a predetermined market share.

**Target Value:** A value that a product is expected to possess. Most often this value is different from what a single unit actually does exhibit.

**Tolerance Design:** This is a sophisticated version of parametric design used to optimize tolerance, reduce costs, and increase customer satisfaction.

**Transaction:** Physical (including electronic) documents associated with activities that impact information.

**Value Added Cost:** The incremental cost of an activity to compete a required task at the lowest overall cost.

**Variation Reduction:** The variation in the output of a process

produces nonuniformity in the product and is perceived as quality. Reduced variation increases customer satisfaction and reduces warranty cost arising from variation. To achieve better quality, a product must perform optimally and should give less variation around the optimum performance.

**Waste:** The net total process output minus good process output.

## **7.0 BIBLIOGRAPHY**

### **7.1 Sitations**

1. The Charles Stark Draper Laboratory, Inc.: pg. 1
2. Stoll 1988: pg. 67
3. Pignatiello: pg. 247-48
4. Eureka & Ryan 1988: pg. 2
5. King 1989: pg. 34-1
6. Lewis 1990: pg. 3
7. Phadke 1989: pg. 275
8. Cooper 1990: pg.
9. Eureka & Ryan 1988: pg. 2
10. Eureka & Ryan 1988: pg. 14
11. Eureka & Ryan 1988: pg. 18
12. Akao 1990: pg. 5
13. Mitsufuji (Akao 1990): pg. 53
14. Akao 1990: pg. 150
15. Furukawa (Akao 1990): pg. 149

16. Maekawa (Akao 1990): pg. 213
17. Takamura (Akao 1990): pg. 115
18. Baker 1986: pg. 34
19. Kackar 1986: pg. 23
20. Gunter 1987: pg. 45
21. Phadke 1989: pg. 6
22. Pignatiello 1988: pg. 247-48
23. Phadke 1989: pg. 63
24. Phadke & Taguchi 1988: pg. 26.3.1
25. Taguchi 1987: pg. 151
26. Nair & Pregibon (Box 1988): pg. 29
27. Lewis & Connelly 1990: pg. 4-1
28. Andreasen 1988: pg. 47
29. Boothroyd & Dewhurst 1988: pg. 42
30. Boothroyd & Dewhurst 1989: pg. 2-1
31. Boothroyd & Dewhurst 1989: pg. 4-1
32. Boothroyd & Dewhurst 1989: pg. 5-1
33. Berliner & Brimson 1988: pg. 1
34. Berliner & Brimson 1988: pg. 101
35. Miller & Vollmann 1985: pg.
36. Cooper 1988 a: pg. 53
37. Kaplan 1989: pg. 245
38. Turney 1990: pg. 40
39. Kaplan 1988: pg. 64
40. Berliner & Brimson 1988: pg. 95
41. Cooper 1990 I: pg. 80

42. Johnson 1988: pg. 24

## 7.2 References

American Supplier Institute (ASI): QFD a Collection of Presentations and QFD Case Studies.

Akao Y.: Hinshitukenakatuyou No. Jissai. 1988 by Japan Standards Association. English Translation: Quality Function Deployment. Productivity Press. Massachusetts 1990.

Andreasen M.M.: Design for Assembly Expanded to CIM. Developments in Assembly Automation. March 1988. I

Andreasen M.M.: Design for Assembly. Second Edition. IFS Publications. New York 1988. II

Andreasen M.M., Ahm T.: Design for Flexibility. Developments in Assembly Automation. March 1987.

Arpino F., Groppetti R.: ASSYST. Developments in Assembly Automation. March 1988.

Ashworth A.: Life-Cycle Costing: A Practical Tool ?. Cost Engineering. Vol. 31, No 3. March 1989.

Aswad A.: Quality Function Deployment: A System's Approach. Proc. 1989 IIE Integrated Systems Conference & SIM Conference.

Aswad A.: Quality Function Deployment. SAE Technical Paper Series.

Bailey J.: Implementation of ABC Systems by UK Companies. Management Accounting. February 1991.

Baker T.B.: Quality Engineering by Design: Taguchi's Philosophy. Quality Progress. December 1986.

Bassler R., Schmaus T.: Procedure for Assembly-Oriented Product Design. Developments in Assembly Automation. March 1988.

Berliner C., Brimson J.A.: Cost Management For Today's Advanced Manufacturing: The CAM-I. Harvard Business School Press. Massachusetts 1988.

Boothroyd G.: Design For Assembly. Mechanical Engineering. February 1988.

Boothroyd G., Dewhurst P.: Product Design For Manufacture And Assembly. Manufacturing Engineering. April 1988.

