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Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering

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Abstract

This paper investigates the strategic application of materials and manufacturing process information during the design process. Design For Manufacture and Assembly (DFMA) has become an important concurrent engineering imperative for cost effective product design. The basis of design for manufacture and assembly is a systematic procedure for analysing product designs based on the application of quantifiable data. The procedure generates a large amount of information and even in computerised form presents difficulties for decision-making except for the simplest of products. Guidelines encapsulating qualitative information on best design practice facilitate the procedure. Methods are described for effective integration of quantitative and qualitative materials, manufacturing and assembly process information during product design. A discussion is also included on the differences between designing for new products and in designing for changes in existing products.

Keywords: Design for manufacture; Design for assembly; Design for manufacture and assembly; New product development; Concurrent engineering

1. Introduction

Design For Manufacture (DFM) is a systematic procedure to maximise the use of manufacturing processes in the design of components and Design For Assembly (DFA) is a systematic procedure to maximise the use of components in the design of a product. To be effective in product design, the procedures are often combined as Design For Manufacture and Assembly (DFMA). The aim of DFMA is to maximise the use of manufacturing processes and minimise the number of components in an assembly or product. DFMA is a systematic procedure for analysing proposed designs from the perspective of assembly processes. To obtain the maximum benefit from DFMA, the procedure is applied as early as possible in the design process and used within a concurrent engineering teamwork environment. In conjunction with the procedure, designers can make use of DFMA guidelines to help manage and reduce the large amount of information involved. DFMA guidelines are statements (rules of thumb, tips, aids, hints, suggestions, etc.) of good design practice that have been empirically derived from past experience.

The normal result of DFMA, as an integral part of the design process, is simpler and more reliable products that are less expensive to manufacture and assemble. However, products designed in this way tend to have a smaller number of complex components, making maintenance and upgrading difficult and expensive. The emphasis on reducing manufacturing costs has, therefore, been at the detriment of in-service costs. This may not be a particular problem for mass-produced (typically minimal maintenance, low priced, short life span) products such as the majority of domestic appliances. It is important, however, for more expensive products such as motorcars and aeroplanes, that maintenance is required in order to ensure their expected life spans. Over the years, long life products such as motorcars have also seen the growing trend towards using components that cannot be maintained. This has kept the cost of maintenance low but is wasteful of resources.

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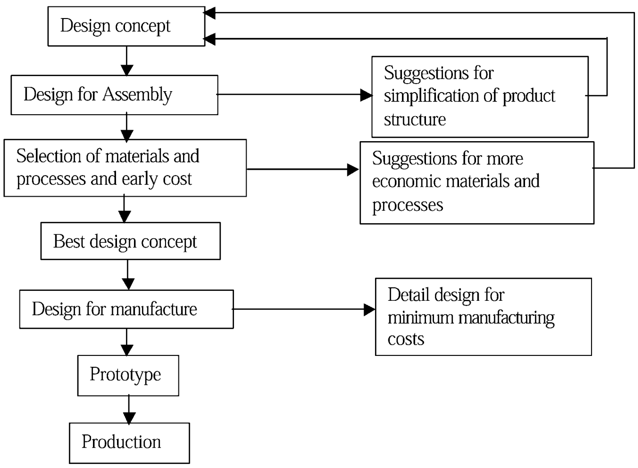

Fig. 1. Typical stages in a DFMA procedure (courtesy of Boothroyd and Dewhurst [2]).

With regard to the practice of designing for future upgrading, this is presently limited for most products but seen regularly in industrial electronics for example to facilitate future improvements in functionality and performance and in large made-to-order products such as ships which regularly receive refits. In the future, government legislation, particularly environmental protection and the need to control the use of precious resources, might change this situation. Manufacturers will be forced to provide alternative uses for the materials and components used in their products' manufacture when they reach the end of their design lives. This is already being seen with motorcar manufacturers but little has been done so far for mass produced consumer products. To be effective, consumers will need to play their part and accept higher prices for their products. In return the products will last longer, but contain more adjustable and/or replaceable components to maintain appropriate function, and upgrades of components and/or subassemblies to provide improvements. DFMA procedures will need to reflect the changing situation, adapting to compromise, and handling larger amounts of diverse information.

2. Design for manufacture and assembly process

The DFMA procedure can typically be broken down into two stages as shown in Fig. 1. Initially, Design for assembly is conducted, leading to a simplification of the product structure and economic selection of materials and processes. After iterating the process, the best design concept is taken forward to Design for Manufacture, leading to detailed design of the components for minimum manufacturing costs. The procedure is cost driven and importantly depends on the product design already existing. The procedure outlined, and there are many variations [1], optimises the original product design to produce a new and improved design. Most of the DFMA procedures today are computerised and DFMA can be done very quickly, once essential data is entered, allowing 'what if' scenarios to be conducted. DFMA procedures can be supported with guidelines, which are often supplemented by the experience of the designer. The importance of the contribution from guidelines cannot be over emphasised. In fact some DFMA is done purely through experience, with little or no support from a systematic procedure or formal guidelines. This approach is highly dependent on the knowledge and experience of the individual designer or collective design knowledge and experience of the company concerned.

