Product design for manufacture and assembly

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Design is the first step in manufacturing, and it is where most of the important decisions are made that affect the final cost of a product. Since 1980, analysis techniques have been made available which can guide designers towards products which are easy to manufacture and assemble. The availability of these techniques has created a revolution in manufacturing industry, especially in the USA, leading to reduced product cost, better quality, shorter time to market, lower inventory, few suppliers, and many other improvements.

The paper first stresses the importance of taking careful account of manufacturing and assembly problems in the early stages of product design. Then, using a case study, the philosophy of the Design for Manufacture and Assembly (DFMA) methodology and its application are explained. The historical development of design-for-assembly and design-for-manufacturing techniques in Japan, Europe and the USA is presented. A review of published case histories emphasizes the enormous advantages to be gained by adopting this relatively new approach as the major tool in concurrent and simultaneous engineering. Finally, a discussion of the various roadblocks affecting DFMA implementation is followed by a discussion of current developments, which include product design for disassembly, service and recycling.

Keywords: assembly, manufacture

It has been estimated that, in the USA, manufacturing contributes about 23% of the gross national product, and, more importantly, about 70% of all wealth-producing activities. Those who complacently say that the USA is changing to a service economy may eventually find that they no longer have the means to purchase these services. The USA has been losing \$340M per day to its foreign competitors, and the national debt is now around \$4 000 000M!

Competitiveness has been lost in many areas, most notably, as can be seen in *Figure 1*, in automobile manufacture. In 1990, the results of a \$5M worldwide study of this industry was published[1]. The study attempted to explain the wide variations in automobile assembly-plant productivity throughout the world. *Figure 2* (which is taken from this study) shows that Japan has the most productive plants. However, it was found that automation could only account for one-third of the total difference in productivity between plants, and that, at any level of automation, the difference between the most and least efficient plants is enormous. For example, the least-automated Japanese domestic plant (in which 34% of all steps are accomplished automatically), which is also the most efficient plant in the world, needs one-half of the human effort of one comparably automated European plant, and one-third of the effort of another. The European plant that is the most automated in the world (in which 48% of all assembly steps are automated) requires 70% more effort to perform a standard set of assembly tasks on a standard car than does the most efficient plant, which is only 34% automated.

The question is that of whether manufacturability and ease of assembly are more important than automation in improving productivity. The authors of the study conclude that no improvements in operation can make a plant fully competitive if the product design is defective. However, they fail to make a direct connection between product design and productivity, and an attempt is made in this paper to show that there is now overwhelming evidence to support the view that product design for manufacture and assembly can be the key to high productivity in all manufacturing industries.

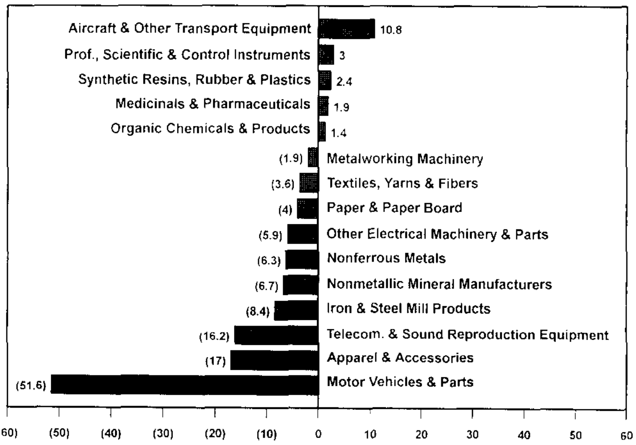

Figure 1 Breakdown of US trade balance [Values in $\$ \times 10^9$.]

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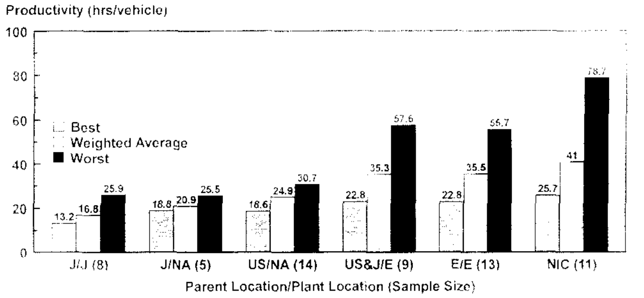

Figure 2 Worldwide automobile assembly-plant productivity (volume producers in 1989)
[Adapted from Reference 1. The volume producers include the US 'big three', Fiat, PSA, Renault and Volkswagen in Europe, and all of the Japanese companies. J/J: Japanese-owned plants in Japan, J/NA Japanese-owned plants in North America, including joint-venture plants with American firms, US/NA: US-owned plants in North America, US&J/E: US- and Japanese-owned plants in Europe, E/E European-owned plants in Europe, NIC: plants in newly industrializing countries: Mexico, Brazil, Taiwan and Korea. Source: International Motor Vehicle Program Study.]

DESIGN FOR MANUFACTURE AND ASSEMBLY

In the context of this paper, design is the first step in manufacture, and it is an activity that starts with sketches of parts and assemblies, and progresses to the drawing board or CAD workstation, where assembly drawings and detailed part drawings are produced. These drawings are then passed to the manufacturing and assembly engineers, whose function is to optimize the processes used to produce the final product. Frequently, it is at this stage that manufacturing and assembly problems are encountered and requests are made for design changes. Sometimes, these design changes result in considerable delays in the final product release. In addition, the later in the product design and development cycle the changes occur, the more expensive they become. Therefore, not only is it important to take manufacture and assembly into account during product design, but also these considerations must occur as early as possible in the design cycle.

This is shown qualitatively by the chart in *Figure 3*, which shows that extra time spent early in the design process is more than compensated for by savings in time when prototyping takes place. Thus, in addition to reducing product costs, the application of the Design for Manufacture and Assembly (DFMA) methodology* shortens the time taken to bring the product to market. As an example, the Ingersoll Rand Company reported[2] that the application of DFMA reduced product development time from two years to one. In addition, the design team reduced the number of parts in a portable compressor radiator and oil-cooler assembly from 80 to 29, decreased the number of fasteners from 38 to 20, trimmed the number of assembly operations from 159 to 40, and reduced the assembly time from 18.5 min to 6.5 min. Development started in June 1989, and the new design went into full production in February 1990.

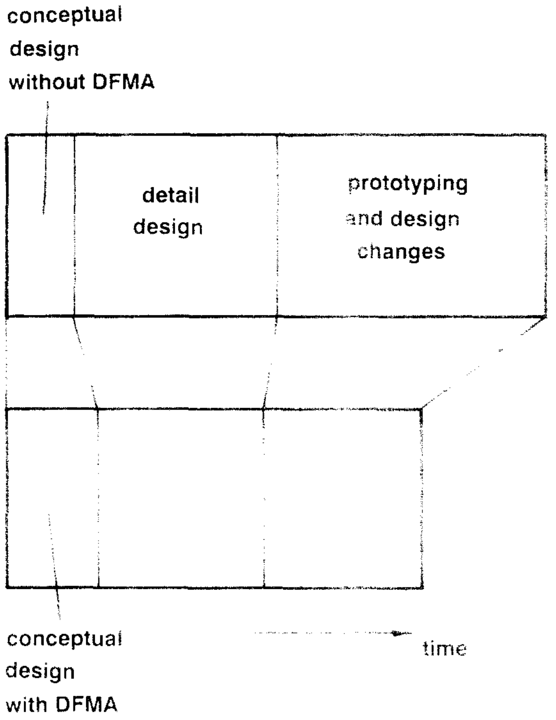

Figure 3 Shorter design-to-production times through use of DFMA early in design process

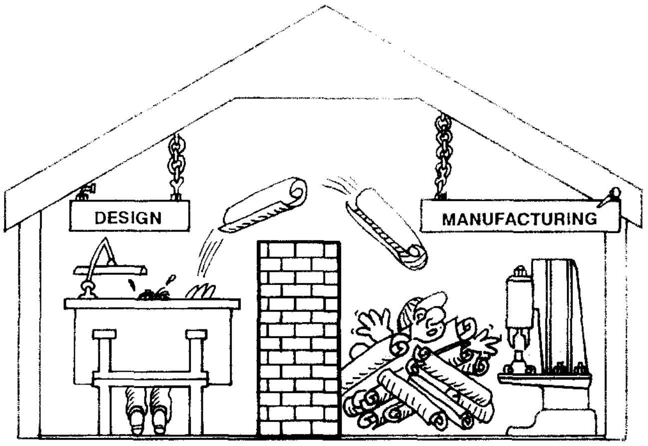

Figure 4 'Over the wall' design
[Reproduced by courtesy of Munro & Associates Inc., Suite 309, 911 W Big Beaver Road, Troy, MI 48084, USA.]