Boothroyd G., Dewhurst P.: Product Design for Assembly. Boothroyd Dewhurst, Inc. Rhode Island 1989.

Box G.: Signal-to-Noise Ratios, Performance Criteria, and Transformations (with discussions). Technometrics. Vol. 30, No 1. February 1988.

Box G.E.P., Draper N.R.: Evolution Operations: A Statistical Method for Process Improvement. John Wiley and Sons. New York 1969.

Bruns H. Jr., Kaplan R.S.: Accounting and Management: Field Study Perspectives. Harvard Business School Press. Boston 1987.

Butler : Life-Cycle Cost. Presentation, Virginia Tech. September 1990.

Byrne D.M., Taguchi S.: The Taguchi Approach to Parameter Design. Quality Progress. December 1987.

Cognition Inc.: MCAE. Billerica, Massachusetts.

Cohen L.: Quality Function Deployment: An Application Perspective from Digital Equipment Corporation. National Productivity Review. Summer 1988.

Cooper R.: The Rise of Activity-Based Costing-Part One: What Is an Activity-Based Cost System ?. Journal of Cost Management. Summer 1988.

\_\_\_ : The Rise of Activity-Based Costing-Part Two: When Do I Need an Activity-Based Cost System ?. Journal of Cost Management. Fall 1988.

\_\_\_ : The Rise of Activity-Based Costing-Part Three: How Many Cost Drivers Do You Need, and How Do You Select Them ?. Journal of Cost Management. Winter 1989.

\_\_\_ : The Rise of Activity-Based Costing-Part Four: What Do Activity-Based Cost Systems Look Like ?. Journal of Cost Management. Spring 1989.

Cooper R.: Explicating The Logic Of ABC. Management Accounting. November 1990.

Cooper R., Kaplan R.S.: How Cost Accounting Distorts Product Costs. Management Accounting. April 1988.

Daetz D.: The Effect of Product Design on Product Quality and Product Cost. Quality Progress. June 1987.

Dewhurst P., Boothroyd G.: Early Cost Estimation in Product Design. Journal of Manufacturing Systems. Vol. 7, No 3.

Eureka W.E., Ryan N.C.: The Customer-Driven Company. ASI Press. Michigan 1988.

Gager R.: Designing for Productivity Saves Millions.

Appliance Manufacturing. January 1986.

Gunter B.: A Predictive on the Taguchi Methods. Quality Progress. June 1987.

Hariman J.: Influencing rather than informing: Japanese management accounting. Management Accounting. March 1990.

X Hauser J.R., Clausing D.: The House of Quality. Harvard Business Review. May-June 1988.

Heidenreich P.: Designing for Manufacturability. Quality Progress. May 1988.

Heitger L.E., Matulich S.: Cost Accounting. McGraw Hill Inc. New York 1985.

Hiramoto T.: Another Hidden Edge-Japanese Management Accounting. Harvard Business Review. July-August 1988.

Holbrook A.E.K., Sackett P.J.: Design for Assembly-Guidelines for Product Design. Developments in Assembly Automation. March 1988.

Hunter J.S.: Statistical Design Applied to Product Design. Journal of Quality Technology. Vol. 17, No 4. October 1985.

Hunter J.S.: Signal to Noise Ratio Debate. Letter. Quality Progress. May 1987.

Huthwaite B., Spence G.: The Power of Cost Measurement in New Product Development. National Productivity Review. Vol.8, No 8. Summer 1989.

Huthwaite B.: The Link Between Design and Activity-Based Accounting. Manufacturing Systems. October 1989.

Huthwaite B.: Checklist For DFM. Machine Design. January 25, 1990.

John J.A., Quenouille M.H.: Experiments: Design & Analysis. Second Edition. MacMillan Publishing Co. New York 1977.

Johnson H.T., Kaplan R.S.: The Importance of Long-Term Product Costs. The McKinsey Quarterly. Autumn 1987.

Johnson H.T.: Activity-Based Information: A Blueprint For World-Class Management Accounting. Management Accounting. June 1988.

Kackar R.N.: Off-Line Quality Control, Parameter Design, and the Taguchi Method. Journal of Quality Technology. Vol. 17, No 4. October 1985.

Kackar R.N.: Taguchi's Quality Philosophy: Analysis and Commentary. Quality Progress. December 1986.

Kaplan R.S.: Measuring Manufacturing Performance: A New Challenge for Managerial Accounting Research. The Accounting Review. Vol. LVIII, No.4 , October 1983.

Kaplan R.S.: One Cost System Isn't Enough. Harvard Business Review. January-February 1988.

