Design for Assembly and Disassembly

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Summary

A review is made of design for assembly (DFA) methods developed over the last fifteen years. It is found that implementation of DFA at the early conceptual stage of design has led to enormous benefits including simplification of products, lower assembly and manufacturing costs, reduced overheads, improved quality and reduced time to market. DFA is now being broadened to include consideration of the difficulty of manufacture of the individual parts to be assembled and is providing the necessary basis for teamwork and simultaneous engineering.

More recently, environmental concerns are requiring that disassembly for service and recycling be considered during product design - in fact, total life cycle costs for a product are becoming an essential part of simultaneous engineering. This keynote paper concludes with a discussion of current developments of design for disassembly (DFD).

Key Words: Design, Assembly, Disassembly

Terminology

First, we should try to define what is meant by "design for assembly." The term is sometimes used to mean the design of the system for performing assembly work, but in the present context it will be taken to mean the design of the product for ease of assembly. Also, to some individuals, "assembly" means the fitting together or joining of separate components or parts. In other words, the "adding" of a part to a partially complete product. However, before the part can be added or "inserted" it must often be separated from other parts, grasped, oriented and moved to the product. In this paper, "assembly" will be taken to mean both the acquisition and the insertion of the part. Also, the term "disassembly" can have different meanings. For example, the disassembly of certain parts from a product in order to replace a service item would mean the careful unscrewing of screws, removal of parts, and placing them in accessible locations for subsequent reassembly. However, in disassembly for recycling the same may be true, but parts may also be forcibly separated resulting in breakage.

It appears that many of those who supplied information for this keynote paper misunderstood the term design for assembly. Whereas we consider this to be product design for assembly, we received many contributions referring to the design of the assembly system.

Introduction

It has long been recognized that the final cost of a product is largely determined during its design and that designers must take manufacturing into account from the outset. The establishment of a sub-committee of the CIRP "O" group "design for economic manufacture" in 1970, chaired by Prof. Chisholm, was an indication of great interest in the subject. Even in those days, however, one could still hear the phrase "we design it -- you build it." This attitude has now become known as "over-the-wall" design[1], meaning that the designer throws the drawings over the "wall" that separates design and manufacture so that the manufacturing engineer must wrestle with the problems created by the designer (Fig. 1).

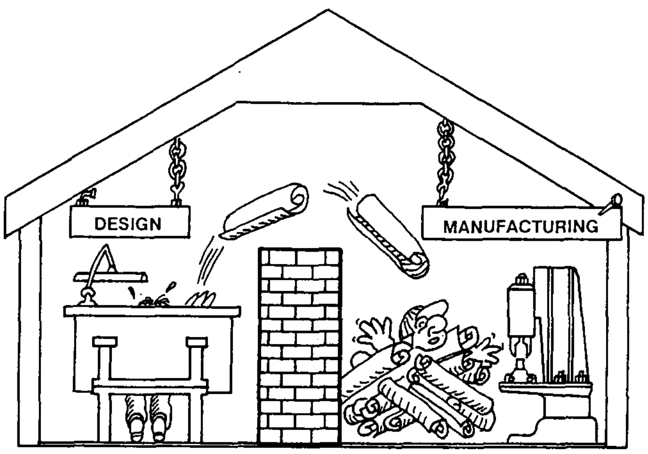


Fig. 1 "Over the Wall" design (Courtesy Munro & Associates[1])

As early as the 1960's several companies were developing guidelines for use during product design. Perhaps one of the best known examples is the Manufacturing Producibility Handbook published for internal use by General Electric in the U.S.A.[2] Here, manufacturing data was accumulated into one large reference volume with the idea that designers would have, at their fingertips, the manufacturing knowledge necessary for efficient design. However, the emphasis was on the design of individual parts for "producibility" and little attention was given to the assembly process. This approach led, for example, to the curious recommendation illustrated in Fig. 2 "substitute a small number of simple shapes to provide a function rather than a single complex shape." In fact, when one has considered the means whereby the separate simple parts in Fig. 2 might be secured, the total cost of this recommended design would be far greater than that of the single part.

It has now become clear that the objective should be to simplify the product structure to reduce assembly cost and reduce the total parts cost. In fact, design for assembly (DFA) should always be the first consideration.

Development of DFA Methods

Significant benefits from the use of DFA were not realized until systematic analysis tools were made available in the late 1970's. The reason is that design guidelines, even if they provide sound recommendations do not help the designer any more than saying "try to design so that the product is easy to assemble." Examples of changes made to simplify assembly in other products never seem to apply to the product under consideration and, in order to cover a reasonable proportion of possible design changes, the design guideline handbook would be huge -- leaving the designer to thumb through numerous examples with little chance of success in the end.

Interestingly, most of the first efforts to develop systematic procedures for assembly analysis concentrated on product design for ease of automatic assembly. The Hitachi Assembly Evaluation Method AEM[3] described later was directed at simplifying automatic insertion of parts. The Boothroyd Dewhurst DFA method[4] grew out of collaborative research on design for automatic feeding and automatic insertion

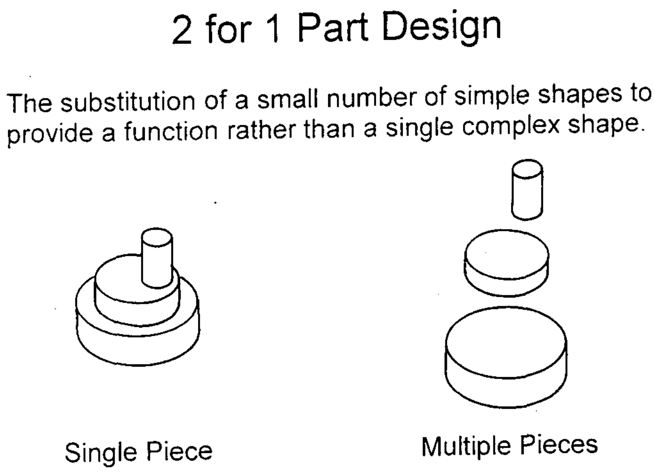


Fig. 2 Misleading Producibilty Recommendation[2]

carried out at the University of Massachusetts in the U.S.A. and the University of Salford in the U.K. This emphasis arose from the fact that when a company desired to automate the assembly of a product, they were forced to reconsider its design. There are many examples of products for which automatic assembly is simply not feasible without redesign but none where manual assembly is not feasible.

However, it is now the application of design for manual assembly that is resulting in staggering cost savings in many products because of the resulting simplification of the product and the reductions in total manufacturing costs. When the original methods were being developed it was not even realized that there was such a problem. Even if a problem were recognized, the proposed solution was often to consider automation of the assembly process. Redesign for ease of manual assembly was not generally considered.

The idea behind most systematic DFA methods is to consider each part in turn as it is inserted into the product, gauge the difficulty of the assembly process, and then sum the results to obtain a numerical rating of assembly difficulty. Hopefully, different individuals analyzing the same product will obtain similar ratings.

Hitachi AEM Method

In 1980 the Okochi Memorial Prize was awarded for the development of an automatic assembly system for tape recorder mechanisms[5]. In the process of developing this system the product design was considered carefully using the Assembly Evaluation Method (AEM) developed at Hitachi. This method is based on the principle of "one motion for one part." For more complicated motions, a point-loss standard is used and the assemblability of the whole product is evaluated by subtracting points lost.

In a 1986 paper by Miyakawa and Ohashi[3] some details of the Assembly Evaluation Method were presented. The method uses two indices at the earliest possible stage of design, namely the Assembly Evaluation Score E which is used to assess design quality or the difficulty of assembly and the Assembly Cost Ratio K used to project assembly costs relative to current assembly costs. The method does not distinguish between manual, robot, or automatic assembly because, Myakawa and Ohashi believe, there is a strong correlation between the degree of assembly difficulty using these three methods. They also believe that it is difficult for designers to consider the method of production during the early stages of design.

In the AEM, approximately 20 symbols are used to represent assembly operations. Each symbol has an index which can be used to assess the assemblability of the part under consideration. The principal benefits of applying AEM are claimed to be:

- -a reduction in assembly labor
- -the facilitation of factory automation
- -reduction in the design period
- -improved reliability of products and automated equipment

By 1986 more than 1,500 engineers at Hitachi had been trained to use this method and it was claimed that the method was saving tens of millions of dollars annually.

In a 1990 paper by Miyakawa et al[6], a new Assemblability Evaluation Method is described where examples of the symbols and penalty scores used are given (Table 1) together with examples of their application (Table 2). It is explained that the AEM was developed originally in 1976, but after ten years of use it was felt necessary to improve the methodology.

