A SURVEY OF DFM METHODS

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ABSTRACT

The need for reducing the time to bring a product concept to market, along with the need for reducing a product's cost and improving its quality, while maintaining its functionality, has lead to the evolution of design for manufacturing (DFM). In its broadest sense, DFM is the simultaneous development of product and process design. This paper surveys DFM methods, beginning with methods with a holistic approach to the design process, followed by methods developed for specific domains. Rational, rather than intuitive, nature of these methods is investigated. A comparison of the methods is provided. Shortcomings of the methods, if any, are pointed out and ways to improve the existing methods are suggested.

INTRODUCTION

Design methods, in general, have been broadly classified into two types: creative methods, which rely on the intuition of the designer and logical methods, which encourage a systematic approach to design. The methods surveyed in this paper fall into the second category. Although creative thinking is an essential part of any product development process, working towards improving the product design from the manufacturability point of view, in a 'rational' manner, has gained immense importance. This does not imply a digression from creativity; in fact, the two complement each other as we shall see later in this paper.

In this context, the DFM philosophy has played a vital role since the late 70s. At this point of time, DFM activities include: development of formalized DFM principles, computer aided DFM techniques and quantitative evaluation methodologies [Stoll, 1986]. However, the history of DFM dates back to even before the Second World War. DFM was a part of the engineering design philosophy, especially among the American auto giants, Ford and Chrysler. It was the use of this philosophy that helped them design and manufacture weapons, battle tanks and other wartime necessities on a large scale. Extensive use of DFM practices also resulted in doubling of America's gross national product and growth of the aviation industry ten-fold during wartime when there was a severe shortage of material and labor [Ziemke and Spann, 1993]. Ziemke and Spann point out the effectiveness with which the Germans employed the DFM philosophy in the production of their deadly fighter aircraft, the ME-109 and easily outnumbered its British rival, the Spitfire. After WW2, however, the use of DFM practice and principles virtually disappeared until the late 70s when Ford Motor Co. rediscovered it in the manufacture of their extremely popular car, the Taurus. Since then, extensive research has been carried out in the area.

A DFM method, at minimum, must carry out one of the following tasks:

1. Present a non-patterned approach to problem solving, keeping in view manufacturability, yielding desirable solutions.
2. Specify rules and techniques that will improve assemblabilty at reduced cost, ease handling of components, etc.
3. Specify rules and techniques for economic manufacture, appropriate selection of materials and processes.
4. Analyze manufacturabilty and provide redesign suggestions to improve design.
5. Provide some fundamental principles of good design.
6. Help in achieving a robust design, improve a product's quality.

Although a method that carries out any of the aforementioned tasks is invaluable in an integrated design and manufacturing environment, a true DFM method has an holistic approach to the product development process and encompasses every task mentioned.

LITERATURE SURVEY

DFM methods, as such, may be applied at the following four stages of the design process [Mill et al., 1994]:

1. *The conceptual design stage*: the product shape, design is unknown.
2. *Assembly stage*: manufacturing methods are unknown.
3. *Selection of materials, processes*: production processes are unknown.
4. *Detail design*: detailed manufacturing methods may be investigated.

The following survey concentrates on methods in all areas except design for assembly (DFA), although DFA is an integral and important part of the DFM philosophy. The survey begins with methods with a holistic approach and then goes on to describe methods developed for specific domains.

DFMAÔ (Design For Manufacture and Assembly)

This method, developed by Boothroyd and Dewhurst, originated as a design for assembly method but has developed since to include a wider range of activities in the design process. DFA still plays a major role in this method; however, it is the companion DFM methods within DFMA that help judge the contributions of DFA. The following are the stages in the DFMA method:

- DFA, with feedback to concept development stage about simplification of product structure.
- Selection of materials, processes and early cost estimation.
- Detailed design for manufacture, on the best design concept.