Most of the pioneering and ongoing research in the field known today as DFMA can be attributed to Boothroyd and Dewhurst [2]. The procedure-based process analyses product designs by performing: a functional analysis; a manufacturing analysis; a handling analysis; and a fitting analysis. Each analysis stage generates cost indices, allowing problematic areas to be easily identified and priorities for redesign to be suggested. Repeating parts or all of the process will test the design change effectiveness. An alternative to the structured approach is the integration of all relevant areas and a greater emphasis on supporting the design process [3]. The latter approach is inherently more conducive to supporting directly concurrent team working. The two approaches, although only subtly different when combined, provide structured integration. A benefit of this is the mapping of product, process and people and as a consequence consideration of life cycle aspects.

3. Selecting appropriate manufacturing and assembly processes

A typical product contains many components, each requiring a variety of processes. There is usually more than one method of manufacturing a component from a given material. There are many classifications of processing methods for materials, but hierarchically can be divided into the following categories:

- casting;
- forming and shaping;
- machining;
- joining; and
- finishing

The selection of the most appropriate manufacturing process is dependent on a large number of factors but the most important considerations are shape complexity and material properties. DFM needs to take into consideration all the above and more in order to support decision making and provide this information in a timely and appropriate manner. Ultimately, most information can be reduced to a cost, the paramount driver to economical design. DFM converts most manufacturing information to cost indices, effectively normalising the disparate information and allowing direct comparisons to be made. In computer form 'what-if' scenarios can be readily conducted using DFM, allowing optimal solutions to be determined quickly and easily. DFA can be treated in a similar way and if integrated with DFM, allow manufacturing and assembly issues to be investigated simultaneously. DFMA in combination with a strategic application of design guidelines forms a power design tool by avoiding over prescriptive procedures and retaining flexibility for a variety of uses and operational styles. This is particularly important today because of a growing emphasis, reinforced by legislation, on life cycle costs and the need to be more sensitive to the environment both during the life of products and after their use.

Efficient assembly, whether manual/or automatic, is as important as efficient component manufacture in the creation of new products. Careful consideration, therefore, needs to be given to the simplicity, rate and cost of assembling components as well as utilising maximum benefit from component materials and manufacturing processes. This will undoubtedly necessitate a compromise between component manufacture and product assembly to achieve cost effective products. The ultimate choice is often a business one based on available resource, strength of competition and market demand. DFMA as an integral part of a concurrent engineering team working environment is assured. DFMA as a design tool imparts the discipline for manipulating the normally large amounts of quantitative manufacturing/assembly information but as a design philosophy act as a mechanism for drawing in qualitative manufacturing/assembly information.

4. The nature of design guidelines

Design guidelines are one of the main sources of explicit knowledge on the practice of design. The main sources of design guidelines include the literature, the direct experiences of practising designers and the established design practices in engineering organisations. The last two sources are less accessible than the literature because of the psychological, social and contextual considerations involved. Design guidelines are often found where the course of action is not clear but where one particular action has been found to work well in the past. Design guidelines, therefore, are more frequently specific to a particular domain and can represent a wide range of experience in the use of existing technology. Design for manufacture and assembly guidelines are further specific in that they concentrate on a particular aspect of design and range from high level and generic to low level and domain specific good practice.

5. The use of design guidelines in the design process

Designing, like any problem solving process, involves making decisions. The nature of the problems depends on the context and the level of abstraction. Design guidelines aid the decision making process. Most guidelines are empirical and based on intuition and experience. These guidelines are already known by the designer, being triggered by tasks or events as the design proceeds, or obtained from reading relevant texts or talking to colleagues. The latter tends to be more difficult and slower to retrieve, but in combination with the former tends to stimulate the thought process. Guidelines exist for all stages of the design process, but predominate for the detailed stage. This is reflected in the use of design for manufacture and assembly guidelines.

At the conceptual design stage of the design process, concrete information is limited and abstract thinking about manufacturing and assembly is prevalent. At the detail design stage of the design process, specific information is considerable and clarifying fine detail about manufacturing and assembly to recognised formats dominates. In between conceptual and detail design the range of information increases as the design of the product is configured and optimised with specific information to facilitate its manufacture.