The new system considers the influence of dimensional accuracy, configurational accuracy, the size and mass of parts, the repetition of operations, the length of a screw, etc., on the assembly cost. Improved definitions for the elemental operations symbols were introduced to reduce the user's subjective influence on the analysis and evaluation accuracy. Formulas and constants were also approved. The methodology has now been programmed for a personal computer.

Boothroyd Dewhurst DFA method

Developments of the Boothroyd Dewhurst DFA[4] method started in 1977 with funding from the U. S. National Science Foundation and was first introduced in handbook form in 1980. A software version for the Apple computer was introduced in 1982 followed

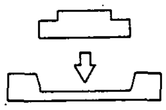
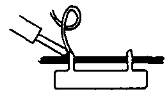
Elemental operation		AEM symbol	Penalty score
	Downward movement	↓	0
	Soldering	S	20

Table 1 Examples of AEM symbols and penalty scores[6]

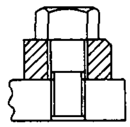
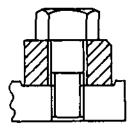
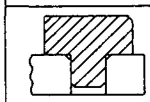
Product structure and assembly operations		Part assemblability evaluation score	Assemblability evaluation score	Assembly cost ratio	Part to be improved
	1. Set chassis	100	73	1	block
	2. Bring down block and hold it to maintain its orientation	50			
	3 Fasten screw	65			
	1 Set chassis	100	88	Approx. 0.8	screw
	2 Bring down block (orientation is maintained by spot-facing)	100			
	3 Fasten screw	65			
	1 Set chassis	100	89	Approx. 0.5	block
	2 Bring down and pressfit block	80			

Table 2 Assemblability evaluation and improvement examples[16]

quickly by a translation for the then new IBM P.C.

As it exists today, the method is applied a: follows:

- -Through the use of three basic criteria th existence of each separate part is questione and the designer is required to provide th reasons why the part cannot be eliminated o combined with others. Those parts that mee the criteria are totalled to give th theoretical minimum number of parts.
- -The actual assembly time is estimated using database of real time standards develope specifically for the purpose[7].
- -A DFA Index (design efficiency) is obtained b comparing the actual assembly time with th theoretical minimum assembly time. The latte is the assembly time for the theoretica minimum number of parts assuming they are eas to assemble.
- -Assembly difficulties are identified which ma lead to manufacturing and quality problems.

In other words, the method is a structure design analysis procedure which guides the desig team towards a robust and elegant product structure.

Experience has shown that enormous savings ar possible from the use of the DFA method and tha these originate from the application of the minimu part count criteria and the elimination of assembl difficulties which represent a major source o quality problems. The resulting simplification o the product structure leads to reductions in assembl cost, but more importantly, even greater reduction in part costs. These savings lead, in turn, t reductions in inventory, suppliers, overheads an time to market accompanied by improved quality an reliability.

The use of the DFA database to estimate assembl time (and hence assembly cost) together wit companion techniques for estimating part costs at th early stages of design, provides the means for th designer to make trade off decisions before fina commitment to a design.

There have been hundreds of published example of successes obtained with the Boothroyd Dewhurst DF method - one was submitted as a contribution to thi keynote paper. Elmaraghy and Kroll[8] used the method to analyze a family of D.C. motors and to redesign them with emphasis on meeting the criteria of the market demands while allowing for robotic assembly.

The initial design had 56 parts with a total estimated manual assembly time of 424.4 seconds and an overall DFA Index of 18.4 percent. For the redesigned motor the total number of parts was 18, the total estimated manual assembly time was 171 seconds, and the overall design efficiency 26.3 percent.

The authors concluded that the DFA analysis proved to be beneficial to the overall redesign of the initial D.C. motor and showed where design inefficiencies existed. They also considered that the thought patterns used in DFA analysis could also be applied to the design of the assembly equipment to make it simpler and more serviceable.

<u>More Recent DFA Analysis Methods</u>

Some ten years following the introduction of the Hitachi AEM and the Boothroyd Dewhurst DFA methods, variations on these started to appear. One of the first was that of Warnecke and Bassler at the University of Stuttgart. In their method[9], which they name Assembly-Oriented Product Design, they assess each part's usefulness or functional value. Thus, both the assembly difficulty and the functional value are evaluated and a combined rating given. This means that parts which have little functional value, such as separate fasteners, and which are difficult to assemble, are given the lowest ratings. Finally, the ratings are used as guides to redesign.

In their paper, B. L. Miles and K. G. Swift describe the application of their "Lucas" method developed during the late 1980's[10]. They begin by summarizing the reasons why the traditional, functionally organized product introduction process is incapable of meeting modern requirements:

- Sequential activity results in protracted lead times.
- Customer requirements, product design, and method of manufacture are inextricably linked with many trade-offs: they cannot be addressed independently by marketing, engineering, and manufacturing functions.
- Scarce design resources are wasted on interdepartmental communications, progress chasing and non-value added activities correcting designs that prove difficult to make or do not fully meet customers' aspirations.
- Manufacturability issues are discovered too late and are the subject of quick fix solutions and compromises.
- All design activity is pushed through a single, ill-defined activity.
- Products are designed with an excessive number of parts which, in addition to the cost of these parts, adds to the cost of supply and stock control.

What is needed, therefore, is the collaborative use of teamwork, simultaneous engineering, project management, and tools and techniques.

In the Lucas method, the steps are:

- Functional analysis where parts are categorized into A parts (demanded by the design specification) or B parts (required by that particular design solution). A target is set for design efficiency which is A/B and expressed as a percentage. The objective is to exceed an arbitrary 60% target value by the elimination of category B parts through redesign. The authors emphasize assembly cost reduction and parts count reduction and include use of the Boothroyd Dewhurst minimum parts criteria in a "truth" table to assist in parts count reduction.
- A handling and feeding analysis where the parts are scored based on three areas: the size and weight of the part, handling difficulties, and the orientation of the part. The score is summed to give the total score for the part and a handling/feeding ratio is calculated which is given by the total score divided by the number of A parts. A target of 2.5 is suggested.
- A fitting analysis which is based on the proposed assembly sequence. Each part is scored depending on whether it requires holding in a fixture, the assembly direction, alignment problems, restricted vision, and the required insertion force. The total score is divided by the number of A parts to give the fitting ratio. Again, it is suggested that this ratio should approach 2.5 for an acceptable design.

In another method, Sony Corporation claims to have developed a unique set of rules for increased productivity in the '80's, involving design for assembly cost effectiveness (DAC). In his paper, Yamigiwa[11] reiterates that it is impossible to design for assembly ease unless one starts at the time of conception before the blueprint for the product is drawn up. The improvement of a design at its inception is referred to as the concept of feed forward design rather than making improvements later with feedback from the manufacturing process.

In the DAC method, factors for evaluation are classified into 30 key words. The evaluations are displayed on a diagram using a one hundred point system for each operation; thus making judgment at a glance easy. A list of operations is presented on the DAC diagram a bar drawn representing the score for that particular operation (Fig. 3). Operations with low scores are easily identified. Since 1987 DAC has been introduced to various companies in Japan and overseas. Emphasis is given to the ease of which an operation can be carried out automatically and the method is used to illustrate problems with the efficiency of the assembly system.

In their paper, Kroll et al[12] also emphasize that design for automatic assembly should be applied as early as possible in the design process. They believe that such an approach leads to design changes that improve the efficiency of the assembly process and lead to simpler robots with fewer tools and grippers and less costly fixtures. Indeed robots may be abandoned in favor of alternative process equipment.

The authors explain that two methods for guiding product design have been suggested and implemented in the past: (i) a qualitative approach which presents the designer with general rules and guidelines accompanied by illustrated examples; (ii) a quantitative approach which assigns time period costs and numerical codes to various part characteristics and assembly operations. The first approach is often considered too general to be practically applied during design. Merely presenting the

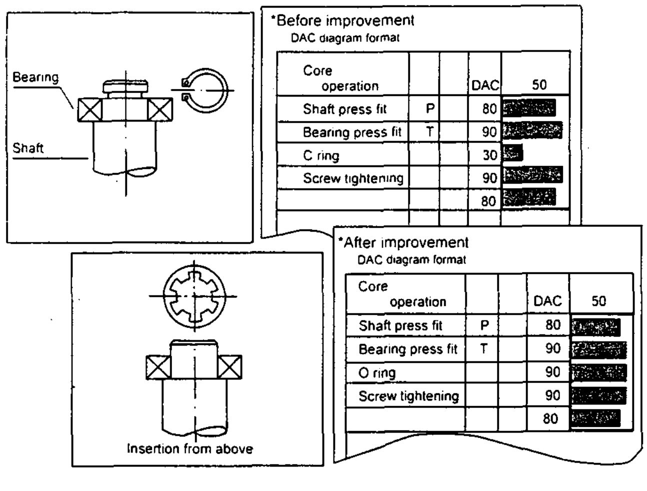


Fig. 3 DAC Example, Sony Corporation[11]

guidelines to the engineer, whether on paper or on a computer monitor falls short of providing a useful methodology. Moreover, general rules are by nature more prone to misinterpretation and the lack of any comparison criteria makes evaluation of alternative designs difficult. The quantitative method requires very specific information such as the expected production rate, the cost of assembly hardware and symmetry properties of parts.

