

DETC2004-57770

NEW DIRECTIONS IN DESIGN FOR MANUFACTURING

Jeffrey W. Herrmann
Department of Mechanical Engineering and
Institute for Systems Research
University of Maryland
College Park, MD 20742, USA

Joyce Cooper
Department of Mechanical Engineering
University of Washington
Seattle, WA 98195, USA

Satyandra K. Gupta
Department of Mechanical
Engineering and Institute for
Systems Research
University of Maryland
College Park, MD 20742, USA

Caroline C. Hayes
Department of Mechanical
Engineering
University of Minnesota
Minneapolis, MN 55455, USA

Kosuke Ishii
Department of Mechanical
Engineering
Stanford University
Stanford, CA 94305, USA

David Kazmer
Department of Plastics Engineering
University of Massachusetts
Lowell, MA 01854, USA

Peter A. Sandborn
Department of Mechanical
Engineering
University of Maryland
College Park, MD 20742, USA

William H. Wood
Mechanical Engineering
Department
University of Maryland Baltimore
County
Baltimore, MD 21250, USA

ABSTRACT

This paper gives an overview of research that is expanding the domain of design for manufacturing (DFM) into new and important areas. This paper covers DFM and concurrent engineering, DFM for conceptual design, DFM for embodiment design, DFM for detailed design, design for production, platform design for reducing time-to-market, design for system quality, design for life cycle costs, and design for environment. The paper concludes with some general guidelines that suggest how manufacturing firms can develop useful, effective DFM tools.

Keywords: Design for manufacture, concurrent engineering, life cycle considerations.

INTRODUCTION

Developing successful new products requires the ability to predict, early in the product development process, the life cycle impact of design decisions. Downstream life cycle issues include considerations of how the product will be made, shipped, installed, used, serviced, and retired or recycled.

Ignoring downstream issues (or producing poor estimates) leads to poor product designs that may cause unforeseen problems and excessive costs downstream. Sometimes, when problems are uncovered during design verification or testing, the problems can be corrected by redesign, but the cost of redesign at this late stage can be prohibitive. Sometimes companies must simply accept higher manufacturing costs and reduced product effectiveness resulting from early design errors. If accurate predictions of life cycle needs can be made early in the design cycle, it allows product development teams to create superior designs. This not only reduces the number of redesign iterations, the time-to-market, and the development and manufacturing costs but also improves the customer's experience.

Unfortunately, downstream life cycle needs are difficult to predict accurately during early design phases for many reasons. First, during the early stages of design, when the geometry and specifications of the product are not yet complete, the manufacturing details and potential problems are very hard to predict. Until the details of the product are completely specified, a complete assessment of the product's

manufacturability cannot be made. Second, the number of and complexity of the life cycle issues that must be considered are overwhelming. Furthermore, the details of manufacturing, packaging and servicing may be outside the area of expertise of the designer. They lack the day-to-day, up-to-date experience possessed by people on the manufacturing line and those servicing the product. The knowledge compartmentalization problem is further exacerbated by the current trend towards locating manufacturing and service organizations overseas. All of these factors contribute to insufficient consideration of life cycle issues at design time.

In an effort to help designers better assess the downstream life cycle impacts of their design choices, manufacturing companies and researchers have developed many design decision support tools referred to as Design for X (DFX) methodologies. The 'X' in DFX represents any one of a variety of design considerations occurring throughout the product life cycle, such as quality, manufacturing, production, or environment. A DFX decision support tool can take many forms. It could be procedure or a set of guidelines on paper, or it could be a computer program that performs various types of analyses resulting in cost, manufacturability, or performance estimates, which are then used by the designer in making decisions.

Design for Manufacturing (DFM) and Design for Assembly (DFA) are two of the most common and popular DFX tools. Traditionally, DFA methods evaluate the ease of assembly, and DFM methods evaluate the feasibility and cost of manufacturing the product at the operation level Bralla (1986), Anderson (1990), Corbett *et al.* (1991), and Boothroyd *et al.* (2002) provide detailed discussions on manufacturability and design. Design guidelines such as those provided by Parmer & Laney (1993), Singh (1996), and Fagade & Kazmer (1998) are examples of DFM methods. As new DFX methods are explored, the definition of DFM has expanded to become synonymous with DFX and concurrent engineering (simultaneous development of a design and the supporting life cycle processes).