Traditionally, the attitude of designers has been 'we design it, you build it'. This has now been termed the 'over-the-wall approach', in which the designer throws the designs over a wall to the manufacturing engineers, who then have to deal with the various manufacturing problems arising because they were not involved in the design effort (see *Figure 4*). One means of overcoming this problem is to consult the manufacturing engineers at the design stage. The resulting teamwork avoids many of the problems that arise. However, these teams, now called simultaneous-engineering or concurrent-engineering teams, require analysis tools to help them study proposed designs and evaluate them from the point of view of manufacturing and assembly difficulty and cost.

HOW DFMA WORKS

By way of example, *Figure 5* shows the requirements of a motor-drive assembly that must be designed to sense

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*'DFMA' is a trademark of Boothroyd Dewhurst Inc., USA.

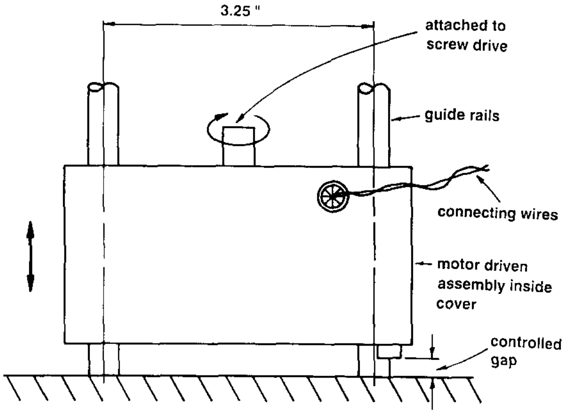


Figure 5 Configuration of required motor-drive assembly

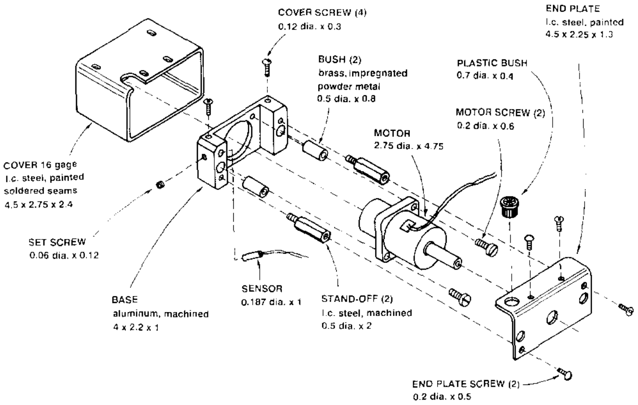


Figure 6 Initial design of motor-drive assembly

and control its position on two steel guiderails. The motor must be fully enclosed for aesthetic reasons, and have a removable cover for access so that the position sensor can be adjusted. The principal requirements are a rigid base that is designed to slide up and down the guiderails, and that supports the motor and sensor. The motor and sensor have wires that connect them to a power supply and a control unit, respectively.

A proposed solution is shown in *Figure 6*. The base is provided with two bushes to provide suitable friction and wear characteristics. The motor is secured to the base with two motor screws, and a hole in the base accepts the cylindrical sensor, which is held in place with a set screw. To provide the required covers, an end plate is secured by two end-plate screws to two standoffs, which are, in turn, screwed into the base. This end plate is fitted with a plastic bush through which the connecting wires pass. Finally, a box-shaped cover slides over the whole assembly from below the base, and is held in place by four cover screws, two passing into the base, and two into the end cover.

Two subassemblies are required, the motor and the sensor, and, in this initial design, there are eight additional main parts, and nine screws, making a total of 19 items to be assembled.

When DFMA began to be taken seriously in the early 1980s, and the consequent benefits were appreciated, it became apparent that the greatest improvements arose from simplification of the product by reduction of the number of separate parts. To give guidance to the designer in reducing the part court, the DFMA methodology^3 provides three criteria against which each part must be examined as it is added to the product during assembly:

- During the operation of the product, does the part move relative to all the other parts already assembled? Only gross motion should be considered; small motions that can be accommodated by integral elastic elements, for example, are not sufficient for a positive answer.
- Must the part be of a material that is different from those of all the other parts already assembled, or must it be isolated from these? Only fundamental reasons relating to materials properties are acceptable.
- Must the part be separate from all the other parts already assembled because necessary assembly or disassembly of other separate parts would otherwise be impossible?

The application of these criteria to the proposed design (see *Figure 6*) during assembly proceeds as follows:

- The base is assembled into a fixture, and, since there are no other parts with which to combine it, it is a theoretically necessary part.
- The two bushes do not satisfy the criteria, and can theoretically be integral with the base.
- The motor is a standard subassembly of parts which is a purchased item. Thus, the criteria cannot be applied unless the assembly of the motor itself is considered as part of the analysis. In this example, we assume that the motor and sensor are not to be analysed.
- Invariably, separate fasteners such as the two motor screws do not meet the criteria, because an integral fastening arrangement is always theoretically possible.
- The sensor is a purchased item.
- The set screw is theoretically not necessary.
- The two standoffs do not meet the criteria; they could be incorporated into the base.
- The end plate must be separate for reasons of assembly.
- The two end-plate screws are theoretically not necessary.
- The plastic bush can be of the same material as, and therefore combined with, the end plate.
- The cover can also be combined with the end plate.
- Finally, the four cover screws are theoretically not necesary.

From this analysis, it can be seen that, if the motor and sensor subassemblies can be arranged to snap or screw into the base, and a plastic cover can be designed to snap on, only four separate items will be needed, instead of 19. These four items represent the theoretical minimum number needed to satisfy the constraints of the product design without consideration of the practical limitations.

It is now necessary for the designer or design team to justify the existence of those parts that have not satisfied the criteria. Justification may arise from practical, technical or economic considerations. In this example, it can be argued that two motor screws are needed to secure the motor, and one set screw is needed to hold the sensor, because any alternatives would be impractical for a low-volume product such as this.

It can be argued that the two powder metal bushes are unnecessary, because the base could be machined from an alternative material with the necessary frictional characteristics.

Finally, it is very difficult to justify the separate standoffs, end plate, cover, plastic bush and associated six screws.

Now, before an alternative design can be considered, it is necessary to have estimates of the assembly times and costs, so that any possible savings can be taken into account when considering design alternatives. Using DFMA time standards and knowledge bases, it is possible to make estimates of assembly costs, and then to estimate the cost of the parts and associated tooling, without having final detail drawings of the parts.

First, *Table 1* shows the results of the DFA analysis; the total assembly time is estimated to be 160 s. It is also possible to obtain an absolute measure of the quality of the design for ease of assembly. The theoretical minimum number of parts is four, as explained above, and, if these parts were easy to assemble, they would take 3 s each to assemble on average. Thus, the theoretical minimum (or ideal) assembly time is 12 s, a figure which can be compared with the estimated time of 160 s, giving an assembly efficiency (or DFA index) of 12/160, or 7.5%.

The elimination of parts not meeting the minimum part-count criteria, and which cannot be justified on practical grounds, results in the design concept shown in *Figure 7*. Here, the bushes are combined with the base, and the standoffs, end plate, cover, plastic bush and six associated screws are replaced by one snap-on plastic cover. The eliminated items entailed an assembly time of 97.4 s. The new cover takes only 4 s to assemble, and it avoids the need for a reorientation. In addition, screws with pilot points are used and the base is redesigned so that the motor is self-aligning. *Table 2* presents the results of a DFA analysis of the redesigned assembly; the new assembly time is only 46 s, and the design efficiency has increased to 26%.

Finally, *Table 3* compares the cost of the parts for the two designs. It can be seen that there is a saving of $13.71 in parts costs. However. the tooling for the new cover is estimated to be $5000 — an investment that would have to be made at the outset. Thus, the outcome of this study is a second design concept that represents a total saving of $14.66, of which $0.95 represents the savings in assembly time.