In the view of Kroll et al, the quantitative approach lacks flexibility by relying on reference data which might not be available to the designer at the time of analysis and in using standard assembly equipment as a basis for comparison. But its two main drawbacks are the implicit way of identifying design improvements, and even more fundamental, its inability to treat products at a higher level than the individual parts. As a result, configuration design can only take place by elimination or integration of parts.

The authors present a knowledge-based computer system to assist engineers in the process of designing products for easier assembly. The emphasis is on the conceptual design stage where the structure of the product as a whole is considered.

In another approach, Angermuller and Moritzen of Siemens go further than most proponents of DFA and suggest that product design should be developed at the same time as production process design and production process evaluation[13]. They describe the concept of a knowledge-based and graphical interactive system MOSIM. This system would allow the design engineer to determine and evaluate assembly processes and assembly consequences of a design based on CAD models.

These authors suggest that the evaluation of ease of assembly is generally not based on the product and its features, but on the resulting feeding, handling, and assembly processes. Determining these processes is commonly regarded as planning. So evaluation requires planning although the planning need not be too detailed. After a brief discussion of the available evaluation procedures, they suggest that, in future, the procedures should be computer-aided and if the knowledge contained in these procedures could be coded in rules, it could be referred to as an expert system. In their paper Angermuller and Moritzen propose to use a 3-D solid CAD model to represent the design and then to extract features from the model. They also consider how assembly processes and assembly sequences might be represented.

Integration of DFA and CAD

Many of those with experience in implementing DFA methods feel that, by the time a designer has fully specified an assembly on a CAD system, it is too late to have a major impact on the design. To have the greatest impact, DFA methods should be applied at the concept stage of design before too much effort has been put into the project. Nevertheless, other researchers, like Angermuller and Moritzen, believe that DFA methods should be incorporated into CAD systems. Unfortunately, CAD systems have not yet been developed to the extent that they can be used efficiently during conceptual design although many CAD vendors are now developing 3D feature-based sketching systems for this purpose.

In order for DFA methods to interact with CAD systems, it will be necessary for methods to be developed for extracting feature information from a CAD system database and then using this information in DFA analysis. A study of this problem has been reported by Rosario and Knight[14].

Eversheim and Baumann[15] explain that the DFA (Design for Assembly) method developed by Boothroyd and Dewhurst has the advantage that the handling, joining and geometry features of a part can be determined independently of one another. This means that assembly specific weak points can be located easily. However, they believe that the method should be implemented on a CAD system. They go on to explain how the DFA methodology could be included in a CAD system and describe a computer supported program system that makes it possible for the first time to take assembly specific aspects into account systematically during the whole design process. It appears that assembly oriented products designed in this way permit effective automation in the assembly sector.

Molloy, Yang and Browne[16] state that the currently available DFM/A techniques are lacking in the following respects:

- They rely on the designer to correctly reply to questions
- They do not reflect all the manufacturing concerns
- They give only quantitative results -- but do not offer recommendations
- There is no mechanism for the capture of rules

These authors are studying the autogeneration of disassembly sequences and the linking of these with computer-aided process planning tools.

Scarr[17] also emphasizes the need to present design information on a CAD-based workstation. He has concentrated on developing guidelines in the form of design rules for the design of products for which automated assembly and robotic assembly techniques are appropriate and then establishing the relationship between design and the manufacturing tolerances assigned to the product.

Some Current Developments

In their contribution to this keynote paper, Schmidt and Bernhart[18] describe a computer-aided method used to evaluate the assemblability of new products on existing automated assembly systems. The new products considered are variations of existing products.

The work is being carried out at the Institute of Machine Tools and Production Science, Karlsruhe and the corresponding software is implemented in C and an object-oriented extension of C under Unix and OSF/MOTIF. Currently the data structure, the method of product structure analysis, including graphical assembly simulation, and the statistical methods have been implemented. Further work is being carried out on the user interface and the methods of processing and parts geometry analysis. Studies in an assembly plant are being carried out to collect statistical data and to specify the relevant characteristics of products and assembly systems. Figure 4 summarizes the steps made in estimating the cost of assembly system modifications due to changes in product features.

It appears that the main concerns in this work are in the development of flexible automatic assembly systems to accommodate product variations. Thus, it is felt necessary to look at all variations in the design of the product in the early stages to ensure that the flexible assembly system built will be able to handle all these variations.

In a contribution by Roth[19] he explains that, at Siemens, they have been using DFA for many years partly based on work published by Boothroyd and Dewhurst. During the General Assembly in Berlin he presented a short paper in the technical committee "Assembly" meeting where he described the manufacture of two products -- a data monitor and a vacuum cleaner -- which had been largely developed with the aid of DFA. Also, they have been applying other methods to improve design for assembly of products and for product recycling and disassembly. However, this is confidential material and he was not able to supply details. Mr. Roth believes that a large share of the assembly and manufacturing costs of a product is a consequence of design decisions. Parts requiring expensive assembly procedures should, therefore, be redesigned. However, the designer frequently does not know enough about assembly and handling operations; therefore, he is not in a position to estimate assembly costs.

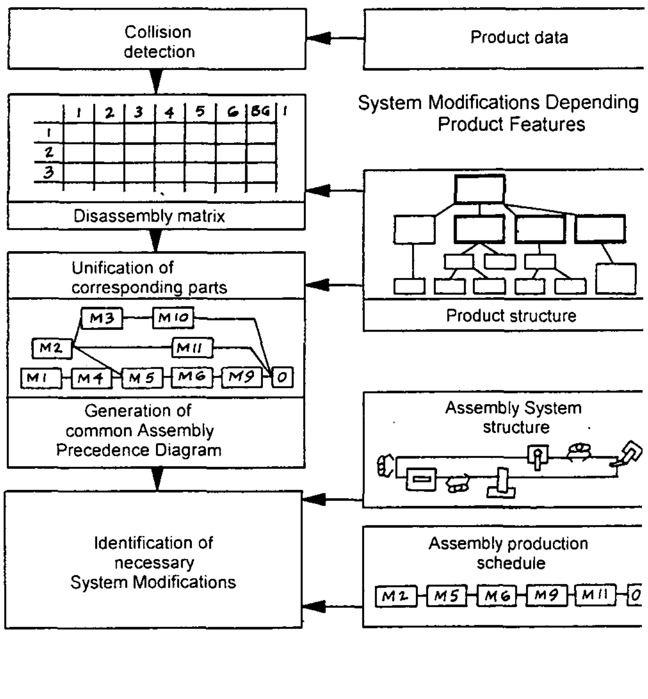


Fig. 4 Cost Estimation for Necessary System Modifications Depending on Product Features[18]

A rather unusual application of DFA is described by Santochi, Giusti and Dini[20] where the problem of tool handling in FMS is considered. It appears that much of tool handling that occurs in FMS is manual. For example, tools and tool holders are manually assembled; they are pre-set manually and are disassembled manually. For a medium-sized industry, the number of items handled can be more than 20,000. In a French aircraft company, tool assembly and disassembly occurs at a rate of 40,000 per year.

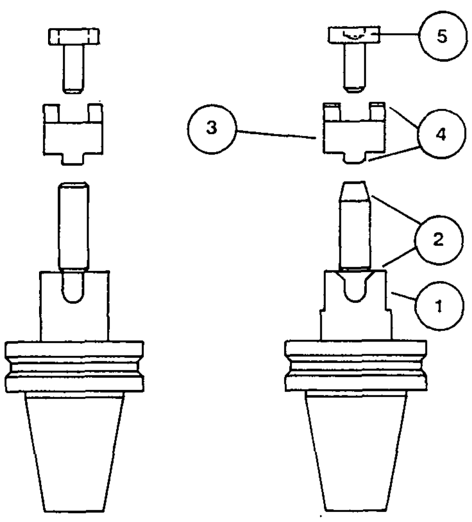
These authors deal with two aspects of the problem:

- Analysis of the possible modifications of the tool holder structure to facilitate robotic manipulation. In other words, design for assembly of tools and tool holders.
- The selection of the parts and the layout of fully automated and integrated plants for tool assembly and disassembly.

Design for assembly (DFA) is applied to the problem including the provision of suitable grasping surfaces, facilitating the coupling of elements by self-centering, The authors apply simplifying connecting interfaces, minimizing the number of parts and facilitating the automatic feeding of parts by avoiding shapes that are difficult to orient. In addition, they have used design for disassembly (DFD) to facilitate robotic disassembly operations. Some of the considerations include extraction devices to separate elements joined with drive fits and facilitating the grasping of assembled parts.