6. Design for manufacture and assembly guidelines

The manufacturing of components means that materials must be converted by a process or series of processes to create functionally useful shapes. Each process involves material set up and subsequent change by a person and/or a machine and is called a manufacturing operation. Each manufacturing operation takes time and has an associated cost. Assembly is an important part of the overall manufacturing process. Assembling a product means that a person and/or a machine must retrieve finished components from storage, handle the components to orient them relative to each other, and mate them. Each act of retrieving, handling, and mating a component is called an assembly operation. Each assembly operation takes time and has an associated cost. The assembly of components can form a significant part of the manufacturing cost of a product, especially when large quantities of components are involved. The use of guidelines on good design practice for manufacturing and assembly can help improve manufacturing and assembly efficiency, thereby reduce the time and costs.

The following is a list of example guidelines for product design for manufacture and assembly [4–16]. The list is not exhaustive and is only a small selection of the large number of guidelines found in the design literature. The guidelines are taken directly from the

Fig. 2. Gate valve.

texts as quotations but although some describe and list guidelines separately, the majority have to be obtained by careful reading. There is also an element of repetition by authors of design texts but this is not a problem as it reinforces the use of certain guidelines. An important observation is that guidelines once isolated from their original text remove valuable qualifying information. This is not critical to understanding most of the guidelines listed below but stripped of detail can result in bland generic statements.

The list of guidelines shown, represent a selection of those consulted during the course of designing a simple gate-valve for a domestic water system as shown in Fig. 2. The Boothroyd and Dewhurst DFMA procedure was followed and the guidelines accessed to facilitate the major decision stages. At the DFA stage, this led to suggestions for a more simplified product structure followed by suggestions for more economical materials and processes. At the DFM stage, this led to a detail design for minimum manufacturing costs.

The valve consists essentially of a cast body machined to receive the sliding gate and threaded actuating stem, and compression fittings (nut and olive) to locate to adjoining pipe work. For hygiene reasons, all the components are made of brass, except for the handle, which is pressed steel and painted and its locating nut, which is zinc-plated steel. These two components are not in contact with the process fluid—in this case drinking water—so do not need to be made of the relatively more expensive brass. On first investigation, the valve is an entirely functional product made in large quantities and comprises of a lot of small components. However, in the area of the valve stem guide and seal there was scope for component reduction but at the expense of component complexity. The design used separate components to guide and seal. There was an opportunity to combine these functions in a smaller number of components, i.e. multiple functions in a single function carrier. The result was a single component that supported the stem and compressed the gland-pack seal eliminating the three separate components.

6.1. Design for assembly stage*

- Standardised components should be incorporated.
- Materials and methods of fabrication must be the cheapest acceptable.
- Manual processes should be reduced to a minimum.
- Interchange ability of components should be arranged.
- The design must be planned for production.
- Make components symmetrical.
- Design a base component to reduce the need for jigs and fixtures.
- Design a stacked product in order to achieve simpler assemblies.
- Products for automatic assembly are easy to assemble manually.
- Minimise tolerance and surface finish demands on components so that production costs are reduced.
- Keep the number of components and assemblies to a minimum.
- Simplify handling of components.
- Do not specify tolerances tighter than essential for correct functioning.
- Do not specify material that is available only on special order purchase unless there is no alternative.
- Do consider the use of economical order quantities.
- Do consider using stock items when you need only a small quantity of components.
- Aim at simplicity and economy of construction including interchangeable components.
- Design for the most suitable production process with economic assembly as a goal.
- Redesign to simply assembly.
- Design components to serve more than one function.
- Eliminate high precision fits whenever possible.
- A reduction in the number of components in a product or assembly should be the first objective of a designer wishing to reduce assembly costs.
- The most obvious way in which the assembly process can be facilitated at the design stage is by reducing the number of different components to a minimum.
- The introduction of automation may result in a cheaper product but one that is quite uneconomical to repair.
- Sharp corners must be removed from components so that they are guided into their correct position during assembly.
- Apart from product simplification, great improvements can often be made by the introduction of guides and tapers which directly facilitate assembly.
- It is always necessary in automatic assembly to have a base component on which the assembly can be

built.
- Make the components symmetrical.
- Avoid component features that induce tangling or nesting.
- It should be pointed out that components that are easy to handle automatically will also be easy to handle manually.
- Attempt to make components symmetrical to avoid the need for extra orienting.
- If symmetry cannot be achieved, exaggerate asymmetry features to facilitate orienting.
- Avoid expensive and time consuming fastening operations.
- Minimise number of components.
- Minimise production steps.
- To achieve a high level of reliability the designer must consider the use of well tried and tested components and materials, rather then new and uncertain ones.
- Standardise and reduce the number of materials and components.
- Avoid unnecessary requirements for accuracy of manufacture.
- Standard sizes and components should be used wherever possible.
- Introduce datum systems whenever a high degree of accuracy is necessary in the location of interchangeable components.
- Will one spanner fit all clamp bolts and nuts?
- Follow symmetrical layouts.
- Designs should be made for ease of packing.
- Use standard components, processes and procedures whenever possible.
- Use bought-out components wherever possible.
- Avoid sharp edges and angles.
- Make sure disassembly is equally practicable as assembly.