Recent developments in DFM research and practice have led to incorporation of DFM techniques at a variety of places in the product development process, including conceptual design, embodiment design, detail design, and design verification. Moreover, DFM techniques now address a wide range of manufacturing and life cycle concerns including product quality, manufacturing system performance, life cycle cost, and environmental issues.

DFM AND CONCURRENT ENGINEERING

Concurrent product and process engineering is the practice of simultaneously designing a product to fulfill particular functions and the manufacturing process by which it will be made. More generally, concurrent engineering is the practice of simultaneously developing solutions that address multiple life cycle issues. In practice, engineered systems are usually too complex to truly consider all issues simultaneously. More commonly, concurrent engineering (and DFM) is accomplished through an iterative "spiral" design process (shown in Figure 1) in which marketing experts, designers, manufacturing engineers, and other personnel jump back and forth between

identification of customer needs, design of the product, and assessment of manufacturing issues.

Barriers to effective DFM and concurrent engineering occur when the people performing marketing, design, and manufacturing cannot communicate or share knowledge. For example, when designers lack detailed knowledge of the current manufacturing practices and the manufacturing engineers are not available to provide this assessment, the designers may not be able to perform sufficient manufacturing assessments of their designs. The result may be commitment to a design that is unnecessarily expensive to manufacture.

In some sense, the basic objective of DFM is not new. Manufacturers and craftspeople have always tried to design products that are inexpensive to manufacture. Before the industrial revolution, the salesperson, designer, and craftsman were often the same person. This person had a detailed understanding of the customer's needs, how the design would meet those needs, and how it would be made. Concurrent engineering naturally occurred within that person's head. However, as industries have grown in size and complexity, marketing, design, and manufacturing departments have evolved into separate organizations, each with their own specialized knowledge. While this makes the streamlined creation of complex products possible, it has also increased the knowledge and communication barriers between these areas. The recent trend towards moving manufacturing facilities overseas has exacerbated these communication difficulties. The result is that DFM and DFX are more difficult to accomplish, product quality and customer satisfaction may be compromised, and much time and money may be lost.

The goal behind many DFX tools is to supply designers with manufacturing, quality, environmental impact, or other life cycle knowledge that is otherwise inaccessible. This can be accomplished through many methods such as (1) the development of a set of manufacturability rules that designers apply to their designs, (2) software "auditors" and "critics" that automatically apply such rules to electronic CAD designs and provide advice for improvement, cost analysis, and (3) simulation models that predict the product's performance during various life cycle phases. Examples will be described in the following sections of various ways in which these methods may be applied in any or all of the life cycle stages shown in Figure 1.

DFM IN CONCEPTUAL DESIGN

Conceptual design is the process by which customer needs are translated into requirements on function (what the design must do) and performance (how well it does it). Design freedom is at its highest here; this freedom is 'spent' by making design commitments whose effects may not be known fully until production begins. Often only rough estimates of manufacturability are available in conceptual design. DFM must help direct the allocation of design freedom toward designs with high manufacturability. The key concept here is 'designs': Toyota's successful use of set-based design underscores the value of delaying design commitment when there is no clear-cut 'best' design (Sobek *et al.*, 1999). For DFM in conceptual design, this means developing multiple functional approaches and propagating them through further design stages, eliminating or revising candidates as they are

proven inferior. Decision-based design (Chen *et al.*, 2003) provides a normative framework for culling design candidates under estimated performance metrics.

Performance metrics are continually refined through the design process. Perhaps the most commonly used DFM tool throughout all stages of product development is Quality Function Deployment (QFD). QFD was first put forth in 1966 in quality assurance work by Akao and Oshiumi (see, for instance, Akao, 1990). Subsequent research used the matrix to address technical trade-offs in the quality characteristics by adding a “roof” to the top of the matrix, which became the “House of Quality.” QFD converts customer demands (WHATs) into quality characteristics (HOWs) and systematically develops a quality plan for the deployment of the finished product. In practice today, QFD is used to translate the voice of the customers into a set of design elements that can be deployed vertically top-down through a four-phase process: Product Planning, Part Deployment, Process Planning, and Process Control. Figure 2 shows the methodology flow of the four phases of QFD. During each phase one or more matrices are prepared to help plan and communicate customer needs, technical characteristics, and design and process information.

From a technology development standpoint, DFM in conceptual design presents two main issues: how to develop functions in response to common DFM desires (e.g., low part count, low part complexity, ease of assembly, and loose tolerances) and how to close the QFD ‘loop’ to propagate standard downstream concerns back into conceptual design. For the former, the current state of the art is the collocation of design and manufacturing team members. As enterprises become less vertically integrated, collocation becomes impractical; reverse engineering can substitute as a means of accessing ready manufacturing experience (Verma and Wood, 2004). By providing designers with access to a broad, consistent basis of experience, reverse engineering can potentially improve the degree to which manufacturability can shape conceptualization.