After discussing these detailed aspects of DFA and DFD, the authors go on to consider specific problems associated with tools and tool holders. This work was carried out at the Institute of Mechanical Technology of Pisa and one example of the results of this work where a tool holder for shell mills was modified in order to simplify assembly is shown in Fig. 5.

Ong of the Nanyang Technological Institute, Singapore[21] points out that DFMA implementation can have a significant impact on overheads. The cost overheads (direct or indirect) are rarely considered by manufacturing managers and design engineers although these form a major cost element and account for about 80% of the value-added in manufacturing industries[22]. Attention is generally focused on reducing manufacturing and assembly costs, the design of products, the introduction of new technologies and increasing productivity. However, overhead costs, when inappropriately applied, can be a major stumbling block for a manufacturer to become competitive. Reduction in cost resulting from well designed products, processes and technologies can be wiped out by accountants when overheads of 400% or more of direct labor or operating costs are applied.



1,3 Flat Grasping Surfaces

2,4 Chamfers on the toolholder and on the driving ring

5 Standardization of the locking system

Fig. 5 Toolholder for Shell Mills[20].

Ong goes on to say that one of the ways for a manufacturer to become competitive is the implementation of the Activity-based Costing (ABC) system[23-26]. The basic concept behind product costing in an ABC system is that the cost of a product equals the cost of the raw materials plus the sum of the costs of all the activities required to produce the product. The ABC system is generally more time consuming but more accurate in product costing and avoids the cost distortions found in traditional costing systems. The trend now is towards the implementation of ABC systems on product costing (which includes the overhead) and then the impact of DFMA on the "real" costs can be obtained.

In a communication from Seliger and Barbey[27], the work at the Institute of Machine Tools and Manufacturing Technology in Berlin in connection with the simultaneous planning of product and assembly organization is described. The emphasis is on ensuring that product designs allow for complete automation. Analysis of the ways in which manual assembly can be integrated with automatic assembly using precedence graphs of the products, leads to the development of similar product structures for new products.

<u>PCB Design for Assembly</u>

In 1985, Adachi et al of the NEC Corporation reported[28] that they were developing techniques for design for ease of assembly of printed circuit boards. Their primary interests in design for assembly were in reducing product structure complexity in order to avoid complicated assembly motions and reducing the variety of parts, so that they can be accommodated in automatic facilities. Thus, a product design which has the following two attributes is defined as "a product designed for ease of assembly."

- the product can be assembled by a few simple motions
- the variety of parts and subassemblies has been minimized

The authors present a chart (Fig. 6) which lists all those product design features that lead to ease of assembly.

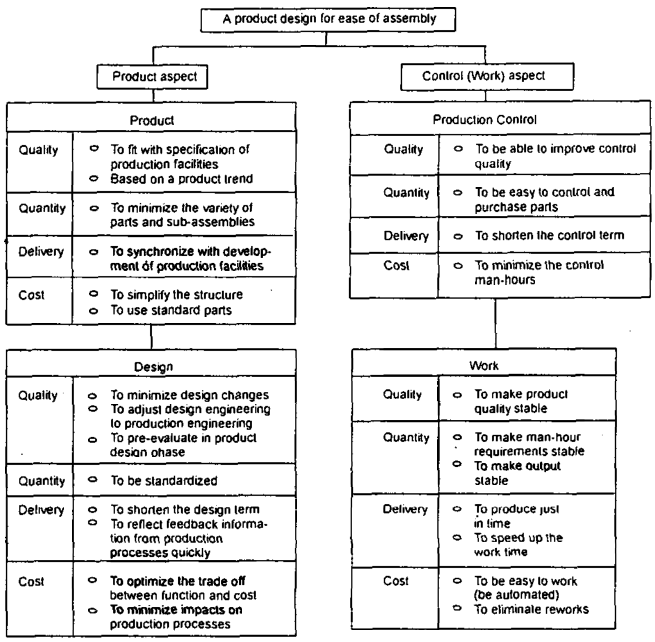


Fig. 6 Product Design Requirements for Ease of Assembly[28]

The PCB DFA tool was developed first because the proportionate cost of PCB's had been increasing. The tool is based on a one hundred point evaluation method with demerit marks given for five factors that would hamper automation. In this method PCB designers evaluate the level of ease of automation. The five factors that would hamper automation are as follows:

-many parts cannot be inserted automatically
-many different parts are used
-there is a lot of soldering and retouching
-there are a lot of parts which must be inserted after soldering
-there are a lot of wire harnesses

These factors are quantified on a worksheet where a formula is used to calculate demerit marks to be subtracted from the initial one hundred points.

This evaluation tool had been applied in several NEC Corporation divisions and had resulted in improvements in automation insertion ratios and achieved improved cooperation between design and production.

However, it appears that the NEC tool was not the first systematic analysis tool for PCB DFA. In fact, some six years earlier, the Xerox Corporation had published a method for assessing the manufacturability of PCBs[29]. In this method, ten leading cost drivers (attributes) in the design of PCBs are identified. The designer gives a rating of one to five for each attribute which is then multiplied by a coefficient developed from historical data. Table 3 presents a listing of the attributes and coefficients. The sum of the products of attributes and coefficients give the manufacturability index for the PCB.

Design for Manufacture

DFA has generated a revolution in design practices, not because it reduces assembly costs, but because it has a far greater impact on the total manufacturing costs of a product. The reason is that DFA simplifies the product structure, reduces the number of parts and thereby reduces the total cost of the parts. However, in order to judge the effects of DFA at the early design stage, companion methods for estimating part costs must be made available and accordingly many of those who have developed DFA methods are now turning their attention to methods of assessment of part manufacturing difficulties.

For example, the Hitachi researchers[30] have introduced a Machining Producibility Evaluation Method which, combined with their AEM gives an overall Producibility Evaluation Method (PEM).

i	K_i	Attributes
0	-2.8238	Constant Value
1	0.4034	Piggybacks
2	0.6177	Solderside Components
3	0.1105	Heat Tolerance
4	0.8445	Large Assemblies
5	0.0731	Screws & Mechanicals
6	0.1477	Harnesses
7	0.8485	Component Spacing
8	0.6004	% Auto-Insert
9	0.0676	Orientation
10	0.1105	Component Size

Table 3 Xerox manufacturability index for PCB assemblies - polynomial coefficients and attributes[29]

Similarly, Toshiba Corporation[31] has developed a Processability Evaluation Method which, combined with other methods including the Assemblability Evaluation Method provides an overall Producibility Evaluation. Method (PEM). The authors define processability as being proportional to the part's cost. The part's cost is determined by the selection of the part processing method and then by the design of the part shape. Various processing methods are considered for a particular part. The part's cost is then determined for all combinations of the selected processing methods and suitable materials. Then the part's design is evaluated to see whether it fits a particular processing method and, finally, a processability evaluation is carried out.

Since 1985, Boothroyd, Dewhurst and Knight have developed methods for designers to obtain cost estimates for parts and tooling during the early phases of design. Studies have been completed for machined parts,[32] injection molded[33] and die cast parts,[34] sheet metal stampings[35] and powder metal parts.[36]

Implementation of DFA

Experience has shown that there are many barriers to the implementation of DFA. Quite frequently it will be suggested that since assembly costs for a particular product form only a small proportion of the total manufacturing costs, there is no point in performing a DFA analysis. Figure 7 shows the results of one analysis where the assembly costs were extremely small compared with material and manufacturing costs. However, DFA analysis would suggest replacement of the complete assembly with, say, a machined casting. This would reduce total manufacturing costs by at least 50 percent.

The view is often expressed that DFA is only worthwhile when the product is manufactured in large quantities. It could be argued, though, that use of the DFA philosophy is even more important when the production quantities are small. This is because, commonly, reconsideration of an initial design is usually not carried out for low volume production. Applying the philosophy "do it right the first time" becomes even more important, therefore, when the production quantities are small.

Everyone seems to think that their own company is unique and, therefore, in need of unique databases. However, when one design is rated better than another using a DFA database, it would almost certainly be rated in the same way using a customized database.

Some say DFA is only value analysis. It is true that the objectives of DFA and value analysis are the same. However, it should be realized that DFA is meant to be applied early in the design cycle and that value analysis does not give proper attention to the structure of the product and its possible simplification. Experience has shown that DFA can make significant improvements even after value analysis has been carried out.