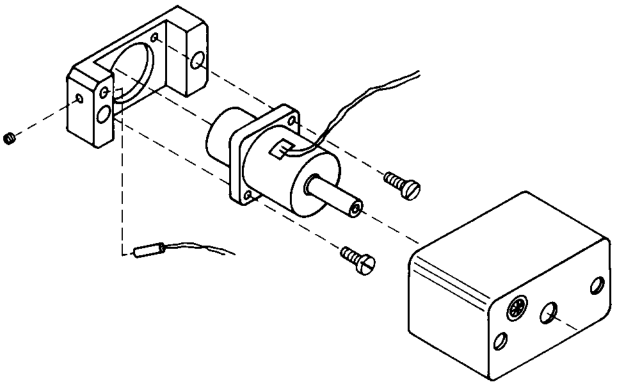


Figure 7 Redesign of motor-drive assembly following design-for-assembly analysis

Table 1 Results of DFA analysis for initial design of motor-drive assembly

Item	Number	Theoretical part count	Assembly time, s	Assembly cost, US cents
Base	1	1	3.5	2.9
Bush	2	0	12.3	10.2
Motor subassembly	1	1	9.5	7.9
Motor screw	2	0	21.0	17.5
Sensor subassembly	1	1	8.5	7.1
Set screw	1	0	10.6	8.8
Standoff	2	0	16.0	13.3
End plate	1	1	8.4	7.0
End-plate screw	2	0	16.6	13.8
Plastic bush	1	0	3.5	2.9
Thread leads	—	—	5.0	4.2
Reorient	—	—	4.5	3.8
Cover	1	0	9.4	7.9
Cover screw	4	0	31.2	26.0
Totals	19	4	160.0	133.0

[Design efficiency = 4 × 3/160 = 7.5%.]

Table 2 Results of DFA analysis for redesign of motor-drive assembly

Item	Number	Theoretical part count	Assembly time, s	Assembly cost, US cents
Base	1	1	3.5	2.9
Motor subassembly	1	1	4.5	3.8
Motor screw	2	0	12.0	10.0
Sensor subassembly	1	1	8.5	7.1
Set screw	1	0	8.5	7.1
Thread leads		—	5.0	4.2
Plastic cover	1	1	4.0	3.3
Totals	7	4	46.0	38.4

[Design efficiency = 4 × 3/46.0 = 26%.]

Table 3 Comparison of part costs for motor-drive assembly design and redesign

Proposed design		Redesign	
Item	Cost, US cents	Item	Cost, US cents
Base (aluminium)	12.91	Base (nylon)	13.43
Bush (2)	2.40*	Motor screw (2)	0.20*
Motor screw (2)	0.20	Set screw	0.10*
Set screw	0.10*	Plastic cover (includes tooling)	8.00
Standoff (2)	5.19		
End plate	5.89		
End-plate screw (2)	0.20*	Total	21.73
Plastic bush	0.10*		
Cover	8.05		
Cover screw (4)	0.40*		
Total	35.44		

[*Purchased in quantity. Purchased motor and sensor subassemblies not included. Redesign: tooling cost for plastic cover = $5000.]

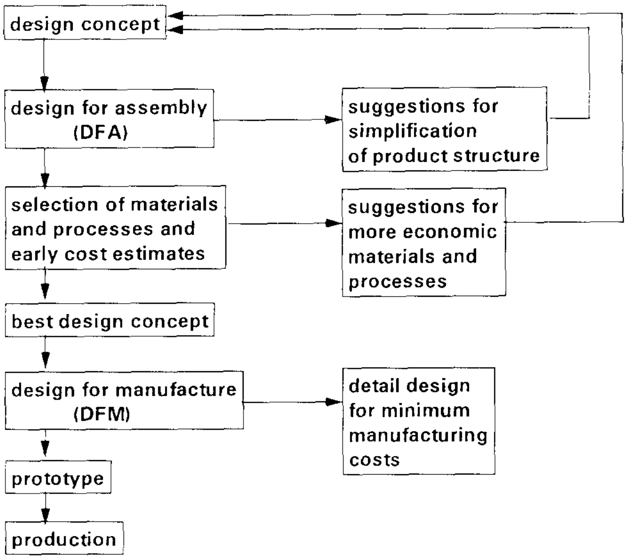


Figure 8 Typical steps taken in simultaneous engineering study using DFMA

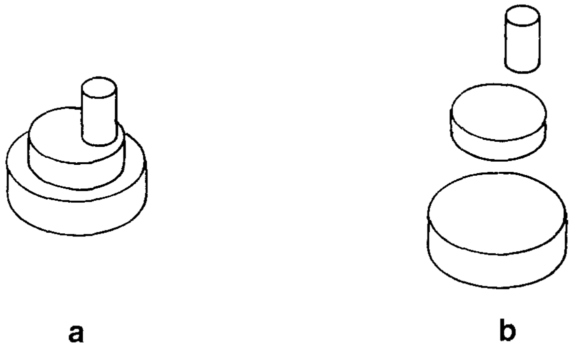


Figure 9 Misleading producibility recommendation[4]; (a) single piece, (b) multiple pieces
[Two-for-one part design: the substitution of a small number of simple shapes to provide a function rather than a single complex shape.]

It can be noted that the redesign suggestions arose through the application of the minimum part-count criteria during the design-for-assembly analysis; the final cost comparison was made after assembly-cost and parts-cost estimates were considered.

Figure 8 summarizes the steps taken when using DFMA during design. The design-for-assembly (DFA) analysis is conducted first, leading to a simplification of the product structure. Then, early cost estimates for the parts are obtained for both the original design and the new design in order to make tradeoff decisions. During this process, the best materials and processes to be used for the various parts are considered. For example, would it be better to manufacture the cover in the new design from sheet metal? Once the materials and processes have been finally selected, a more thorough analysis for design for manufacture (DFM) can be carried out for the detail design of the parts.

DEVELOPMENT OF DFA AND DFM METHODS

As early as the 1960s, companies were developing guidelines for use during product design. Perhaps one of the best known examples is the *Manufacturing Producibility Handbook*, which was published for internal use by General Electric in the USA[4]. In this, 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 shown in *Figure 9*: 'substitute a small number of simple shapes to provide a function rather than a single complex shape'. In fact, when one considers the means whereby the separate simple parts in *Figure 9* might be secured, one can see that 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.

DESIGN FOR ASSEMBLY

Significant benefits derived from the use of DFA were not realized until systematic-analysis tools became available around 1980. The reason was that design guidelines, even if they provide sound recommendations, do not help the designer any more than by 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)[5] described further below was directed at simplifying the automatic insertion of parts. The Boothroyd Dewhurst design-for-assembly (DFA) method[3] grew out of collaborative research on design for automatic feeding and automatic insertion carried out at the University of Massachusetts, USA, and the University of Salford Industrial Centre, UK. This emphasis arose from the fact that, when a company desired to automate the assembly of a product, it was 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. Also, when redesign for automatic assembly was undertaken, it was frequently found that the resulting product was so easy to assemble manually that automatic assembly could no longer be justified. The IBM Pro-Printer is an example of this experience[6].

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 and assembly costs.

As with the method just described, 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. Ideally, different individuals analysing the same product will obtain similar ratings, thus providing the means for independent evaluation of a design.

HITACHI AEM METHOD

In 1980, the Okochi Memorial Prize was awarded for the development of an automatic-assembly system for tape-recorder mechanisms[7]. In the process of developing this system, the product design was considered carefully using the Assembly Evaluation Method 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.

The AEM method, described in 1986 by Miyakawa and Ohashi[5], uses two indices at the earliest possible stage of design, namely the assembly-evaluation score E, which is used to assess the design quality or the difficulty of assembly, and the assembly-cost ratio K, which is 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 degrees of assembly difficulty using these three methods.

In the AEM, approximately 20 symbols represent the various assembly operations. Each symbol has an index to assess the assemblability of the part under consideration. Examples of the symbols and penalty scores[8] are given in *Figure 10*, and examples of their application are given in *Figure 11*.

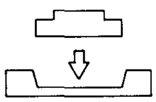
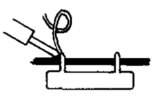
Elemental operation		AEM symbol	Penalty score
	Downward movement	↓	0
	Soldering	S	20

Figure 10 Examples of AEM symbols and penalty scores[8]

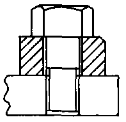
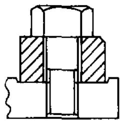
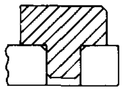
Product structure and assembly operations		Part assemblability evaluation score	Assemblability evaluation score	Assembly cost ratio	Part to be improved
	1 Set chassis.	100	73	1	block
	2. Bring down block and hold it to maintain its orientation	50			
	3. Fasten screw.	65			
	1. Set chassis.	100	88	Approx. 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			

Figure 11 Assemblability evaluation and improvement examples[8]

By 1986, more than 1500 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.

BOOTHROYD DEWHURST DFA METHOD

The development of the Boothroyd Dewhurst DFA[3] method, which was described above, started in 1977 with funding from the US National Science Foundation, and it was first introduced in handbook form in 1980. Soon afterwards, the Salford University Industrial Centre produced a UK version of the handbook[9] which was authored by K G Swift. These handbooks included analysis methods and databases for both manual and high-speed automatic assembly. For each process, the handling of the parts and their insertion were considered separately. The original procedure for design for automatic assembly was the result of collaboration between the author of this paper and A H Redford and K G Swift in Salford.