For the latter issue, integrating DFM into QFD can be achieved through an iterative process that brings the results of process planning and control matrices into the part deployment matrix. For example, once a process plan has been conceived, features that make components easier to fabricate or easier to assemble into the final product can be added to the list of technical and part characteristics. Such iterations ease the transition to embodiment design and allow manufacturing to be considered at the earliest stage of design. Again, experience in this process not only provides early estimates of downstream metrics but also helps link performance metrics directly to function (Dong and Wood, 2003).

DFM IN EMBODIMENT DESIGN

For many products, process constraints play a significant role in determining the detailed features of the final form of the components. Thus, a component’s final form can be specified only after selecting the most appropriate process and material combination. Embodiment design includes process and material selection and involves a number of complex problems. For example, the manufacturing process, material type, and component size are highly interdependent. A component may require multiple processes to achieve the required form and

finish, so processes must be selected at the same time, which makes cost estimating more complex. Adding to the problem is difficulty in accounting for imprecision in design parameters.

During embodiment design, designers traditionally select processes and materials based on their own experience or the experience of the manufacturing engineer. Most designers are familiar with only a few manufacturing processes and there exist a large number of complex manufacturing processes and materials that are being used widely all over the world. Therefore, if designers rely on their own knowledge, they might not consider unfamiliar manufacturing processes that could be an attractive alternative to the more familiar processes. Rapid changes in manufacturing technologies are making this problem more severe.

Recently, several different software systems have been developed to support material and process selection during embodiment design. Recent representative systems include WiseProM (Gupta *et al.*, 2003), MAS (Smith, 1999), and CES (Ashby and Esawi, 1999). Given design requirements in terms of not only manufacturability but also business, material, and form requirements, these systems help designers select the proper combination of materials and processes to meet design requirements prior to detailed design.

Current systems use simplistic approximations of production tool lead time and production rate, which depend upon the manufacturing facility. The next generation of systems will need to incorporate these parameters in a better way. Furthermore, current systems use only manufacturing costs in performing process and material selection. Because life cycle costs have a major role in the decision, they should be considered in the next generation of systems.

DFM IN DETAILED DESIGN

Given the selection of materials and processes during embodiment design and facing the impending release of the product design to manufacturing, a host of DFM techniques are frequently applied in an effort to identify issues, catch mistakes, and avoid downstream changes. During detailed design, integration with Computer Aided Design (CAD) tools becomes critical to product and process analysis. For example, integration of Failure Modes and Effects Analysis (FMEA) and Computer Aided Manufacturing (CAM) into CAD is common.

Detail design is concerned with both the shape and tolerance of a part. Applying DFM to shape is highly process-dependent and can be accomplished through design standards or expert systems. More generic to all processes is the consideration of tolerance and its effect on function.

Specifically, FMEA is a DFM method used during detailed design that became so prevalent that it is now a military specification, MIL-STD-1629. In FMEA, the development team systematically evaluates and documents each failure mode, as well as the failure mode’s potential impact on system performance, safety, and maintenance. Each failure mode is then ranked by the severity of its effect in order that appropriate corrective actions may be taken to eliminate or control the high risk items. Subsequently, further detailed, embodiment, or even concept design may be required to address the revealed shortcomings. Current research (Chao and Ishii, 2003) is striving to lower the burden of conducting FMEA through automation with wizards while extending and validating its

usefulness. FMEA can address manufacturing operations to identify ways in which the product design leads to manufacturing problems.

The analysis of tolerances and tolerance stack-up remains important. Previously, industry standards were blindly accepted as limits on product design and manufacturing. Currently, Six Sigma approaches promote the characterization and classification of manufacturing processes, with downstream statistical data being fed back to set the component tolerances during detailed design. Simultaneously, engineers have begun using analysis techniques such as Monte Carlo analysis to predict the distribution of the design performance, rather than simply accepting or rejecting the design based on worst case scenarios. Using these techniques, engineers can correctly recognize, specify, and control those few tolerances that dominate the design performance, thereby leading to improved product performance at lower cost.