Since the introduction of DFA, many other acronyms have been proposed, for example, design for quality (DFQ), design for competitiveness (DFC), design for reliability, and many more. Some have referred to this proliferation of acronyms as alphabet soup! Many have even suggested that design for performance is just as important as DFA. One

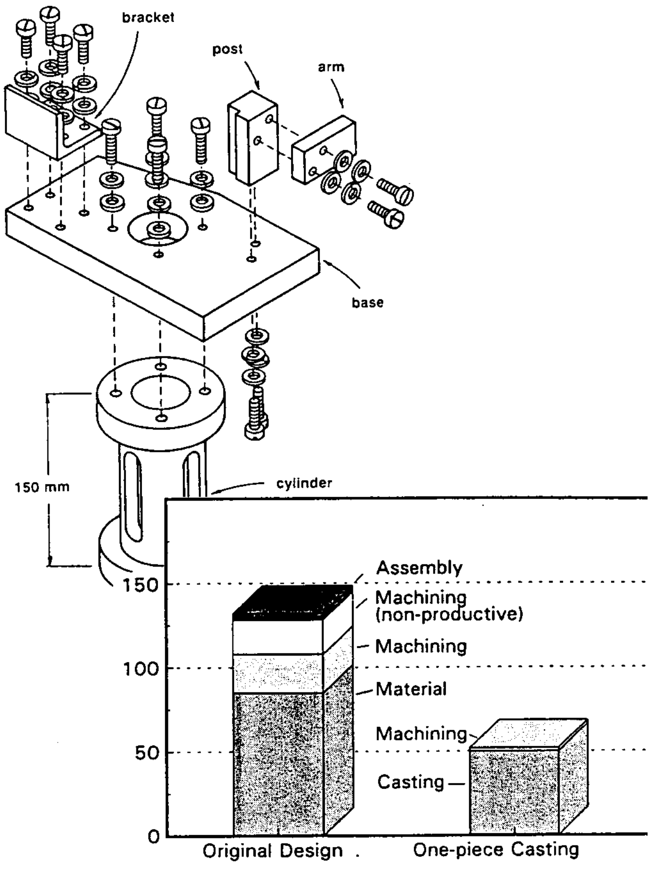


Fig. 7 DFA analysis can reduce total costs significantly even though assembly costs are small.

cannot argue with this. However, DFA is the subject that has been neglected over the years while adequate consideration has always been given to the design of a product for performance, appearance, etc. The other factors, such as quality, reliability, etc., will follow when proper consideration is given to the manufacture and assembly of the product. In fact, Fig. 8 shows a relationship between the design efficiency (Boothroyd Dewhurst DFA Index) and the resulting product quality measured in defective parts per million[37]. Each data point on this graph represents a different product manufactured by Motorola. It clearly shows that if design for assembly is carried out leading to improved design efficiencies, then improved quality will follow.

Some say that DFA leads to products that are more difficult to service. This is absolute nonsense. Experience shows that a product that is easy to assemble is usually easier to disassemble and reassemble. In fact, those products that need continual service involving the removal of inspection covers and the replacement of various items should have DFA applied even more rigorously during the design stage. How many times have we seen an inspection cover fitted with numerous screws, only to find that after the first inspection only two screws are replaced?

There is a danger in using design rules because they can guide the designer in the wrong direction. Generally, rules attempt to force the designer to think of simpler-shaped parts which are easier to manufacture. This can lead to more complicated product structures and a resulting increase in total product costs. In addition, in considering novel designs of parts which perform several functions, the designer needs to know what penalties are associated when the rules are not followed. For these reasons the systematic procedures used in DFA which guide the designer to simpler product structures and provide quantitative data on the effect of any design. changes or suggestions are found to be the best approach.

Results of DFA Applications

DFA provides a systematic procedure for analyzing proposed designs from the point of view of assembly and manufacture. This procedure results in simpler and more reliable products which are less expensive to assemble and manufacture. In addition, any reduction in the number of parts in an assembly produces a snowball effect on cost reduction because of the drawings and specifications that are no longer needed, the vendors that are no longer needed, and the inventory that is eliminated. All of these factors have an important effect on overheads which, in many cases, form the largest proportion of the total cost product.

DFA tools encourage dialogue between designers and the manufacturing engineers and any other individuals who play a part in determining final product costs during the early stages of design. This means that team working is encouraged and the benefits of simultaneous or concurrent engineering can be achieved.

The savings in manufacturing costs obtained by many companies who have implemented DFA are astounding. For example, Ford Motor Company has reported savings in the billions of dollars as a result of applying DFA to the Ford Taurus line of automobiles. NCR anticipates savings in the millions of dollars as a result of applying DFA to their new point-of-sales terminals. These are high volume products. At the other end of the spectrum, where productions quantities ar low, Brown and Sharpe have been able, through DFA, to introduce their revolutionary coordinate measuring machine, the Microval, at half the cost of their competitors, resulting in a multi-million dollar business for the company.

More recently, General Motors has been releasing details of improvements made to their designs. For example, redesign of the Chevrolet headlamps and panel assembly has resulted in 86% fewer parts, 86% fewer operations and 71% less assembly time with annual savings estimated at $3.7 million.[38] In their 1992 Cadillac Seville, the dashboard, seats, bumpers and other elements were redesigned with DFA. The result is 20% fewer parts and, for the rear bumper alone, a 50% reduction in assembly time and annual savings of almost $500,000.

Figure 9 shows the effect of DFA on part count reduction summarizing published results of success stories resulting from the application of the Boothroyd Dewhurst DFA software.

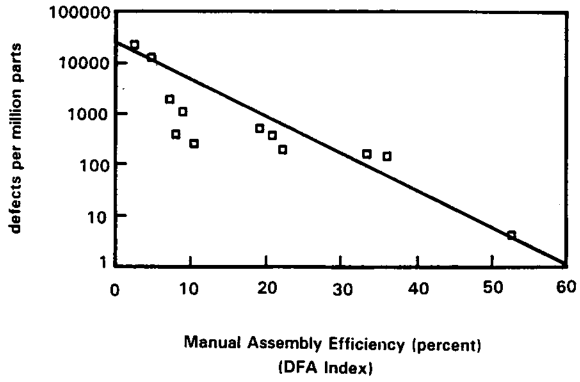


Fig. 8 Improved assembly design efficiency results in increased reliability[37]

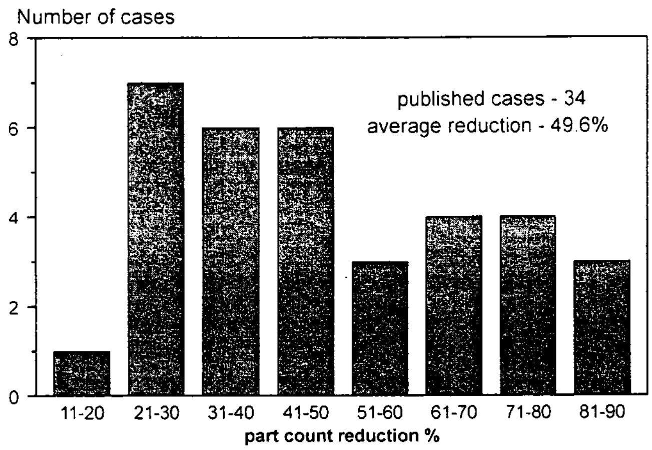


Fig. 9 Summary of published data showing effect of Boothroyd Dewhurst DFA on part count reduction.

Design for Disassembly (DFD)

The rapidly growing concern for environmental protection, occupational health and resource utilization has stimulated many new activities in the industrialized world to cope with the urgent problems created by the steadily increasing consumption of industrial products.

One of the major problems is the disposal of used products. Even though recycling is increasing, huge amounts of solid waste are disposed in landfills creating serious pollution and occupational health problems and it is an unacceptable waste of valuable resources. In the former West Germany for example 2 million cars are dumped each year. Most of the metal parts are reused, but, according to Leich[39], about 400,000 tons are shredded fractions of plastics, glass and wood, and of this, 130,000 tons are plastics. In the U.S.A. it is estimated[40] that the automotive industry over the next four years will generate over 230,000 tons of plastics. Another activity generating huge amounts of solid waste is the disposal of household appliances. These problems are now being recognized by industry due to legislation and consumer demands. Automotive companies are working to improve recyclability by marking materials and changing designs, for example. The appliance and computer industries have also taken up the challenge as well as recycling companies. The Appliance Recycling Centers of America (ARCA) are looking at DFD (Design for Disassembly) to facilitate recycling[41]. The dismantling of products appears to be one of the most serious problems. The products of today are not designed for easy dismantling or disassembly. Integrated design, certain fastening and assembly principles and surface coatings, for example, can make it very difficult to disassemble the product and to separate materials into non contaminated groups.