Once DFA has been applied, a producibility evaluation is carried out to assess part manufacturing difficulties and part cost. The parts are designed and part costs are estimated at early stages using various combinations of processes and materials. A combination suitable for design is chosen and this makes way for a thorough analysis for detailed design. Methods for early cost estimates for parts and tooling have been developed for the following processes by Boothroyd, Dewhurst and Knight [Boothroyd, 1994]: machining, injection moulding, die-casting, sheet metal stamping and powder metallurgy.

DFMA has by far been the most successful DFM method and is used extensively in industry today. Texas Instruments, General Motors, Ford Motor Co., Motorola, to name a few, are users of DFMA. As a specific example of reduction of the product development time using DFMA, the Ingersoll Rand Company reduced this time from two years to one [Boothroyd, 1994].

The Lucas DFM methodology

This method integrates various modules like Quality Function Deployment, DFA, manufacturing analysis, design to cost, Failure Mode and Effects Analysis and Taguchi methods [Molloy et al., 1998]. There is a common database serving all these modules, obviating the need for data transfer between the modules. The DFA module is very similar to the one used in DFMA, developed by Boothroyd and Dewhurst. The manufacturing costs of designed components are computed by quantifying the manufacturability parameters and using them as cost coefficients in the following equation [Swift et al., 1989]:

Manufacturing Cost (M) ; $VC_{mt} + R_{cc}P_c$

where V is the volume of the material needed, C_{mt} is the volumetric cost of material, P_c is the basic cost of producing the ideal design of component by a specific process and R_{cc} is the relative cost coefficient assigned to a component.

The manufacturing analysis module considers a wider range of processes than the DFMA. The processes include: die-casting, plastic moulding, machining (capstan and auto), impact extrusion, powder metallurgy, forging, press working and sand casting [Swift et al, 1989].

Notwithstanding the popularity and success of DFMA and Lucas DFM methods, there is much scope for improvement. These DFM methods are somewhat holistic in their attempt to integrate design and manufacturing. However, both these methods lack any serious effort at the conceptual design stage. This is a critical point, considering 70% of the product cost is fixed at this stage. Another shortcoming of these methods is their inability to provide redesign suggestions to modify shapes in the case of an unsuitable design. Employing a technique based on DFM principles at the conceptual design stage might well be a solution to both these shortcomings.

CyberCut

This system developed at University of California at Berkeley, uses a feature based design system in conjunction with a knowledge based process planner to promote design for manufacture [Wright and Dornfeld, 1998]. The design process used is DSG (Destructive Solid Geometry). In this process, a designer removes features such as blind holes, pockets, etc., from a solid block. These features are mappable to CNC machining processes, thereby reducing the complexity of process planning. The feature creation is governed by rules contained in the in-built ‘macro planner’. An example of such a rule is prohibiting a designer from creating a hole, which is a feature, too close to an edge. The resulting geometry is converted to a machining script using Berkeley’s micro planner. The system includes a knowledge based process planner, a manufacturability analysis service (MAS) and a novel fixturing method called the Reference Free Part Encapsulation (RFPE).

An interesting aspect of this system is that it is internet based. The design tool is written in Java and a Java class is created for each feature. Constraints for the feature are contained in that class.
A client may design his components on the net by downloading CyberCut's design environment or may submit ACIS files directly for assessing process planning. CyberCut also carries out the fabrication of the part using a computerized machine tool.
A pitfall of this method is the constraint imposed on the designer, while using DSG. It limits the parts that can be designed. But it may well be a good price to pay for incorporating DFM philosophy.

The Nippondenso Method and DFM Guidelines

Nippondenso is a car products company in Japan that manufactures products such as radiators, anti-skid brake system, alternators and generators, Toyota being its chief customer. The huge orders that the company receives comprises various models of its products and different mixes as well. The company came up with the following response to remove the bottlenecks in production [Whitney, 1988]:

1. The combinatorial method of meeting model-mix production requirements.
2. In-house development of manufacturing technology.
3. Wherever possible, manufacturing methods that do not need jigs and fixtures.