In addition to FMEA, CAD/CAM software is an important DFM tool for detailed design that utilizes CAD software to describe part geometries to, for example, define toolpaths to direct the motion of a machine tool to form the part. Today, most new machine tools incorporate CAM and Numerically-Controlled (NC) technologies. To further facilitate DFM, CAD/CAM systems can be integrated with process planning and other technologies such as Group Technology (GT) and Cellular Manufacturing. Finally, Flexible Manufacturing Systems (FMS) and Just-In-Time Production (JIT) are important concepts made possible by CAD/CAM systems, affecting the integration of manufacturing cells, productivity and quality in a wide variety of strategic industries (e.g., http://www.gsd.harvard.edu/inside/computer_resources/manual/cadcam/whatis.htm).

No matter the stage in the design process, DFM is recognized as an important component of product development. As such, practice and theory have developed within very specific areas of DFM including Design for Quality, Design for Production, Design for Life Cycle Cost, and Design for Environment, as described below.

DESIGN FOR PRODUCTION

The performance of production lines, factories, and supply chains depends upon product design. The rapid introduction of new products means that existing facilities outlive new products. Instead of designing the facility around the product, the product must be designed to fit the facility. For example, the length of a new automobile's chassis is a critical design variable that must be determined early in the vehicle development process. In order to avoid expensive modifications to the robotic assembly line that will make the vehicle, the chassis length is constrained by the size of the existing automated fixtures.

Often, manufacturing system performance is disregarded during product design because it is considered hard to model. Recently, however, researchers and manufacturing firms have created and used a number of concrete, feasible Design for Production (DFP) techniques. A product development team can evaluate the performance of a production line, factory, or supply chain before production begins. They can use this information to avoid problems (such as bottlenecks) and reduce costs. Herrmann and Chincholkar (2001/2002) give a detailed

review of DFP approaches, and Chincholkar *et al.* (2003) survey a range of DFP studies in detail.

Boeing developed a DFP approach for an aircraft tubes (described by Wei and Thornton, 2002). The manufacturing stage includes bending, trimming, connector welding, and pressure test. The assembly stage places the tubes into the aircraft. Partially finished goods are stored between the two stages, and this is controlled by a reorder point policy. The DFP tool relates total cost (due to poor quality tubes work-in-process, and finished goods inventory) to the tube geometry, gauge tolerance (a constraint on tube variation), and production lot size.

Hewlett Packard used an inventory model to determine if a redesigned deskjet printer could yield better supply chain performance (described by Lee *et al.*, 1993). The redesign was a generic printer version with modules that distribution centers use to create product variants for different markets. The inventory model showed that the changes would reduce the supply chain's total inventory investment by eighteen percent.

PLATFORM DESIGN FOR TIME-TO-MARKET

Most DFM applications to date have focused on a particular model of a product at a particular point in time. Recent challenges in fast time-to-market are drawing attention to product architecture, i.e., achieving platforms that cover diverse market segments over multiple generations. This challenge, also known as "Design for Variety" (DFV), has attracted significant attention by almost every industry, as the performance of the platform directly affects the profitability of the business.

The critical step is to identify the drivers for platform design. Typical drivers include investment recovery (important in high investment projects such as semiconductors and aircraft engines), responding to fast changes in market needs and technology advances (pertinent in computers and communications), and effective response to customized needs (telecommunication infrastructure, manufacturing automation facility).

System and service products pose additional challenges. Platform design for hardware products has evolved by focusing on standard components that comprise the base of the platform, while producing derivative products using differentiating elements. For automotive systems, the chassis and powertrain comprise the base, while the body and interior are the differentiating elements. For system products such as medical imaging services, it is often not clear what the base platform should be.

The key in platform design is in identifying the standard solution elements that cover a wide range of market segments over multiple generations, while accomplishing customization with short lead time (development, manufacturing, and delivery) elements. Studies on variety complexity (Martin and Ishii, 2002) and product modularity (Yang and Ishii, 2003) have shown that the effective definition of "standard vs. differentiating" elements and the interfaces among them lead to successful product platforms. Another important aspect is a knowledge base of best practices that supports systematic concept generation for effective platforms. In the next decade, extending DFM tools to product platforms will hold the key to achieving a competitive manufacturing business.

DESIGN FOR SYSTEM QUALITY

Many products and services today require combinations of hardware and software as well as external infrastructure. Typical examples include mobile phones that utilize the Internet (IP phones). Applying DFM techniques to such products must address not only the phone handset but also the complex software that controls the device and the communication infrastructure. Medical imaging diagnostic equipment and services are another example.