Later, in the USA, the author and his colleague P Dewhurst developed a personal computer program for DFA which was introduced in 1982. In 1983, a new handbook, based on the lessons learned in implementing DFA in industry, was introduced, and, since then, design for robot assembly and PCB assembly have been added[3].

MORE RECENT DFA ANALYSIS METHODS

Some ten years after 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, Germany. In their method[10], which they named Assembly-Oriented Product Design, they assess each part's usefulness or functional value. Thus, both assembly difficulty and functional value are evaluated, and a combined rating is given. This means that parts which have little functional value (such as separate fasteners) and that are difficult to assemble are given the lowest ratings. These ratings are then used as guides to redesign (see *Figure 12*).

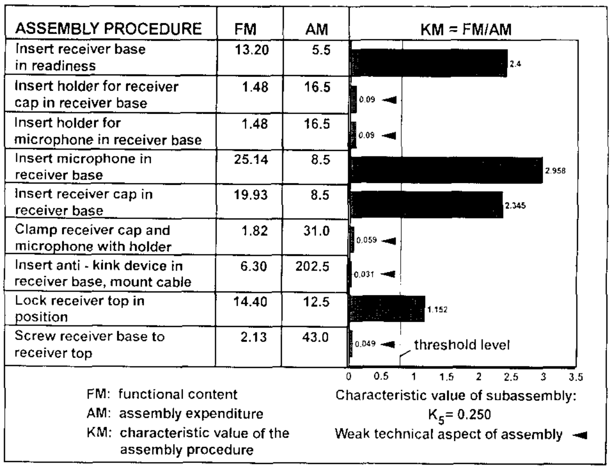
In their paper, B L Miles and K G Swift describe the application of the Lucas method developed at the University of Hull, UK, during the late 1980s[11].

In the Lucas method, the three steps are as follows:

- A functional analysis is carried out in which parts are categorized into A parts (demanded by the design specification), and B parts (required by that particular design solution). A target is set for design efficiency, which is $A/(A+B)$ and is 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 the use of the Boothroyd Dewhurst minimum-parts criteria in a 'truth' table to assist in part-count reduction.
- A handling and feeding analysis is carried out in which the parts are scored on the basis of 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 the total score divided by the number of A parts. A target of 2.5 is recommended.
- A fitting analysis is carried out which is based on the proposed assembly sequence. Each part is scored on the basis of 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 recommended that this ratio should approach 2.5 for an acceptable design.

This Lucas method is based, in part, on the original 1980 collaborative work of the author and Professor Swift described above.

In another method, Sony Corporation claims to have developed a unique set of rules for increased productivity involving design-for-assembly cost effectiveness (DAC). In his paper, Yamigiwa[12] reiterates the view 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, as opposed to making improvements later with feedback from the manufacturing process.

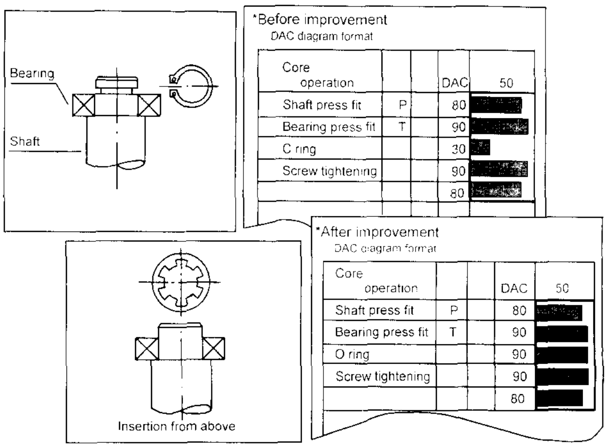


ASSEMBLY PROCEDURE	FM	AM	KM = FM/AM
Insert receiver base in readiness	13.20	5.5	2.4
Insert holder for receiver cap in receiver base	1.48	16.5	0.09 ◄
Insert holder for microphone in receiver base	1.48	16.5	0.09 ◄
Insert microphone in receiver base	25.14	8.5	2.958
Insert receiver cap in receiver base	19.93	8.5	2.345
Clamp receiver cap and microphone with holder	1.82	31.0	0.059 ◄
Insert anti - kink device in receiver base, mount cable	6.30	202.5	0.031 ◄
Lock receiver top in position	14.40	12.5	1.152
Screw receiver base to receiver top	2.13	43.0	0.049 ◄

FM: functional content
AM: assembly expenditure
KM: characteristic value of the assembly procedure

Characteristic value of subassembly:
$K_5 = 0.250$
Weak technical aspect of assembly ◄

Figure 12 Evaluation of subassembly from technical viewpoint of assembly (University of Stuttgart, Germany)[10]



*Before improvement
DAC diagram format

Core operation			DAC	50
Shaft press fit	P		80	
Bearing press fit	T		90	
C ring			30	
Screw tightening			90	
			80	

*After improvement
DAC diagram format

Core operation			DAC	50
Shaft press fit	P		80	
Bearing press fit	T		90	
O ring			90	
Screw tightening			90	
			80	

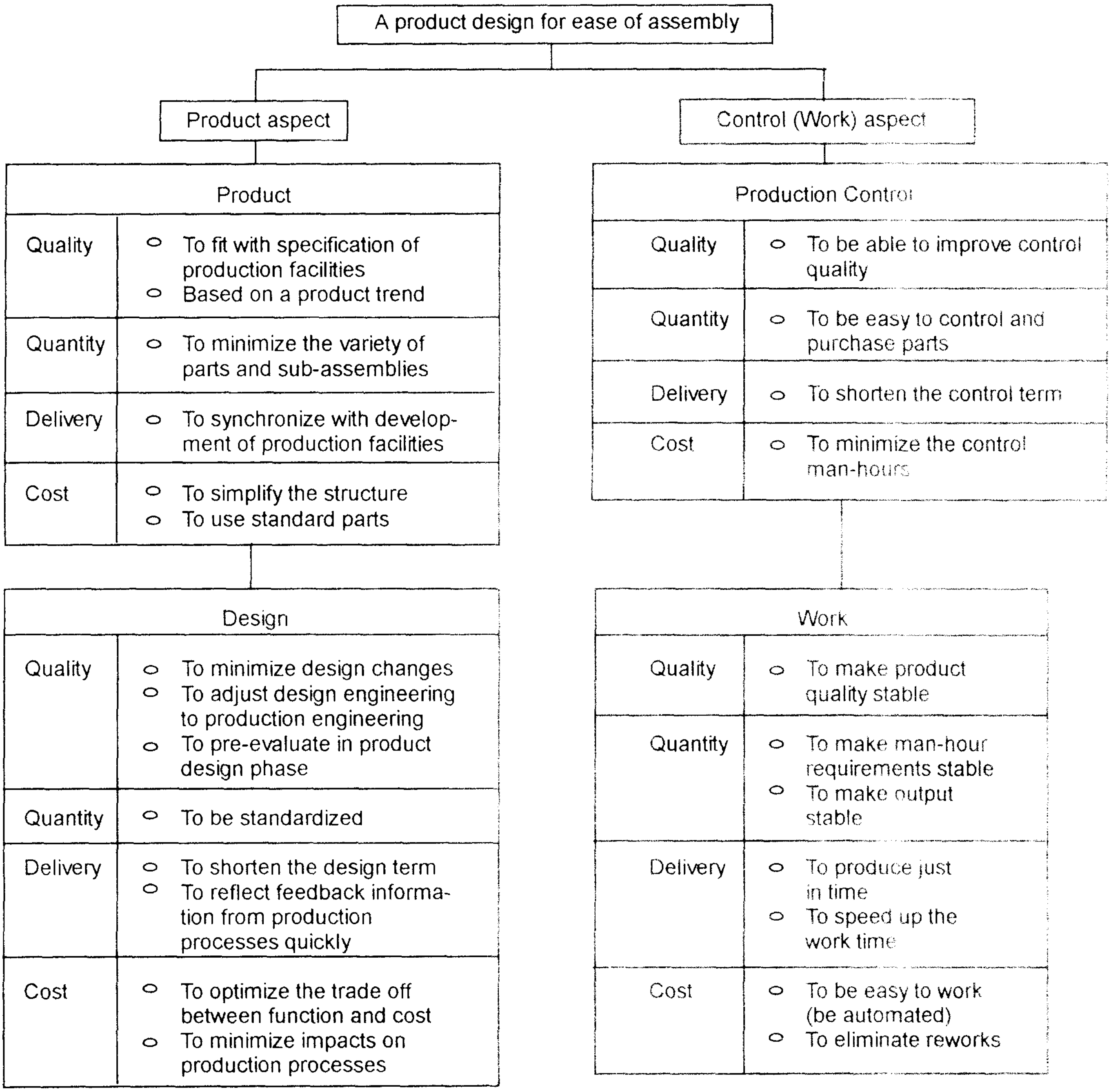
Figure 13 Design-for-assembly cost-effectiveness (DAC) example (Sony Corporation)[12]

In the DAC method, factors for evaluation are classified into 30 keywords. The evaluations are displayed on a diagram using a 100-point system for each operation, thus making judgment at a glance easy. A list of operations is presented on the DAC diagram, and a bar is drawn that represents the score for that particular operation (see *Figure 13*). Operations with low scores are easily identified. Since 1987, DAC has been introduced in various companies in Japan and overseas. Emphasis is given to the ease with which an operation can be carried out automatically, and the method is used to illustrate problems with the efficiency of the assembly system.