The combinatorial method consists of dividing the product into generic parts or sub-assemblies and designing the parts for interchangeability, so a variety of products may be produced. The in-house manufacturing team helps in designing the parts. Avoiding the use of jigs and fixtures helps in economical batch-size-of-one production.
This method is derived, basically, from the DFM guidelines which are a set of rules used to optimize the manufacturing system with respect to productivity, cost and quality. DFM guidelines are a prescription whereas the Nippondenso method is a description. A sample of the DFM guidelines list follows [Bedworth et al, 1991]:

- Design parts to be multifunctional.
- Design parts or ease of fabrication.
- Minimize part variations.
- Avoid separate fasteners.
- Avoid flexible components; they are difficult to handle.
- Use parts of known capability.
- Emphasize standardization.
- Undertake engineering changes in batches.
- Use the simplest possible operations.
- Minimize setups and interventions.

These guidelines are nothing more than suggestions and the designer is at liberty to override them when necessary. The drawback of this method is that a general design or manufacturing strategy cannot be designed. Rules have to applied and modified based on different situations and conditions.

Producibility Measurement Tool

This manufacturabilty evaluation method, designed for the Department of the Navy resembles the Delphi technique. The method relies on opinions of experts based on their past experience. A producibility index is computed using a Producibility Assessment Worksheet (PAW), the criteria for which is chosen by the management [Producibility Measurement Guidelines, 1991]. An important aspect of this tool is the review of the preliminary drawing or sketch of the product by a manufacturing engineer along with design engineers. The PAW is prepared after this step. The PAW is basically for the selection of an appropriate manufacturing process, once the product design is determined. Evaluators fill in PAWs based on their experience, assigning points to parameters like design to cost, tooling, materials, etc. for each manufacturing process considered. The process with the highest Producibility Assessment Value (PAV) is chosen, since it has the highest probability of success.

The positive side to this method is that it applies the DFM philosophy where it matters most – the conceptual design stage. Design engineers and manufacturing engineers work in tandem to come up with a design that has a good manufacturability rating. However, it is in the DFM philosophy to have a ‘rational’ approach rather than an intuitive one. And Delphi technique, on which this method is based, is classified under intuitive design methods. It would advisable, therefore, to select manufacturing processes in a more structured manner rather than saying "…. Therefore, this process would most probably be suitable for manufacturing this part."

Feature Based Manufacturability Evaluation

Gupta and Nau have presented an approach for the manufacturability analysis of machined parts [Gupta and Nau, 1995]. Alternative interpretations of the parts is generated as a collection of machining features, a machining feature being a portion of the workpiece affected by a machining operation. The interpretations are mapped on to operation plans and a manufacturability analysis is carried out on these plans. It is assumed that the design is available as a solid model with information on tolerances and surface finish. It is also assumed that information about available machining operations is available. Following are the important steps of the method [Gupta and Nau, 1995]:

1. Generate all the possible machining features for the designed part; each feature representing a machining operation. If it is not possible to machine the design using these features, the part is unmachinable.
2. A feature based model (FBM) is created from the set of features generated in step 1. An FBM is a set of machining features containing no redundant features. An iterative procedure yields the most promising FBM, the one with the best operation plans. A good operation plan is one that

    - does not violate machining practices,
    - is able to produce required design tolerances and surface finishes and
    - meets production time and costs.

1. The design is machinable if one or more satisfactory plans are obtained in step 2.

A major shortcoming of this process is its inability to provide redesign suggestions.

A Framework for Manufacturability Evaluation

This is also a feature based manufacturability evaluation method developed by Shah et al. They have identified four measures for analyzing manufacturability [Shah et al, 1990]:

1. Total product cost.
2. Feature-by-feature cost.
3. "Good practice" Rules Violation (GPRV) Record.
4. Least Cost Processing Opportunity (LCPO) Record.