A key objective is achieving ultra-high reliability and availability of the entire system to deliver functions and value to the customer (Kmenta and Ishii, 2000; Rhee and Ishii, 2003). Whereas traditional DFM tools effectively identified potential failure modes in system hardware, there is an acute need for effective methods to identify the failure modes associated with the interfaces among the various modules that comprise the system: hardware, software, and infrastructure. Tools such as QFD and FMEA have high potential in addressing system quality, yet structured studies for this target are limited to date. Defining and describing the system are the keys to effective tools. Unlike hardware, system products have amorphous (shapeless) elements. In many cases, the product may not have a mature structure, so one must define the structure of the system by applying concept development techniques before applying analysis techniques such as FMEA. Both representing the system and applying a strategic sequence of DFM tools are necessary for establishing a solid theory for system DFM.

DESIGN FOR LIFE CYCLE COSTS

There are many well known modeling methodologies that address product manufacturing costs: process flow based models, technical cost models, cost of ownership models, and activity based costing. These are often supplemented by yield and tolerance modeling, learning curve modeling, and test & rework economic models. However, manufacturing is just one phase of a product's life cycle.

While manufacturing costing is relatively mature, life cycle cost modeling is much more difficult. For many consumer products, manufacturing represents the dominant cost. However, even for consumer products, the manufacturer must be concerned with the costs of product development, time-to-market impacts, distribution, liability, marketing and sales, and the disposal or recycling of the product at the end of its life (if applicable). For other types of products, e.g., airplanes, copy machines, traffic lights, and even computer networks, life cycle (sustainment) costs such as warranty, reliability, maintenance, upgrades, and obsolescence can dominate. See, for example, Figure 3. In addition, only twenty percent (20%) of the life cycle cost of an F-16 fighter aircraft is the manufacturing cost. These sustainment costs are borne by both the manufacturer and the customer.

Life cycle costing is much more difficult because different classes of products have different types of life cycles. For example, products that have a long field life are especially susceptible to technology obsolescence. In particular, electronic parts obsolescence is a common problem for electronic systems (Solomon *et al.*, 2000). For example, most electronic parts have short lifetimes (from an availability perspective) relative to the design cycle of an aircraft, let alone

an aircraft's support life. In such industries, qualification and certification requirements may make replacing obsolete technologies and parts with newer parts prohibitively expensive. The need to quantify and reduce the cost of sustainment has given rise to design refresh planning (Singh *et al.*, 2002) and the analysis of system viability (Sandborn *et al.*, 2003). Viability is a measure of the producibility, supportability, and evolvability of a system and can serve as a metric for assessing both sustainability of a product and technology insertion opportunities

DESIGN FOR ENVIRONMENT

In addition to estimating cost and other traditional manufacturing performance measures, manufacturing firms are interested in evaluating and reducing the environmental impact of their products. Firms want to reduce the energy that the manufacturing processes consume and the hazardous materials that are produced. Firms are also concerned about pollution prevention and environmental management standards (ISO 14000), customer expectations for products that use less energy and require less maintenance, and regulatory efforts, especially in Europe, to improve the use of recycled materials and the recyclability of products. To date, most efforts have focused on developing Design for Environment (DFE) and Life Cycle Assessment (LCA) tools and software for specific products and sectors for all stages of design.

During conceptual design, material check lists or justification schemes for high impact materials and matrix assessments that consider multiple impacts for each life cycle stage are common DFE tools. As materials and processes are selected during product embodiment and detailed design, software such as IDEMAT for materials selection, CAD-based product disassembly tools such as Boothroyd and Dewhurst's DFE tool, and Life Cycle Assessment (LCA) software are used to analyze the environmental impact of product designs. In fact, the current trend is to develop tools and software for specific products and sectors for all stages of design.

Because of the need to balance environmental concerns with other DFX requirements, DFE's life cycle view has made explicit linkages to supply chain management, pollution prevention and environmental management standards (ISO14000), and customer expectations for products that use less energy and require less maintenance, and regulatory efforts, especially in Europe, to improve the use of recycled materials and the recyclability of products. As such, many companies have integrated related DFE efforts into their business models. Examples include Supplier Scouting at AT&T, Supplier Training at General Motors, Supplier ISO14000 Registration at Ford, 3M's Pollution Prevention Pays Program, and Xerox's Asset Recycle Management Program.