PCB DESIGN FOR ASSEMBLY

In 1985, Adachi *et al.* of the NEC Corporation reported[13] 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 to avoid complicated assembly motions, and reducing the variety of parts so that they could 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.



Product	
Quality	○ To fit with specification of production facilities ○ Based on a product trend
Quantity	○ To minimize the variety of parts and sub-assemblies
Delivery	○ To synchronize with development of production facilities
Cost	○ To simplify the structure ○ To use standard parts

Design	
Quality	○ To minimize design changes ○ To adjust design engineering to production engineering ○ To pre-evaluate in product design phase
Quantity	○ To be standardized
Delivery	○ To shorten the design term ○ To reflect feedback information from production processes quickly
Cost	○ To optimize the trade off between function and cost ○ To minimize impacts on production processes

Production Control	
Quality	○ To be able to improve control quality
Quantity	○ To be easy to control and purchase parts
Delivery	○ To shorten the control term
Cost	○ To minimize the control man-hours

Work	
Quality	○ To make product quality stable
Quantity	○ To make man-hour requirements stable ○ To make output stable
Delivery	○ To produce just in time ○ To speed up the work time
Cost	○ To be easy to work (be automated) ○ To eliminate reworks

Figure 14 Product-design requirements for ease of assembly (NEC)[13]

The authors present a chart (see *Figure 14*) which lists all the product-design features that lead to ease of assembly.

The PCB evaluation tool was developed first because the proportionate cost of PCBs had been increasing. The tool is based on a 100-point evaluation method, with demerit marks being 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:

- There are many parts that cannot be inserted automatically.
- Many different parts are used.
- There is much soldering and retouching.
- There are many parts which must be inserted after soldering.
- There are numerous wire harnesses.

These factors are quantified on a worksheet, where a formula is used to calculate demerit marks to be subtracted from the initial 100 points.

This evaluation tool has been applied in several NEC Corporation divisions, and it has 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 PCBs. In fact, some six years earlier, the Xerox Corporation had published a method for assessing the manufacturability of PCBs[14]. In this method, ten leading cost drivers (attributes) in the design of PCBs are identified. The designer gives a rating of 1–5 for each attribute which is then multiplied by a coefficient developed from historical data. *Table 4* lists the attributes and coefficients. The sums of the products

Table 4 Xerox manufacturability index for PCB assemblies: polynomial coefficients and attributes[15]

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 and mechanicals
6	0.1477	Harnesses
7	0.8485	Component spacing
8	0.6004	% autoinsert
9	0.0676	Orientation
10	0.1105	Component size

of attributes and coefficients give the manufacturability index for the PCB.

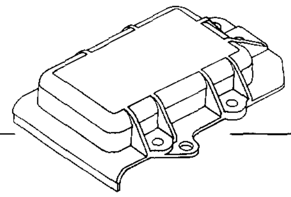
DESIGN FOR MANUFACTURE

Design for assembly has generated a revolution in design practices, not principally because it usually 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, to judge the effects of DFA at the early design stage, companion methods for the early estimation of 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[15] have introduced a Machining Producibility Evaluation Method which, combined with their AEM, gives an overall producibility-evaluation method (PEM).

Similarly, Toshiba Corporation[16] has developed a Processability Evaluation Method which, combined with other methods, including an assemblability-evaluation method, provides an overall producibility-evaluation method. Processability is defined 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[17], injection-moulded parts[18], die-cast parts[19], sheet-metal stampings[20] and powder-metal parts[21]. The objective of these studies was to provide methods with which the designer or design team can quickly obtain information on costs before detailed design has taken place. For example, an analysis[22] of an injection-moulded heater cover gave the results shown in *Figure 15*. It was evident that certain wall thicknesses were too large, and that, through some fairly minor design changes, the processing cost could be reduced by 33%. If these studies had taken place at the early design stage, the designer could also have considered the cost for an equivalent sheet-metal part for example. In fact, the use of these analysis techniques is now allowing designers and purchasing managers to challenge suppliers' estimates. In one example, it has been reported that Polaroid Corporation has saved $16 000–20 000 on the cost of tooling for an injection-moulded part[23].



	Existing Design	Redesign
Cost of one cavity and core	$ 8,032	$11,625
Cycle Time (s)	42.8	13.3
Number of cavities required	6	2
Cost of production mold	$36,383	$22,925
Cost per part (inc. 5 cents for material)	25.1 cents	16.8 cents

Figure 15 DFM analysis of injection-moulded heater cover[22]

RESULTS OF DFMA APPLICATIONS

DFMA provides a systematic procedure for analysing 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 product cost.

DFMA 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.

Defence contractors have an especially difficult problem in applying design for manufacture and assembly. Often, the designers do not know who will be manufacturing the product they are designing because the design will eventually go out for bid after it has been fully detailed. Under these circumstances, communications between design and manufacturing are not possible. In addition, defence contractors do not have the normal incentives with regard to minimizing the final product cost. We have all heard horror stories about the ridiculously high cost of seemingly simple items such as toilet seats and door latches used by the military. This means that the defence industry in general is an extremely fertile area for the successful application of DFMA.

Texas Instruments

The first case study described here has been provided by the Defense Systems and Electronics Group of Texas

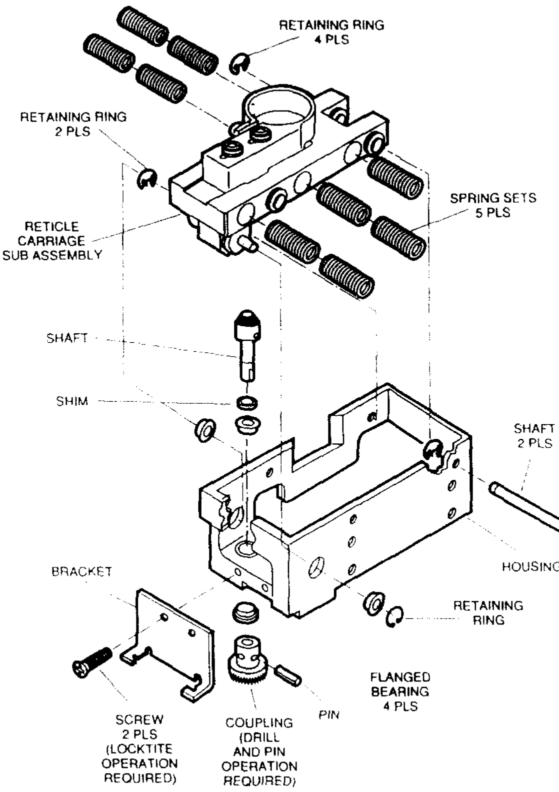


Figure 16 Original design of reticle assembly for thermal gunsight[24]

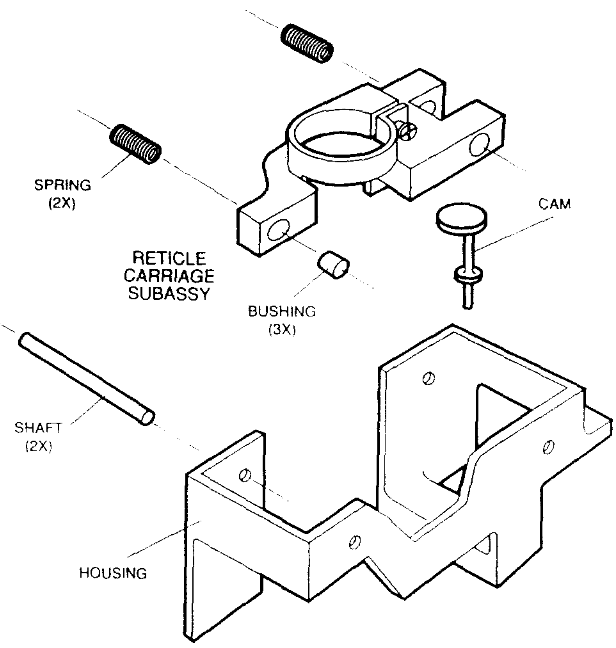


Figure 17 New design of reticle assembly after DFMA[24]

Instruments, Dallas, TX, USA[24]. The original design shown in *Figure 16* is for a reticle assembly for a thermal gunsight used in a ground-based armoured vehicle. It is used to track and sight targets at night, under adverse battlefield conditions, and it is used to align the video portion of the system with the trajectory path of the vehicle's weapon to ensure accurate remote-controlled aiming. It makes steady, precise adjustments of a critical optical element, while handling ballistic shock from the vehicle's weapon systems and mechanical vibrations generated by the vehicle's engine and rough terrain. It must also be lightweight, as this is a major consideration for all such systems.