The system uses a combination of GPRV and LCPO techniques. The GPRV technique comprises a set of rules that provide general guidelines for production. If the rules are violated, more expensive or complex, toolings or fixturings have to be employed. This method is complemented by the LCPO technique which determines process feasibility and optimal process sequences. The cost of violating a rule in GPRV is computed using this technique. The system developed allows interactive creation of geometric models. The designer may submit the feature to be evaluated whether or not the design is complete. The system goes on to determine an optimal sequence of processes based on cost. Economic redesign suggestions are generated by the system.
Comparing the feature based manufacturability evaluation method presented in [Gupta and Nau, 1995] and [Shah et al, 1990], the former distinctly lacks two features present in the latter. The former system is essentially modeled on the LCPO technique whereas Shah et al’s system is modeled on a combination of GPRV and LCPO techniques. Secondly, the former system does not offer the benefit of redesign suggestions to the designer, which is done by the latter system.

Failure-Mode and Effects Analysis

This DFM method aims at improving the product quality by such a design that prevents anticipated failures. The first step is to list all possible types of failures: fatigue, fracture, buckling, etc. [Bedworth et al, 1991]. The failures are then ranked according to the effect they have on the system and starting from the highest ranked failure design changes are made to prevent the failures. A design change may imply either simplification of design or strengthening of parts.

Group Technology

This is a DFM method in the sense that it improves the design efficiency as well as product quality. The basic principle is that of interchangeability of components. If a part of required dimensions already exists as a standard, it need not be redesigned. Also, a slightly modified process plan of an existing part may be utilized for a part that is similar to that part.

Taguchi Method

Taguchi method involves the use of statistical design of experiments for robust design of product [Syan & Swift, 1994]. It comprises parameter design and tolerance design. Parameter design is the determination of a robust combination of design parameters that affect the output of the system. A robust design indicates that the product operates as desired under any condition. Tolerance design comprises setting tolerances for design parameters. In the Taguchi method, this is done with the use of a loss function. Any deviation of the parameters from the intended value results in a loss either to the customer or the company. Tolerances are set based on cost calculations of such losses. From a DFM point of view, Taguchi method is invaluable, since in terms of time and money, experimentation is expensive and hence selection of the right set of noise factors and interpreting the results correctly are very important [Dixon and Poli, 1995].

DISCUSSIONS AND CONCLUSION

Even though DFM is a rather mature field, there is a lack of serious effort in developing methods for the most important area of conceptual design [refer Table 1]. Only a couple of methods have attempted to consider manufacturability at such an early stage. More concrete DFM methods need to be developed and applied to this stage. A suggestion of such a method would be Collaborative Sketching or Method 6-3-5 with alternating design and manufacturing engineers instead of the traditional group of design engineers.

Tasks** **Method**	1	2	3	4	5	6
DFMA				«		
Lucas DFM				«		
CyberCut						
Nippondenso, DFM guidelines				«		
Producibility Guidelines				«		
Feature Based, Gupta & Nau				«		
Feature Based, Shah et al						

FMEA						
Group Technology						
Taguchi Method						

- In column 4 indicates inability to provide redesign suggestions.

Tasks 1-6 are mentioned in the introduction

Table 1. Comparison of DFM methods.

The aim of developing DFM methods for specific domains has been to achieve an integrated design and manufacturing environment. But as long as such methods are not integrated themselves to make a full fledged DFM system, their effectiveness is drastically reduced. As a specific example, Swift et al [Swift et al, 1989] reflect the importance of such integration in the following statement: "… the absence of such facility [that of manufacturabilty analysis] is one of the major reasons for the limited adoption of design for assembly, DFA, techniques." Thus it is imperative to have a holistic approach to integrate design and manufacturing.

A major shortcoming in the currently available DFM methods is their inability to give redesign suggestions to modify shape. They lack reasoning with regards to explicit shapes. Most of them are very high level rules that cannot give a quantitative trade off. The best such methods can do, such as the system developed by Shah et al does, is to provide redesign suggestions, to alter process sequence, for example, as far as a machining feature is concerned. There is much scope of improvement in this area.

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