Interestingly, Rounds and Cooper (2002) investigate the development and use of DFM and DFE design requirements in product design. They find that most of the DFM requirements assessed also apply to DFE and vice versa. Specifically, given a DFM goal of reducing cost, reducing the time to manufacture a product yields not only cost savings but also a reduction in energy use (Ufford, 1996). Similarly, improvements in material and energy efficiency reduce raw material and energy costs as well as materials and waste management costs.

DFX THROUGH NON-TECHNOLOGICAL SOLUTIONS

Achieving effective DFM and DFX may require more than a technological solution in the form of a set of rules or a computer program. It may require additional changes:

- The organization (who reports to whom?);
- The responsibilities assigned to designers and engineers (who receives the heat when a downstream problem occurs? And who must bear the agony of fixing a problem?);
- The training given to marketing personnel, designers, and process engineers; and
- The culture within the organization.

All of these affect how knowledge and information is communicated between people carrying out marketing, design, and manufacturing functions. Understanding the flow of information and decision-making in a product development organization is crucial for successfully implementing new design tools (Herrmann and Schmidt, 2002).

For example, even if a manufacturability assessment is a part of design verification, there is often a tendency for designers to perform the manufacturability assessment inadequately for numerous reasons. The manufacturing aspects are probably not the designers' area of expertise, schedule pressures may leave little time for the analysis, and there is a tendency on the part of designers to believe that the manufacturing people can solve any problems that occur. The underlying problem is not that manufacturability consideration was absent from the design verification, but that the people performing the analysis did not have sufficient manufacturing training to do it well, and the responsibility for solving manufacturing problems did not fall on the designers. Thus, there is little motivation to do it well. Furthermore, geographical distance, language barriers, and cultural gaps between design and manufacturing personnel reduce the likelihood that designers will seek the manufacturers' help.

Thus, addressing DFX issues in practice may require studying the entire organization, not just the individual designer. Solutions to the problems described above include the following: changing the design team organization so that manufacturing personnel are included in the design verification team; providing designers and manufacturers with cross training so that they can understand each other's constraints better and make mutually beneficial suggestions for improvement; and assigning joint responsibility for problems down the line. Design and manufacturing teams need to have joint responsibility and accountability for the success of the product.

However, such changes require a long-term investment in training, travel, and team building. Unfortunately, there is always a strong tendency to sacrifice long term investments in favor of short term exigencies. Most importantly, the organization must have a strong commitment to DFX from the top level to make these investments happen, aided by methods for assessing the cost benefits of specific DFX investments.

CONCLUSIONS

The scope of DFM tools has expanded in many ways: to applications for different phases of design, to manufacturing system performance, to platform design and system quality, and

to life cycle cost and environmental considerations. Though this variety is tremendous, there are some general guidelines that suggest how manufacturing firms can gain from DFM tools. Useful, effective DFM tools are based on the specific products and performance measures of interest and are used in the design phases that have the most impact on performance. Creating DFM tools should take into account the information available, the effort involved in making that information accessible, the information needed to evaluate the product and make a decision, and the time constraints for using the tool.

Certainly, a product development team should consider the product's entire life cycle. Different techniques consider different phases of the life cycle and may make contradictory design improvement suggestions. Therefore, successfully employing techniques such as DFM requires using them in a coordinated way to design a more profitable product.

REFERENCES

- [1] Akao, Y., *Quality Function Deployment; Integrating Customer Requirements Into Product Design*, Booknews, Inc., 1990.
- [2] Anderson, D. M., *Design for Manufacturability*, CIM Press, Lafayette, CA, 1990
- [3] Ashby, M.F., and A. M. Esawi, "Cost estimation for process selection," *Proceedings of ASME Design for Manufacture Conference*, Las Vegas, Nevada, September, 1999.
- [4] Boothroyd, Geoffrey, Peter Dewhurst, Winston Knight, *Product Design for Manufacture and Assembly*, Second Edition, Marcel Dekker, New York, 2002
- [5] Bralla, James, *Design for Excellence*, McGraw-Hill, New York, 1996
- [6] Chao, Lawrence P., and Kosuke Ishii, "Design Process Error-Proofing: Failure Modes and Effects Analysis of The Design Process," in *Proceedings of the ASME 2003 International Design Engineering Technical Conferences and Computers and Information In Engineering Conference*, Chicago, Illinois, September 2-6, 2003.
- [7] Chen, Wei, Linda Schmidt, and Kemper Lewis, "Decision Based Design Open Workshop," <http://dbd.eng.buffalo.edu/>, accessed May 24, 2003.
- [8] Chincholkar, Mandar M., Jeffrey W. Herrmann, and Yu-Feng Wei, "Applying design for production methods for improved product development," DETC2003/DFM-48133, *Proceedings of the ASME 2003 International Design Engineering Technical Conferences and Computers and Information In Engineering Conference*, Chicago, Illinois, September 2-6, 2003.
- [9] Corbett, J., M. Dooner, J. Meleka, and C. Pym, *Design for Manufacture, Strategies, Principles and Techniques*, Addison-Wesley, Workingham, England, 1991
- [10] Dong, H., and W. H. Wood, "Issues in integration of design and manufacturing for mechatronics," DETC2003/DFM-48134, *Proceedings of the ASME 2003 International Design Engineering Technical Conferences and Computers and Information In Engineering Conference*, Chicago, Illinois, September 2-6, 2003.
- [11] Fagade, Adekunle and David Kazmer, "Economic Design of Injection Molded Parts Using DFM Guidelines - A Review of Two Methods for Tooling Cost Estimation," *Annual*