In the near future it is to be expected that the requirements placed on industrial companies by legislation and consumer demands. will be increased. Alting[42] lists the expected requirements as follows:

-the manufacturer will become responsible for environmentally safe disposal or recycling of his product either through existing disposal channels or by accepting return of the product.
-insurance companies will demand documentation for a life-cycle design approach before accepting liability insurance for a product.
-environmental and occupational health agencies will demand a life-cycle design approach to ensure that the manufacturer has considered the consequences of the product in all its life-cycle phases.
-company shareholders will demand an inclusion of environmental and occupational health issues in the annual reports.

Furthermore, the companies themselves will find it necessary to respond to the market demands for "green products."

Clearly, a new approach will be necessary in the design of products to solve the many problems related to their production, use and disposal. Further, as a part of these methods, rules and guidelines for product design for ease of disassembly (DFD) must be developed.

Life-cycle design as a framework for DFD

Product specifications form the basis for a design. Selection of solutions is based on criteria containing elements like company policy, product properties, manufacturing properties and costs. Normally, neither the specification nor the criteria contain environmental, occupational health, resource utilization and recycling requirements. The cost of disposal is "hidden in our taxes" and is not accounted for by the designer.

A new approach is necessary whereby all life-cycle phases (development, production, distribution, usage, and disposal or recycling) are considered simultaneously from the conceptual product design stage through the detailed design stage (Fig. 10). Selection of technical solutions should be guided by criteria containing the main elements shown in the outer circle in Fig. 10 - namely, environmental protection, working conditions, resource utilization, life-cycle costs, manufacturing properties, product properties and company policy. In this new approach policies must be established for environmental, occupational health and resource issues as well as for the disposal or recycling of the used products. The life-cycle costs of the product must be developed so they can be used as selection criteria.

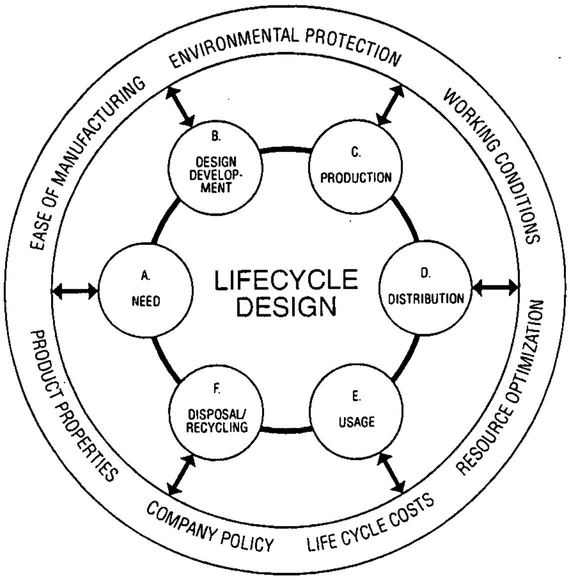


Fig. 10 The life-cycle design concept, Alting[42]

Table 4 shows some interrelated issues in life-cycle design. When DFD is considered it must fulfil the requirements of production, distribution, usage and disposal or recycling. Therefore, it is not sufficient to consider recycling alone as the goal - all the phases must be considered simultaneously. The life-cycle costs of a product can be pictured (Table 5) as built-up from the costs for

-the manufacturer
-the user
-society

If the conceptual designer is able to estimate the costs for the user and society he will be able to modify his design accordingly. Based on a life-cycle cost model he will also be able to foresee the consequences of the DFD method because DFD will reduce the cost for the user and society due to environmental, occupational health and resource utilization improvements.

DESIGN	PRODUCTION	DISTRIBUTION	USAGE	DISPOSAL/-RECYCLING
• product specifications • design principles -product structure -functional units -materials • design guidelines -manufacture -assembly -distribution -usage (service/repair) -disposal -recycling • assessment of consequences on -environment -occupational health -resource utilization	• production systems -processes -joining and assembly -automation • energy utilization • material utilization • environmental and occupational health issues • organization	• distribution principles • transportation processes • energy utilization • environmental and occupational health issues • product structure (size, weight, packaging units) • disassembly during transportation	• usage functions • maintenance (repair, service) • energy consumption • material consumption • environmental and occupational health issues	• recycling market, structure, organization • re-use • re-manufacture • dismantling -functional units -materials -incineration -dumping • recycling processes • energy issues • environmental and occupational health issues
• life-cycle cost	production costs	distribution costs	usage costs	disposal/recycling costs

Table 4 Some of the interrelated issues in the product life-cycle.

	COMPANY COST	USERS COST	SOCIETY COST
NEED	market recognition		
DESIGN	development		
PRODUCTION	materials, energy, facilities, wages, salaries etc.		waste pollution health damages
DISTRIBUTION	transportation storage waste	transportation storage	waste pollution packings health damages
USAGE	warranty service	energy, materials, maintenance	waste pollution health damages
DISPOSAL		disposal dues	waste handling disposal health damages pollution
RECYCLING		recycling dues	waste pollution health damages

Table 5 The life-cycle cost elements, Alting[42].

DFD developments underway

The following descriptions are based on contributions to this keynote paper from CIRP members. They are, therefore, only to be considered as indicators of the increasing efforts in research and development related to DFD (and the broader life-cycle concept) and not as a result of an exhaustive literature study.

Several activities related to recycling and DFD are being carried out at WZL, Technical University, Aachen[43-46]. A thesis by Barg[43] entitled "A concept for recycling oriented product and production planning" describes steps and procedures in product development that will emphasize recycling as well as DFD. Esser and Schneewind[44] are working on Design for Recycling where DFD plays a major role. Hartmann and Baumann[45] are working with cost models for assembly, and Hartmann and Linnhoff[46] are studying the recycling of products and DFD.

At IPA, Fraunhofer Institute, Stuttgart,[47,48] several activities are focused on recycling oriented topics. As long ago as 1983, Warnecke and Steinhilper[47] considered "designing products with built-in reconditioning features" - a subject which has now become highly topical.

Kahmeyer[48] is studying flexible disassembly using industrial robots. A pilot disassembly cell has been constructed and has been tested with good results when applied to telephone disassembly. Computer disassembly by industrial robots is also being considered. As a result of this work, a set of DFD guidelines have been identified[48].

At the Manchester Polytechnic, U.K., Simon[49] has established a research program on the environmental aspects of engineering design. As a part of this program Design for Dismantling plays a major role. Several rules or guidelines have been developed facilitating re-use, re-manufacture and recycling. Using these guidelines, the designer is made aware of the recycling possibilities and the directions to take in minimizing costs.

At the Swiss Federal Institute of Technology (ETH), Züst is studying environmentally friendly products and processes[50]. Recyclability is an important element of this work.

Seliger and Krause[51] have recently initiated activities at the Technical University of Berlin in the areas of DFD and Product Modeling - including life-cycle issues.

At Karlsruhe University, Schmidt[52] has initiated activities related to recycling and DFD for high value industrial products. Cost-drivers for disassembly are being especially considered.

Alting[42] has initiated a large number of projects at the Technical University of Denmark. A program aiming at developing methods and tools for assessing the environmental. occupational health and resource utilization consequences in the life-cycle phases of a product has five industrial partners (Danfoss, Grundfos, Bang & Olufsen, KEW Industries, and Brdr. Gram). The partners are carrying out new product developments according to the life-cycle concept. Here recycling and DFD are important areas. A project in developing life-cycle cost models as a design tool has recently been initiated. Recycling of electronic products is another area covered in a joint industrial project also aiming at DFD guideline developments. A special project focuses on large off shore steel constructions and ships with emphasis on recycling. The impact of the life-cycle concept on future production systems is discussed by Alting and Pedersen[53].

At the University of Rhode Island Subramani and Dewhurst[54] have established an extensive activity on developing a DFD method supporting their present DFM/DFA research and development. It is their intention to computerize their DFD method.

At Daimler-Benz, many activities related to environmentally friendly products and productions as well as to recycling are ongoing[55].

Leich[39] describes how Bayer, Hoechst and BASF have founded an organization to support the recycling of plastics - especially in the automotive industry. Areas like proper material selection, marking and DFD are being considered.

In an editorial note, Holt[40] describes how the SAE Plastics Committee has prepared a document SAE J1344 on the marking of plastic parts to facilitate recycling.

Various DFD activities were described by Brooke[56] at an SME Seminar on.

In his paper, "Design for Disassembly Focuses on Fastening" Babyak[57] discusses fasteners that will facilitate disassembly.

Remich [41] describes an electric kettle which was designed to be fully recyclable. The kettle is marketed by Great British Kettles, USA.

The PRAVDA-project[58] is a group of six disassembly projects run by major German motor manufactures and scrap vehicle companies to accommodate expected legislation on the recycling of old cars requiring the manufacturer or the seller to reclaim and recycle all materials.