The assembly consists of a carriage subassembly, housing, drive shaft and coupling, connector bracket, two shafts, springs, and associated hardware. The coupling is driven by a similar coupling on the system which drives the carriage subassembly in a lateral direction on the two shafts. Springs are used to negate any backlash in the gears. The current design requires over 12 h of metal-fabrication time, and more than 2 h of assembly time.

The TI group performed a design-for-assembly analysis to determine what could be done to simplify the design and make it less expensive. The results of the analysis showed that fasteners and reorientations of the assembly were the two main contributors to the assembly time. Special operations for drilling and pinning couplers and applying adhesive to screws were also major contributors. The main objective during the redesign was to reduce hardware, eliminate unnecessary parts, standardize the remainder, and reduce or eliminate reorientations. Once the analysis had begun, several design alternatives were proposed within a matter of hours. Eventually, the best features of the alternative proposals were combined to produce a new design (see *Figure 17*).

The new design incorporated the use of a cam to provide the conversion from rotational to linear motion. The cam takes up less room than the gearbox arrangement; this allows the driving point to be moved from the end of the carriage assembly towards the middle, reducing torque on the carriage and resulting in a smoother motion. The cam also eliminates the need for a coupling and a drill-and-pin operation. Virtually all the fasteners were eliminated by reducing the number of parts that needed to be secured, and incorporating the use of self-securing parts, such as press-fit shafts and bushings. The two major metal-fabrication items were changed to cast aluminium (injection-moulded plastic was ruled out because of low production volume and ballistic-shock requirements), and the connector bracket was incorporated into the housing, thus eliminating two parts, associated hardware, and a special operation to apply adhesive to the screws. The fabrication time was also greatly reduced, owing to the use of a casting rather than a machined component, and the elimination of unnecessary parts as indicated during the design-for-assembly analysis. This new design was also analysed using the design-for-assembly procedure, and *Table 5* lists the results for the original design and for the redesign. It can be seen from *Table 5* that very impressive results were obtained in all aspects of the manufacture of this assembly. In addition, the savings in overheads, which are particularly high in the defence industry, will be enormous. In the original design, there were 24 different parts, and in the new design there are only eight. This means that the documentation, acquisition and inventory of 16 part types has been eliminated. One can only imagine what the potential savings would be if DFMA were applied throughout the defence industry!

Brown & Sharpe

The need for a low-cost, high-accuracy coordinate-measuring machine (CMM) was the impetus behind the development of the MicroVal personal CMM by Brown

Table 5 Results of DFMA redesign of reticle assembly[25]

	Original design	Redesign	Improvement, %
Assembly time, h	2.15	0.33	84.7
Number of different parts	24	8	66.7
Total number of parts	47	12	74.5
Total number of operations	58	13	77.6
Metal fabrication time, h	12.63	3.65	71.1
Weight, lb	0.48	0.26	45.8

& Sharpe[25]. The primary design consideration was to produce a CMM which would sell for one-half of the price of the existing product. The CMM was to compete with low-priced imports which had penetrated the CMM market to an even greater extent than imports had in the automative industry. Since the CMM customer is not driven by price alone, the new CMM would have to be more accurate than the current design, while also being easier to install, use, maintain and repair.

Brown & Sharpe started with a clean sheet of paper. Instead of designing the basic elements of the machine and then adding on parts which would perform specific functions required for the operation of the machine, it was decided to build as many functions into the required elements as was feasible. This concept was called integrated construction. However, until the DFA methodology was applied, the cost objectives could not be met with the original design proposal. After DFA, for example, the shape of the Z rail was changed to an elongated hexagon, thus providing the necessary antirotation function. As a result, the number of parts required to provide the antirotation function was reduced from 57 to four. In addition, the time required to assemble and align the antirotation rail was eliminated. Similar savings were made in other areas, such as the linear-displacement measuring system and the Z-rail counterbalance system. On its introduction at the *Quality Show* in Chicago, IL, USA, in 1988, the machine became an instant success, setting new industry standards for price and ease of operation. The product has proved popular not only in the USA and Europe, but also in Japan.

NCR

Following a year-long competition for the USA's 'outstanding example of applied assembly technology and thinking', *Assembly Engineering* magazine selected Bill Sprague of NCR Corporation, Cambridge, OH, USA, as the PAT (Productivity Through Technology) recipient. Sprague, a senior advanced-manufacturing engineer, was recognized for his contribution in designing a new point-of-sale terminal called the NCR 2760. The DFA methodology, used in conjunction with solid modelling, assisted NCR engineers in making significant changes from the previous design. Those changes translated into dramatic reductions and savings, as follows[26]:

- 65% fewer suppliers,
- 75% less assembly time,
- 100% reduction in number of assembly tools,
- 85% fewer parts,
- a total lifetime manufacturing cost reduction of 44% (translating into savings of millions of US dollars).

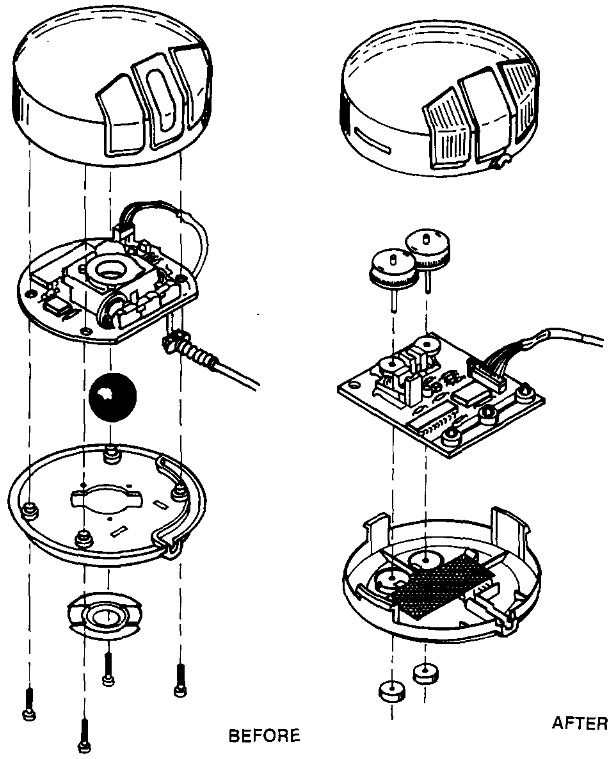


Figure 18 Old and new designs of Digital mouse[27]

Indeed, Sprague estimated that the removal of one single screw from the original design would reduce lifetime product costs by as much as $12 500.

Digital Equipment

A multifunctional design team at Digital Equipment Corporation redesigned the company's computer mouse[27]. They began with the competitive benchmarking of Digital's products and mice made by other companies. They used DFMA software to compare such factors as assembly times, part counts, assembly operations, labour costs, and total costs of the products. They also consulted with hourly-paid people who actually assembled the mice. Gordon Lewis, the DFMA coordinator and team leader, stated that DFMA gives the design team a 'focal point so that [they] can go in and pinpoint the problems from a manufacturing perspective and a design perspective'. 'It's the 80/20 rule', said Mr Lewis. 'You spend 80% of your time on 20% of your problems'. 'DFMA is one of the tools that helps design teams identify the right 20% of the problems to work on', he said.