Kaplan R.S.: Management Accounting for Advanced Technological Environments. Science. Vol. 245, 25 August 1989.

Kaplan R.S.: The Four-Stage of Cost Systems Design. Management Accounting. February 1990.

Kaplan R.S., Atkinson A.A.: Advanced Management Accounting. Prentice Hall. New Jersey 1989.

Kaplan R.S., Johnson H.T.: The Rise and Fall of Management

Accounting. Harvard Business Scholl Press. Massachusetts 1987.

King B.: Better Designs in Half the Time. GOAL/QPC. MA 1989.

Koons F.J.: Manufacturing Cost Management. Cost Engineering.  
Vol. 32, No 5. May 1990.

Leon R.V., Shoemaker A.C., Kacker R.N.: Performance Measures  
Independent of Adjustment (with discussions). Technometrics.  
Vol. 29, No 3. August 1987.

Lewis G.M., Connelly H.K.: Product Design For Assembly. SME  
Publications. July 1990.

Matthews L.M.: Estimating Manufacturing Costs. McGraw-Hill  
Co. New York 1983.

Michaels J.V., Wood W.P.: Design To Cost. John Wiley & Sons.  
New York 1989.

Miller J.G., Vollman T.E.: The hidden factory. Harvard  
Business Review. September - October 1985.

Mizuno, Akao Y.: Quality Function Deployment. JUSE  
(published in Japanese). Edition 1978.

Monden Y., Sakurai M.: Japanese Management Accounting.  
Productivity Press. Cambridge 1990.

Moore L.T., Creese R.C.: Manufacturing Cost Estimation. Cost  
Engineering. Vol. 32, No 5. May 1990.

Murdick R.G., Render B., Russell R.: Service Operations  
Management. Allyn & Bacon. Boston, 1990.

Myers J.L.: Fundamentals of Experimental Design. Second  
Edition. Allyn and Bacon Inc. Boston, 1972.

Nevis J.L., Whitney D.E.: Concurrent Design of Products and

Processes. McGraw-Hill Publishing Co. New York, 1989.

Phadke M.S.: Quality Engineering Using Robust Design. Prentice-Hall. Englewood Cliffs, 1989.

Pignatiello J.J.Jr.: An Overview of the Strategy and Tactics of Taguchi. IIE Transactions. September 1988. Vol. 20, No 2.

O'Guin M.: Focus The Factory With Activity-Based Costing. Management Accounting. February 1990.

Ostrenga M.R.: Activities: The Focal Point Of Total Cost Management. Management Accounting. February 1990.

Quinlen J.C.: Make Better Estimates on Your Computer. Tooling and Production. October 1988.

X Ross P.J.: The Role of Taguchi Methods and Design of Experiments in QFD. Quality Progress. June 1988.

Stoll H.W.: Design For Manufacture. Manufacturing Engineering. January 1988.

X Sullivan L.P.: Quality Function Deployment. Quality Progress. June 1986.

Sullivan L.P.: Reducing Variability: A New Approach to Quality. Quality Progress. July 1984.

Taguchi G.: Jikken Keikakuho, 3rd Edition. Tokyo, Japan: Maruzen, vol. 1 and 2, 1977 and 1978 (in Japanese). English Translation: Taguchi G.: System of Experimental Design. Edited by Don Clausing. New York: UNIPUB/Kraus International Publications, vol. 1 and 2, 1987.

Taguchi G., Clausing D.: Robust Design. Harvard Business Review. January-February 1990.

The Charles Stark Draper Laboratory, Inc.: CSDL-P-2917, A Prototype for Feature-Based Design for Assembly. July 1990.

Trucks H.E.: Designing for Economical Production. Second Edition. Society of Manufacturing Engineers 1987.

Turney P.B.B.: Using Activity-Based Costing to Achieve Manufacturing Excellence. Journal of Cost Management. Summer 1989.

Turney P.B.B., Anderson B.: Accounting for Continuous Improvement. Sloan Management Review. Winter 1989.

Turney P.B.B.: What Is The Scope Of Activity-Based Costing ?. Journal of Cost Management. Winter 1990.

Ulrich K.T., Fine C.H.: Cost Estimation Tools To Support Product Design. Proc. of Manufacturing International. March 1990.

Whitney D.E.: Manufacturing By Design. Harvard Business Review. July-August 1988.

Winchell W.: Realistic Cost Estimating for Manufacturing. Second Edition. SME Publications. MI 1989.

Zorowski C.F.: Product Design Merit: Relating Design to Ease of Assembly. Developments in Assembly Automation. March 1987.

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