Inoue and Sato[60] of the Mechanical Engineering Laboratory (Agency of Industrial Science and Technology, and Ministry of International Trade and Industry) give a short overview of design from the viewpoint of environmental problems. At the MEL an industrial collaboration program "Technologies for ECO-factory" has been initiated. Focus areas are: product technology, production technology, disassembly technology and recycling technology. Within each of these technologies specific research and development areas have been identified.

Team Xerox, Center for Productivity and Assembly, USA[61] is working on Design for Recycling. Xerox is "committed to designing products for optimal recyclability and reusability and equally committed to exploring every opportunity to recycle or reuse waste materials generated by Xerox operations." This shows how a company has established firm policies and initiated cross company activities to enforce the policies.

The above descriptions, even if they only are a small portion of the activities going on within DFD, recycling, life-cycle design. clearly illustrate that the research and industrial communities have understood the seriousness of the problems. It is a must that these issues are now made a part of engineering educational programs.

DFD Considerations

In this section a few of the reported DFD guidelines are described. It should be noted that disassembly concerns the following life-cycle phases:

- -Usage
    - *Maintenance (repair, service)
- -Disposal or recycling
    - *Re-use, re-manufacture of the whole product or functional units
    - *Recycling of materials

Disassembly may also be relevant for

- -Distribution
    - *Large constructions (on site assembly)
    - *Basic transportation (size, weight, packaging for example)
    - *Consumer products assembled by the user

Disassembly requirements will influence production methods and processes. However, it will take much research to structure the field and develop DFD methods, but awareness of the problems has already led to improved designs.

Table 6 shows the DFD guidelines described by Kahmeyer[48]. Table 7 shows Recycle Design Considerations, developed by GE Plastics[59].

Design for Disassembly Guidelines			Main-tenance	Remanu-facturing	Materials-recycling
PHASE I: DRAFT					
Linear and unified disassembly direction	B	A	X	X	X
Sandwich structure with central joining elements	A	A	X	X	X
Base part product structure	B	A	X	X	X
Standardized assembly groups for variants	A	A	X	X	X
Avoid non-rigid parts	C	B	X	X	X
PHASE II: DESIGN					
Integration of parts	B	B	X	X	X
Include nominal breakpoints	B	B			X
Operating spots for destroying separation tools	B	B			X
Minimize number of joining elements	A	A	X	X	
Use joining elements that are detachable or easy to destroy	A	A	X	X	
Parts should be easy to pile or store to save room	C	B		X	
Non-ageing material combination	A	A	X	X	
Non-corrosive material combination	A	A	X	X	
Protect assembly groups from soiling or corrosion	A	B	X	X	
Design of parts for easy transport	C	B		X	
Limitation to number of different materials	B	B			X
Integration of poisonous substances in closed units	A	C	X	X	X
Avoid turning operations for disassembly	C	B	X	X	X
PHASE III: SPECIFICATION					
Standardize parts for multiple use	B	A	X	X	
Standard and simple joining techniques	B	A	X	X	
Marking of central joining elements for disassembly	B	C	X	X	X
Open access and visibility at separation points	A	A	X	X	X
Centre-elements on base parts	C	A	X	X	X
Standard gripping spots near center of gravity	C	B	X	X	X
Enable simultaneous separation and disassembly	B	B	X	X	X
Avoid necessity for simultaneous disassembly at different joining elements	B	A	X	X	X
Use of parts with narrow tolerance	C	B	X	X	X
A: Very important B: important C: less important					

Table 6 DFD Guidelines, Kahmeyer (48).

- Use compatible materials
- Use recyclable materials including bonding aspects
- Minimize material count, using the least number of different polymers
- Minimize assembly operations
- Design for easy separation, handling and cleaning
- Simplify potential uses/users of products and parts
- Use two-way snap fits/break points on snap fits
- Provide standard, easy identification for all materials (molded-in material name or logo)
- Identify separation or cut points
- Use molded-in material name in multiple locations to accommodate cut points
- Avoid secondary finishing operations such as painting, plating, coating and so forth
- Avoid toxic materials/foams, blowing agents (CFC's), heavy metals and so forth
- Minimize waste in production, for example by incorporating material handling programs to lower the cost of manufacturing
- Understand side effects of processes and equipment emissions, such as paint vapor and abusive molding
- Avoid inserts

Table 7 DFD for plastic products [59].

In general it can be assumed that DFD guidelines will include:

-product structure (organization of functional units, easily accessible and easy to assemble, easy to separate, for example)
-design of functional units (not integrated)
-material selection (few identifiable, separable materials for example)
-minimize waste and harmful contaminating materials
-recycling principles and requirements

These few examples only serve the purpose of illustrating the level of DFD guidelines at present. When DFD methodologies or guidelines are developed they will, for example, influence the environmental issues, maintenance (repair, service) traditions.

Influence of DFD on Environmental Issues

DFD has a major influence on recyclability and easy disassembly makes it possible to re-use, remanufacture and recycle materials in an efficient manner. Re-use and re-manufacture will save many resources in prolonging the useful life-time of products and functional units. The automobile industry has used these principles for some time and now the appliance industry is following. DFD will make these activities easier and more economical. Minimizing the use of new resources will prevent new pollution from resource production (materials and energy). DFD will make it easier to separate materials into groups without contamination - for example copper and tin in steel. Plastics will be recycled to a much higher degree than previously. But still much research has to be carried out concerning the properties of recycled materials. New materials must be developed and the number of different materials used in a specific product will tend to decrease.

Close collaboration with the recycling industry will be necessary. If the manufacturer becomes responsible for the environmentally safe disposal of his product, he will be forced to make agreements with recycling companies or establish his own recycling business. This will force new quality requirements on recycling and provide new business opportunities. DFD will enhance recycling and the quality of recycling, leading to much lower environmental damages.

Influence of DFD on Maintenance

Today many products are not repaired when they fail. This is partly due to high repair costs since the products are not designed for repair. If products are designed for repair or service and DFD principles applied, many products would have a longer useful life. DFD will facilitate repair and service and perhaps allow many users to perform the repair or service themselves.

In general a new concept may be that a manufacturer does not sell his products, but only the right to use them. He then makes it his business to service the product and dispose of it after final use. In this case, the manufacturer will be motivated to apply DFD fully and use the life-cycle-design concept, Alting & Pedersen[15].

The enforcement of this development will come from increasing disposal costs and legislation. The legislation may say that the manufacturer is responsible for the product in all life-cycle phases and for the disposal of the product, or it may say that the manufacturer must pay the full disposal costs including environmental and occupational health damages. Therefore, the manufacturer will apply life-cycle design and DFD extensively and develop new business concepts.

The Roles of DFA and DFD in Simultaneous Engineering

The life-cycle concept including DFA and DFD is a powerful tool for simultaneous (or concurrent) engineering. At the conceptual design stage the consequences on the environment, occupational health and resource utilization must be assessed in all life-cycle phases. The authors therefore believe that DFA and DFD will be the cornerstones of true simultaneous engineering.

Conclusions

Since DFA was introduced around 1980, there has been an exponential increase in the number of articles dealing with the subject. As we have seen in this keynote paper, the methodology has expanded to include all aspects of product design for ease of manufacture and assembly. It has also proved to be a catalyst for teamwork and considerations of simultaneous engineering which is the subject of another keynote paper at this CIRP General Assembly.

Because of the enormous volume of literature now available, it was necessary to bias this review in favor of the contributions received from CIRP members. However, other references have been included in an attempt to provide as broad a view as possible.

DFA has proved to have a major influence on the design of products generating better and more competitive products. It has also reduced time to market, reduced overheads and has led to the idea of simultaneous or concurrent engineering. DFD will add a new dimension to DFA so that DFA/DFD covers all life-cycle phases of the product and stimulates simultaneous engineering since it is at the conceptual design stage that DFA/DFD should be applied. Further, new structures and organizations will be seen in the recycling market enabling a much more efficient and economical recycling of materials. New business opportunities will also appear. For example, the manufacturer may not sell their products but only the right to use them so that maintenance and disposal is in the hands of the manufacturers.

Acknowledgements

The authors wish to thank those individuals, too numerous to mention, who submitted contributions to this keynote paper.

References

1. Munro & Associates, Inc., 911 W. Big Beaver Rd., Suite 309, Troy, Michigan 48084.

2. Manufacturing Producibility Handbook, General Electric Co., Manufacturing Services, Schenectady, NY, 1960.

3. Miyakawa, S. and Ohashi, T., "The Hitachi Assemblability Evaluation Method (AEM)," Proc. Int. Conference on Product Design for Assembly, Newport, RI, April 15-17, 1986.

4. Boothroyd, G. and Dewhurst, P., "Product Design for Assembly," Designers Handbook, Boothroyd Dewhurst, Inc., 138 Main Street, Wakefield, RI 02879.