Figure 18 shows the old and new mice. In the new DFMA design, 130 s of assembly for a ball-cage device has been reduced to 15 s for the device that has replaced it. Other changes to the product structure have also brought cost savings. For instance, the average of seven screws in the original mouse has been reduced to zero with snap fits. The new mouse also requires no assembly adjustments, whereas the average number for previous designs was eight. The total number of assembly operations has decreased from 83 in the old product to 54 in the new mouse. All these improvements add up to a mouse that is assembled in 277 s, rather than 592 s for the conventional one. Cycle time, too, has been reduced by DFMA. A second development project that adhered to the new methodology was finished in 18 weeks, including the hard-tooling cycle. 'That's unbelievable', admitted Mr Lewis. 'Normally it takes 18 weeks to do hard tooling alone'.

Motorola

DFMA methods have been used at Motorola to simplify products and reduce assembly costs. As part of the commitment to total customer satisfaction, Motorola has embraced the six-sigma philosophy for product design and manufacturing. It seemed obvious that simpler assembly should result in improved assembly quality. With these precepts in mind, they set about designing the new generation of vehicular adaptors[28].

The portable-products division of Motorola designs and manufactures portable 2-way Handi-Talkie™ radios for the landmobile-radio market. This includes such users as police, firemen and other public-safety services, in addition to the construction and utility fields. These radios are battery-operated, and are carried about by the user.

The design team embraced the idea that designing a product with a high assembly efficiency would result in lower manufacturing costs, and the provision of the high assembly quality desired. They also considered that an important part of any design was to benchmark competitors' products as well as their own. At the time, Motorola produced two types of vehicular adaptor called Convert-a-Com™ (CVC) for different radio products. Several of their competitors also offered similar units for their radio products. The results of the redesign efforts were so encouraging that Motorola surveyed several products which had been designed using the DFA methodology to see if there might be a general correlation of assembly efficiency with manufacturing quality. *Figure 19* shows what they found. The defect levels are reported as defects per million parts assembled, which allows a quality evaluation to be made that is independent of the number of parts in the assembly. Motorola's six-sigma quality goal is *3.4 defects per million parts assembled*. Each result in *Figure 19* represents a product with an analysed assembly efficiency and a reported quality level (see also the results in *Table 6*).

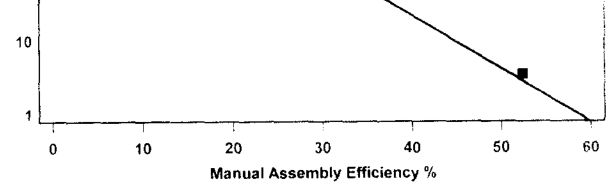


Figure 19 Improved assembly-design efficiency results in terms of increased reliability at Motorola[28]

Table 6 Redesign of vehicular adaptor (Motorola)[29]

	Old product	New product	Improvement, %
DFA assembly efficiency, %	4	36	800
Assembly time, s	2742	354	87
Assembly count	217	47	78
Fasteners	72	0	100

Ford Motor Company

Ford leads the field as an aggressive user of DFMA tools. To date, they have trained thousands of engineers in the DFA methodology, and they have contributed heavily to new research programs, and to expanding the existing DFMA tools. Ford is now even requiring its vendors to conduct DFA analysis prior to submitting bids on subcontracted products.

James Cnossen, Ford's manager of manufacturing systems and operations research, has concluded that 'it's part of the very fabric of Ford Motor Co.'. This is not surprising, when Ford reports savings of over $1000M annually as a result of applying DFMA to the Taurus line of cars.

DFMA has become part of the simultaneous-engineering environment, which supports Ford's 'Concept to Customer' theme. Using the DFMA software, teams made up from product design, manufacturing, suppliers and other representatives regularly meet to review not only the conceptual design of their future products, but also the products that are currently being manufactured. Gains in productivity are shown not only in reduced manufacturing costs, but also in the design leadtime required to bring new products to market. The adoption of these types of engineering tool is allowing Ford to reap tremendous benefits in both quality and customer satisfaction.

The Transmission and Chassis (T&C) Division of Ford is responsible for the design and manufacture of automatic transmissions of Ford vehicles. The transmission is a complex product, with approximately 500 parts and 15 model variations. The steps in the introduction and implementation of DFA in the Transmission and Chassis Division[29] are as follows:

- Provide DFA overview for senior management.
- Choose DFA champion/coordinator.
- Define objectives.
- Choose pilot programme.
- Choose test case.
- Identify team structure.
- Identify team members.
- Coordinate training.
- Have first workshop.

During the workshop:

- Review the parts list and processes.
- Break up into teams.
- Analyse the existing design for manual assembly.
- Analyse the teams' redesigns for manual assembly.
- Teams present results of original design analysis *versus* redesign analysis.
- Prioritize redesign ideas: A, B, C etc.
- Incorporate all the A and B ideas into one analysis.
- Assign responsibilities and timing.

The combined results of all of the workshops held in the T&C Division of Ford indicated potential total assembly labour savings of 29%, a reduction in part count of 20%, and a reduction in the number of operations of 23%.

The cost benefits that have been gained since the introduction of the DFA methodology in the T&C Division are nothing less than staggering. Even more importantly, the changes resulting from DFA have brought substantial quality improvements. Moreover, the design leadtime has been reduced by one-half, and is expected to be halved again. Reduced cost and improved manufacturability was reflected in Ford's profits for 1988.

General Motors

A few years ago, General Motors (GM) made comparisons between its assembly plant for the Pontiac at Fairfax, KS, USA, and Ford's assembly plant for its Taurus and Mercury Sable models near Atlanta, GA, USA. GM found that there was a large productivity gap between its plant and the Ford plant. GM concluded that 41% of the producibility gap could be traced to the manufacturability of the two designs. For example, the Ford car had many fewer parts (ten in its front bumper compared with 100 in the GM Pontiac), and the Ford parts fitted together more easily. The GM study found that the level of automation, which was actually much higher in the GM plant, was not a factor in explaining the productivity gap.

More recently, General Motors has been releasing details of improvements made to their designs through their own adoption of DFMA principles. For example, a 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 \$3.7M[30]. In GM's 1992 Cadillac Seville, the dashboard, seats, bumpers and other elements were redesigned with DFMA. The result is 20% fewer parts and, for the rear bumper alone, a 50% reduction is assembly time and annual savings of almost \$0.5M.

SUMMARY

In the previous section, a small selection of the published detailed DFMA case studies have been mentioned. In each case, a considerable reduction in part count has been achieved, resulting in a simpler product. By way of a summary, *Figure 20* shows the effect of DFA on part-count reduction taken from published case studies, and *Table 7* gives details of other improvements taken from the same case studies.

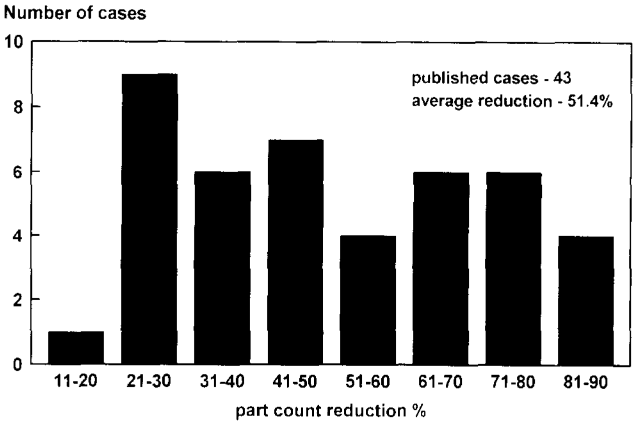


Figure 20 Part-count reductions when Boothroyd Dewhurst DFMA methods were used
[Reductions from 43 published case studies. Average reduction: 51.4%.]

Table 7 Improvements due to DFMA applications

Category	Number of cases	Average reduction, %
Separate fasteners	12	72.4
Assembly operations	10	49.5
Assembly time	31	61.2
Assembly cost	18	41.1
Materials cost	2	48.5
Product cost	12	37.0
Product development/time to market	4	47.5
Manufacturing cycle time	6	57.3
Work in progress	1	31.0
Manufacturing-process steps	1	55.0
Number of suppliers	2	47.0
Adjustments	2	94.0
Assembly defects	3	68.0
Service calls	2	56.5
Failure rate	2	65.0
Fixtures/assembly tools	4	71.0

[Improvements mentioned in 43 published case studies.]

ROADBLOCKS IN IMPLEMENTATION OF DFMA

Experience has shown that there are many barriers to the implementation of DFMA. Quite frequently, it is 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 21* shows the results of one analysis in which the assembly costs were extremely small compared with the material and manufacturing costs. However, DFA analysis suggests the replacement of the complete assembly with, say, a machined casting, and DFM analysis shows that this would reduce total manufacturing costs by at least 50%.