Technical Conference - ANTEC, Conference Proceedings, pp 869-873, 1998

[12] Gupta, S.K., Y. S. Chen, S. Feng, and R. Sriram, "A system for generating process and material selection advice during embodiment design of mechanical components," *Journal of Manufacturing Systems*, 22(1):28-45, 2003.

[13] Harvard Design School, "What is CAD/CAM?" http://www.gsd.harvard.edu/inside/computer_resources/manual/cadcam/whatis.htm, accessed February 18, 2004.

[14] Herrmann, Jeffrey W. and Mandar M. Chincholkar, "Reducing Throughput Time During Product Design," *Journal of Manufacturing Systems*, Volume 20, Number 6, pages 416-428, 2001/2002.

[15] Herrmann, Jeffrey W., and Linda C. Schmidt, "Viewing Product Development as a Decision Production System," DETC2002/DTM-34030, Proceedings of the ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, Canada, September 29 - October 2, 2002.

[16] Kmenta, S., and K. Ishii, "Scenario-based FMEA: A Life Cycle Cost Perspective," DETC2000/RSAFP-14478, Proceedings of the ASME 2000 DETC/CIE Conference, Baltimore, Maryland, 2000.

[17] Lee, Hau L., C. Billington, and B. Carter, "Hewlett-Packard gains control of inventory and service through design for localization," *Interfaces*, Volume 23, Number 4, pages 1-11, 1993.

[18] Martin, M. and K. Ishii, "Design for variety: Developing standardized and modularized product platform architectures" *Research in Engineering Design*, Volume 13, Issue 4, pages 213-235, 2002.

[19] Omnijet, "Investment Costs: Omni Jet Performance & Cost Database," <http://www.omnijet.com/menu/>, accessed February 19, 2004.

[20] Parmer, Curtis and Steve Laney, "DFM&T Guidelines for Complex PCBs," *Surface Mount Technology*, Volume 7, Number 7, pages 29-31, July, 1993.

[21] Prasad, B., "Review of QFD and related Deployment Techniques," *Journal of Manufacturing Systems*, 17(3): pages 221-234, 1998.

[22] Rhee, S., and K. Ishii, "Life Cost-Based FMEA Using Empirical Data," DETC2003/DFM-48150, Proceedings of the ASME 2003 DETC/CIE Conference, Chicago, Illinois, September, 2003.

[23] Rounds, K.S., and J.S. Cooper, "Development of product design requirements using taxonomies of

environmental issues," *Research in Engineering Design*, 13, 94-108, 2002

[24] Sandborn, P., P. Singh, T. Herald, and J. Houston, "Optimum Technology Insertion into Systems Based on the Assessment of Viability," *IEEE Trans. on Components and Packaging Technologies*, Vol. 26, No. 4, December 2003.

[25] Shields, P., "Total Cost of Ownership: Why the price of the computer means so little," http://www.thebusinessmac.com/features/tco_hardware.shtml, December 2001.

[26] Singh, K., *Mechanical Design Principles: Applications, Techniques and Guidelines for Manufacture*, Nantel Publications, Melbourne, Australia, 1996.

[27] Singh, P., P. Sandborn, T. Geiser, and D. Lorenson, "Electronic Part Obsolescence Driven Design Refresh Optimization," *Proc. International Conference on Concurrent Engineering*, pp. 961-970, Cranfield University, UK, July 2002.

[28] Smith, C.S., "The Manufacturing Advisory Service: Web Based Process and Material Selection," PhD thesis, University of California, Berkeley, CA, 1999.