5. Hashizume, S., Matsunaga, M., Sugimoto, N., Miyazawa, S. and Kishi, M., "Development of an Automatic Assembly System for Tape-Recorder Mechanisms," Research and Development in Japan 1980.

6. Miyakawa, S., Ohashi, T. and Iwata, M., "The Hitachi New Assemblability Evaluation Method (AEM), Trans. of the North American Manufacturing Research Institution of SME, May 23-25, 1990.

7. Boothroyd, G., "Design for Economic Manufacture," Annals of CIRP, Vol. 28/1/79, p. 345.

8. Elmaraghy, H.A. and Kroll, L., "Flexible Assembly of a Family of DC Motors," Manufacturing Review, Vol. 2 No. 4, Dec. 1989.

9. Warnecke, H.J. and Bassler, R., "Design for Assembly - Part of the Design Process," Annals of CIRP,Vol. 37/1/88, p. 1.

10. Miles, B.L. and Swift, K.G., "Working Together," Manufacturing Breakthrough, March/April 1992, p. 69.

11. Kroll, E.; Lenz, E. and Wolberg, J. R., "A Knowledge-based Solution to the Design for Assembly Problem," Manufacturing Review, Vol. 1 No. 2, June 1988.

12. Yamigiwa, Y., "An Assembly Ease Evaluation Method for Product Designers: DAC," Techno Japan, Vol. 21 No. 12, Dec. 1988.

13. Angermuller, G. and Moritzen, K., "A Knowledge-based System Supporting Product Design for Mechanical Assembly," 1st Conf. Artificial and Expert Systems in Manufacturing, March 1990, p. 181.

14. Rosario, L.M. and Knight, W.A., "Design for Assembly Analysis: Extraction of Features from a CAD System Database," Annals of CIRP, Vol. 38/1/1989, p. 13.

15. Eversheim, N. and Baumann, M., "Assembly-oriented Design Process," Computers in Industry, 1991.

16. Molloy, E., Yang, H. and Browne, J., "Design for Assembly Within Concurrent Engineering," Annals of CIRP, Vol. 40/1/91, p. 107.

17. Scarr, A.J., "Product Design for Automated Manufacture and Assembly," Annals of CIRP, Vol. 35/1/1986, p. 1.

18. Schmidt, J. and Bernhart, W., "Computer-aided Assembly-oriented Variant Analysis" submitted asa contribution to keynote paper from Lehrstulil und Institut fur Werkzeng maschinen und Betriebstechnik, Univesitat (TH), Karlsruhe, Nov. 16, 1991.

19. Roth, N., letter to G. Boothroyd from Siemens, A.G., Corporate Production and Logistics, ZPL 1 1F 3, P.O. Box 83 09 53, 8000 Muenchen 83, Nov. 11, 1991.

20. Santochi, M., Giusti, F. and Divi, G., "Robotized Tool Assembly for the Automated Tool-room," Proc. of the Int. Conf. on Innovative Metalcutting Processes and Materials, Torino, Italy, Oct. 2-4, 1991.

21. Nee, A.Y.C., letter to G. Boothroyd enclosing a contribution by N.S. Ong, Nanyang Technological Institute, Singapore, Nov. 11, 1991.

22. Miller, T. and Vollmann, T., "The hidden factory," Harvard Business Review, 1985, 63(5).

23. Cooper,1 R., "Implementing an activity-based cost system," Journal of Cost Management, 1990, 4(1), 33-42.

24. Beaujon, G.J. and Singhal, V.R., "Understanding the activity cost in an activity-based cost system," Journal of Cost Management, 1990, 4(1), 55-72.

25. Kaplan, R.S., "Measuring manufacturing performance: A new challenge for managerial accounting research," The Accounting Review, 1983, 58(4), 686-705.

26. Tay, S.L., "The ABCs of ABC," IBM Showcase 1991, August 1991, Singapore.

27. Selinger, G. and Barbey J., "Method for the Simultaneous Planning of Product and Assembly Organization," submitted as a contribution to keynote paper from IPK Fraunhofer Inst., Berlin, Nov. 29, 1991.

28. Adachi, T.; Kobayakawa, S.; Koh, H. and Inoue, I, "Bridging the Gap between a Product Design Sector and a Production Sector: Conceptualization and a Support Tool," 8th International Conference on Production Research 1985.

29. "A Manufacturability Index for PCB Assemblies," Xerox Corp. Electronics Division, Manufacturing Research, El. Segundo, CA, May 1979.

30. Miyakawa, S., "Simultaneous Engineering and the Producibility Evaluation Method," SME Int. Conf. on the Application of Manufacture Technologies, Washington, CD April 17-19, 1991.

31. Takahashi, K., Suzuki, I and Suguro, T., "Producibility Evaluation Method," 10th International Conference of Assembly Automation.

32. Boothroyd, G. and Radovanovic, P., "Estimating the Cost of Machined Components During the Conceptual Design of a Product," Annals of CIRP, Vol. 38/1/1989, p. 157.

33. Dewhurst, P., "Computer-Aided Assessment of Injection Molding Cost - A Tool for DFA Analyses," Report No. 24, Dept. of Industrial and Manufacturing Engineering, University of Rhode Island, 1987.

34. Dewhurst, P. and Blum, C., "Supporting Analyses for the Economic Assessment of Diecasting in Product Design," Annals of CIRP Vol. 38/1/1989, p. 161.

35. Zenger, D. and Dewhurst, P., "Early Assessment of Tooling Costs in the Design of Sheet Metal Parts," Report No. 29, Dept. of Industrial and Manufacturing Engineering, University of Rhode Island, 1988.

36. Knight, W.A., "Design for Manufacture Analysis: Early Estimates of Tool Costs for Sintered Parts," Annals of CIRP, Vol. 40/1/91, P. 131.

37. Branan, B., Motorola Inc., "Design for Assembly Cuts Assembly Defects by 80 Percent," Appliance Manufacture, No. 1991.

38. Munro, A., "The Cadillac Success Story," Proc. International Forum on Design for Manufacture and Assembly, June 15-16, 1992.

39. Leich, S., "Bayer: new initiatives in recycling," Business International, Oct./Nov. 1991.

40. Holt, D.J., "Editorial note (SAE J1344),"Automotive Engineering, Nov. 1991.

41. Remich, N.C., "First Recyclable Appliance," Appliance Manufacturer, June 1991.

42. Alting, L., "Life-cycle design of industrial products," Concurrent Engineering, Vol. 1, Nov. 6, 1991.

43. Barg, A., "Konzeption einer recyclinggerechten Produkt- und Produktionsplanung," Dr.ing. Speach, January 1991 (WZL, Aachen)

44. Esser, H. and Schneewind, J., "Recyclinggerechte Produktentwicklung," Part of Study program "Abfall und Recycling," Nov. 1990 (WZL, Aachen).

45. Hartmann, H. and Baumann, M. "Cost-model for Assembly," Overhead foils sent by WZL, Aachen, 1991.

46. Hartmann, H. and Linnhoff M., "Demontage", Overhead foils sendt by WZL, Aachen, 1991.

47. Warnecke, H.J., and Steinhilper, R. "Designing products with built-in reconditioning features," Proceeding of Design Engineering Conference, Birmingham, 1983.

48. Kahmeyer, M., "Flexible Disassembly with Industrial Robots," Paper sent from IPA, Stuttgart, 1991.

49. Simon, M. "Design for Dismantling," Professional Engineering, Nov. 1991.

50. Züst, R. and ,Wagner, R., "Produkt und Produktionsgestaltung: Wie weiter?" Management Zeitschrift 60, 1991, no. 10.

51. Seliger, G. and Krause, F.L., "Private Communicationes," Techische Universitat, Berlin, 1991.

52. Schmidt, J., "Private Communicationes," Universitat, Karlsruhe, 1991.

53. Alting, L. and Pedersen, M.A., "Life-cycle design of products; An important part of the CIM philosophy," Autofact Proceedings 1991, Chicago.

54. Subramani, A.K. and Dewhurst, P., "Automatic Generation of Product Disassembly Sequences," Annals of CIRP, Vol. 40/1/91, P. 115.

55. Zürn J., "Private Communications," Daimler-Benz, 1991.

56. Brooke, L., "Think DFD!", Automotive Industries, Sept. 1991.

57. Babyak,R., "Design for Disassembly Focuses on Fastening," Appliance Manufacturer, June 1991.

58. "The PRAVDA programme," Business International, Oct./Nov. 1991

59. "Recycling Design Considerations," (GE Plastics, USA), Appliance Manufacturer, June 1991.

60. Inoue, N. and Sato, H., "Design from the Viewpoint of Environmental Problems," Note to the Authors, 92.

61. Hilbert, Harry, "Design for recycling," Center for Producibility and Assembly, Team Xerox.