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

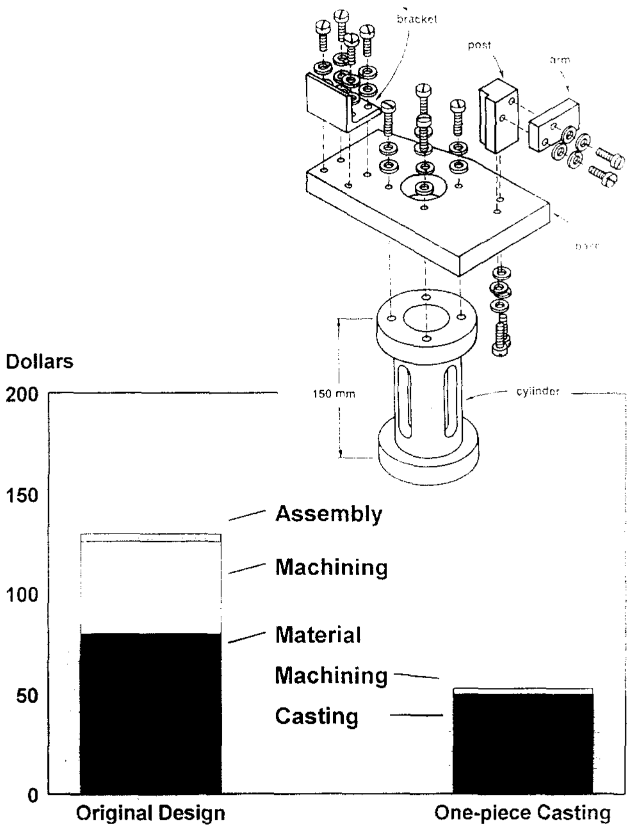


Figure 21 DFA analysis can reduce total costs significantly even when assembly costs are small

Everyone seems to think that his/her own company is unique and, therefore, in need of unique databases. However, when one design is rated as better than another using DFMA databases, it would almost certainly be rated in the same way using customized databases.

Some say that DFMA is only value analysis. It is true that the objectives of DFMA and value analysis are the same. However, it should be realized that DFMA 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 DFMA can make significant improvements even after value analysis has been carried out.

Since the introduction of DFMA, 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 DFMA. One cannot argue with this. However, DFMA 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 and reliability, will follow when proper consideration is given to the manufacture and assembly of the product.

Some say that DFMA 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 DFMA 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 more simply 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 there will be when the rules are not followed. For these reasons, it is necessary to use systematic DFMA procedures which guide the designer to simpler product structures and provide quantitative data on the effect of any design changes.

CURRENT DEVELOPMENTS

Although DFMA principles apply whatever the size of the product, the databases that have already been developed do not take into account the time needed for the assembly worker to acquire parts which are not located within easy reach. With large products, this additional time (which is sometimes referred to as 'walking time') forms a large proportion of the total assembly time, and it is the topic of further study.

Similarly, when products contain significant electrical interconnections, the labour involved in wire preparation, harness assembly and installation can far outweigh the time needed for mechanical assembly. *Figure 22* shows an example in which enormous savings in assembly time were found to be possible through redesign.

In addition to the pressures on manufacturing organizations to improve competitiveness, there is now the added pressure to design products that are easy to disassemble for service and for eventual recycling. *Figure 23* shows the assembly-time breakdown for a digital calliper. In this instrument, considerable disassembly was needed when it was necessary to change the batteries. *Figure 23* shows the total assembly and disassembly times during the life of the product, indicating clearly that the designer should be aware of total 'lifecycle costs' during

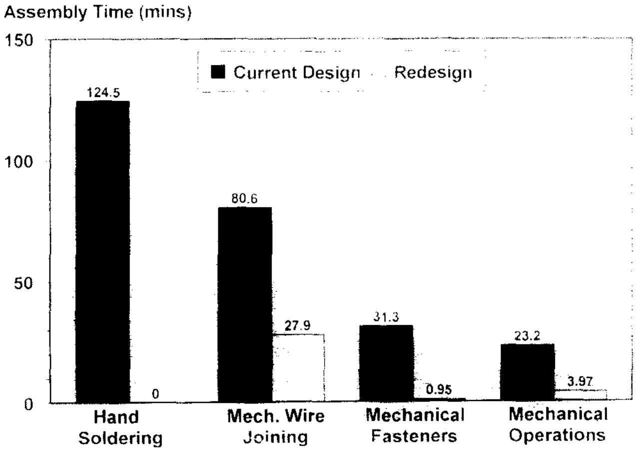


Figure 22 Possible savings in assembly time for product containing multiple electrical interconnections[31]

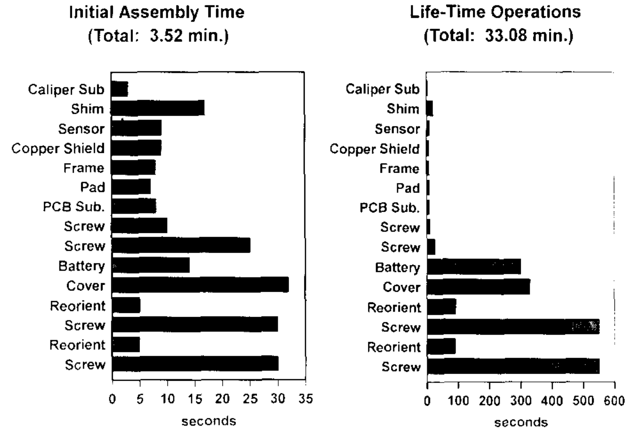


Figure 23 Total lifecycle labour content compared with original assembly time for a digital calliper

design rather than just the initial manufacturing costs. Of couse, these lifecycle costs ideally include the cost of recycling.

CONCLUSIONS

It should be noted that, in all of the case studies described in this paper, a systematic step-by-step DFMA analysis and quantification procedure has been used. However, as pointed out above, some still claim that design rules or guidelines (sometimes called producibility rules) developed by them can give similar results. This is not so. In fact, the application of guidelines or qualitative procedures can lead to increased product complexity, because the guidelines or procedures are usually aimed at simplifying the individual component parts. For example, limiting the number of bends in a sheet-metal part may seem like a good producibility rule, but, in fact, it can lead to an expensive design that incorporates numerous simple sheet-metal parts assembled with a multitude of fasteners. The resulting product will have poor quality, and will entail larger overheads resulting from a larger inventory, more suppliers, and more record keeping. Rather, the objective should be to utilize the capabilities of the individual manufacturing processes to the fullest extent to keep the product as simple as possible.

In spite of all the success stories, the major barrier to DFMA implementation continues to be that of human nature. People resist new ideas and unfamiliar tools, or claim that they have always taken manufacturing into consideration during design. The DFMA methodology challenges the conventional product-design hierarchy. It reorders the implementation sequence of other valuable manufacturing tools, such as SPC and Taguchi methods. Designers are traditionally under great pressure to produce results as quickly as possible, and they often perceive DFMA as the cause of yet another delay. In fact, as numerous case studies have shown, the overall design-development cycle is shortened through the early use of manufacturing-analysis tools, because designers can receive rapid feedback on the consequences of their design decisions where it counts: at the conceptual stage.

One hears a great deal these days about concurrent or simultaneous engineering. In some people's minds, simultaneous engineering means gathering together designers, manufacturing engineers, process monitors, marketing personnel, and the outside 'X-factor' person. Working with teams at the predesign stage is a laudable practice, and it should be undertaken in every company. However, unless one can provide a basis for discussion that is grounded in quantified cost data and systematic design evaluation, directions will often be dictated by the most forceful individual in the group, rather than being guided by a knowledge of the downstream results. The Portable Compressor Division of Ingersoll–Rand has used various aspects of simultaneous engineering for the past ten years. However, the introduction of DFMA in 1989 as a simultaneous engineering tool acted as a catalyst that provided dramatic increases in productivity and reduced new-product development times. In fact, the division has been able to reduce new-product development time from two years to one year.

In conclusion, it appears that, to remain competitive in the future, every manufacturing organization will have to adopt the DFMA philosophy and apply cost-quantification tools at the early stages of product design.

Professor Geoffrey Boothroyd gained a BSc in 1957, a PhD in 1962 for research into the temperature generated in metal cutting, and a DSc from the University of London, UK, in 1974 for research into manufacturing engineering. After his first degree, he spent ten years in the UK heavy-engineering industry, mainly in engineering design. He then became a reader in mechanical engineering at the University of Salford, UK, and specialized for nine years in research into manufacturing engineering. In 1967, he joined the University of Massachusetts, USA, and acted as a consultant to various machine-tool, cutting-tool and automation-equipment industries. He moved to the University of Rhode Island, USA, in 1985, where he develops research and teaching programmes in manufacturing engineering.

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