*Where a guideline suits DFA as well as DFM it appears as DFA.

6.2. Design for manufacture stage

- The designer must be aware of the capabilities of his/her workshop, sub-contractors and materials suppliers.
- Design castings so as to minimise the cost of flash removal.
- Provide just sufficient material at all points where machining is required to permit machining within the limits specified.
- Avoid the use of undercuts where possible.
- Select materials to suit each processing operation best.
- Avoid slow processes and design for high speed continuous processes.
- Eliminate expensive operations not really needed to achieve function and simplify design details.
- Eliminate the need for expensive machining of components to excessively close tolerances.
- Select materials for suitability as well as lowest cost and availability.
- Insure maximum simplicity in overall design.
- Use the widest possible tolerances and finishes on components.
- The designer must make every effort to specify the lowest grade of material that will meet his needs.
- The best way to achieve true reliability is by simplicity.
- Design to fit the manufacturing processes and reduce costs.
- Choose materials for a combination of properties.
- Design castings so that they will combine as many components as permitted and still avoid undue complexity and excessive costs.
- See that all sections are of uniform thickness.
- Fillets should be used at corners wherever possible avoiding sharp corners but not so large to produce heavy cross-sections.
- It is not desirable to design structures with abrupt changes in section.
- Aim to make castings as simple in structure as conditions permit.
- Employ ribs to help avoid warping or are needed for extra stiffness and can be used to lower weight.
- Inside radii on bends should not be less than the thickness of the metal.
- Depth of draw should be kept as small as conditions permit if cost is to be minimised.
- Gauge of stock should be as light as conditions permit.
- If a component is one normally exposed to view, make sure that its appearance is as pleasing as due economy in production permits.
- Avoid square bottom holes when a hole made with a standard drill will meet the requirements.
- Unless removal of burrs is necessary, do not stipulate.
- Design the component so that the number and duration of machining operations required are minimised.
- Select materials that, consistent with minimum cost and with other requirements, machines most readily.
- Design the components so that the smallest diameter of stock that is readily available can be used and so that the overall length is minimised.
- Design the component so that it can be machined with a minimum number of tools and with standard tools unless special ones effect economies.
- Develop the design to contain as many identical components as possible.
- If you cannot eliminate fasteners, standardise them.
- The designer will nearly always be able to reduce the number of components by combining two or more

functions in a single component.
- Ensure changes of section are gradual.
- Allow for the effect of thermal stresses.
- Aim at uniform wall thickness and cross-sections and at gradual changes of cross-section.
- Avoid excessively small tolerances.
- Use standards and codes wherever possible.
- For economic reasons, the attempt should always be made to fulfil several functions with a single function carrier.
- Put a price on every tolerance and finish.
- Manufacturing processes favour objects with planes at right angles to each other and those that can be turned on a lathe.
- Select materials that will lead themselves to low cost production as well as design requirements.

7. Quantitative vs. qualitative information

It is generally recognised that a good principle is to quantify whenever possible. It is easy to waste considerable time on qualitative studies on matters that might be easily and quickly clarified by calculation. Furthermore, an economical design is an optimised design. An optimised design needs accurate data to be effective. It is important that critical design decisions are taken as early as possible in the design process. To achieve this it is necessary to define trade-offs as much as possible early in the design process. Again to do this quantitative data is necessary. The level of precision in the data increases as the design progresses. Qualitative guidelines supplement the process at all levels. Manufacturing and assembly issues along with other design decision-making typify the complex problem solving involved. Many guidelines are learned empirically, from past experience and, as such, are difficult to organise, which is in complete contrast to factual-based information that can be easily stored and recalled. Clearly, it is important to a successful implementation of DFMA that the designer(s) receive adequate and timely guidance and can perform meaningful evaluations to enable product redesign to be easily executed.

8. Conclusions

An approach to DFMA has been defined that systematically facilitates the consideration of quantitative and qualitative design information. The procedure provides a framework to discipline the design process with decision-making supported by guidelines. DFMA (linked DFM and DFA) quantitative evaluation methodologies are already well established and some have been implemented as commercial software packages with DFM application-specific modules. Design guidelines databases because of the heuristic nature of guidelines are less well known although attempts have been made at developing electronic databases. Research indicates that the solution lies in the development of appropriate knowledge representation and artificial intelligence techniques. The use of separate software packages at present is not seen as a major problem but the benefits of integration with the facility to automatically interrogate a guidelines database, as the design progresses, would be very beneficial. The major challenge is to create an intuitive design environment that is conducive to simultaneously handling scientifically based factual knowledge and empirically derived heuristic knowledge.

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