[29] Sobek, D.K., A. Ward, and J. Liker, "Toyota's principles of set-based concurrent engineering," *Sloan Management Review*, pages 67-83, Winter, 1999.

[30] Solomon, R., P. Sandborn, and M. Pecht, "Electronic part life cycle concepts and obsolescence forecasting," *IEEE Trans. on Components and Packaging Technologies*, vol. 23, no. 3, pp. 707-713, December 2000.

[31] Suri, R., K.N. Otto, and C. Painter, "Process capability to guide tolerancing in manufacturing systems," *Proceedings of the Society of Manufacturing Engineers*. MS, n MS99-181, pages 1-6, 1999.

[32] Ufford, D.A., "Leveraging commonalities between DFE and DFM/A," *Proceedings of the 1996 IEEE International Symposium on Electronics and the Environment*, Dallas, Texas, 1996.

[33] Verma, M., and W. H. Wood, "Toward case-based functional design: matching reverse engineering practice with the design process," to appear in *Design Studies*, 2004.

[34] Wei, Y.-F. and A.C. Thornton, "Concurrent Design for Optimal Production Performance," DETC2002/DFM-34163, Proceedings of the ASME 2002 DETC/CIE Conference, Montreal, Canada, 2002.

[35] Yang, T., and K. Ishii, "Modularity: International Industry Benchmarking and Research Roadmap," DETC2003/DFM-48132, Proceedings of the ASME 2003 DETC/CIE Conference, Chicago, Illinois, September, 2003.

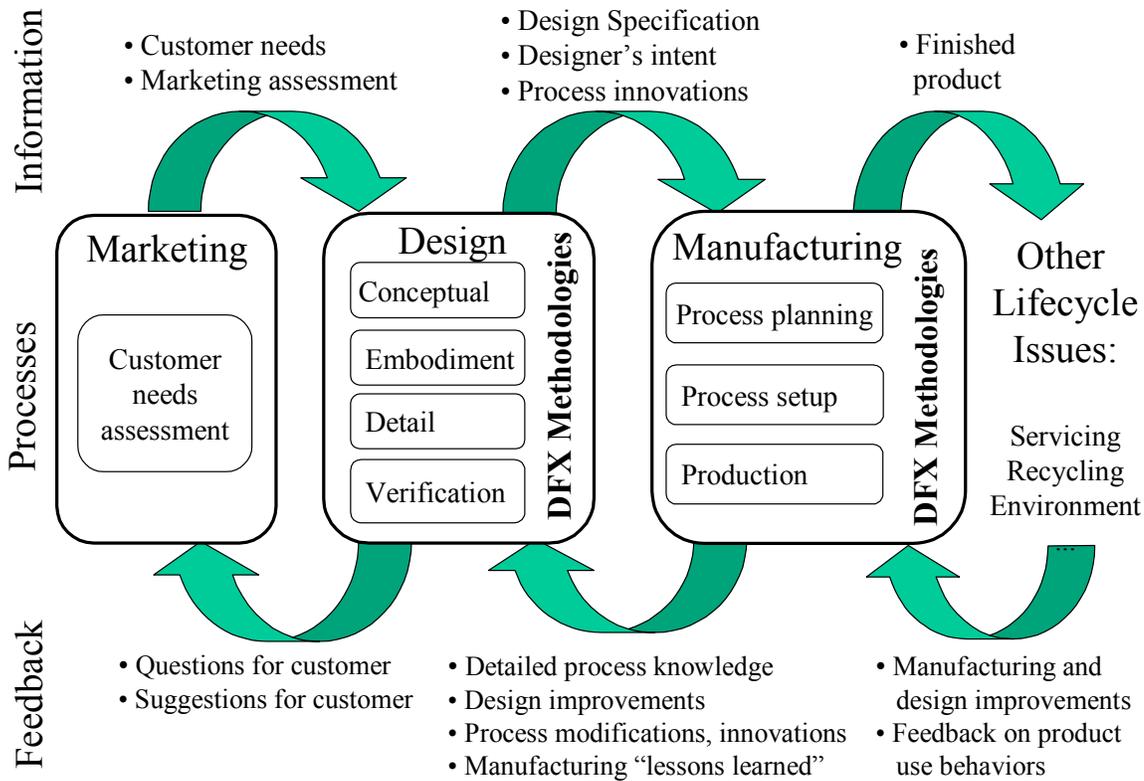


Figure 1: The Design for X Cycle.

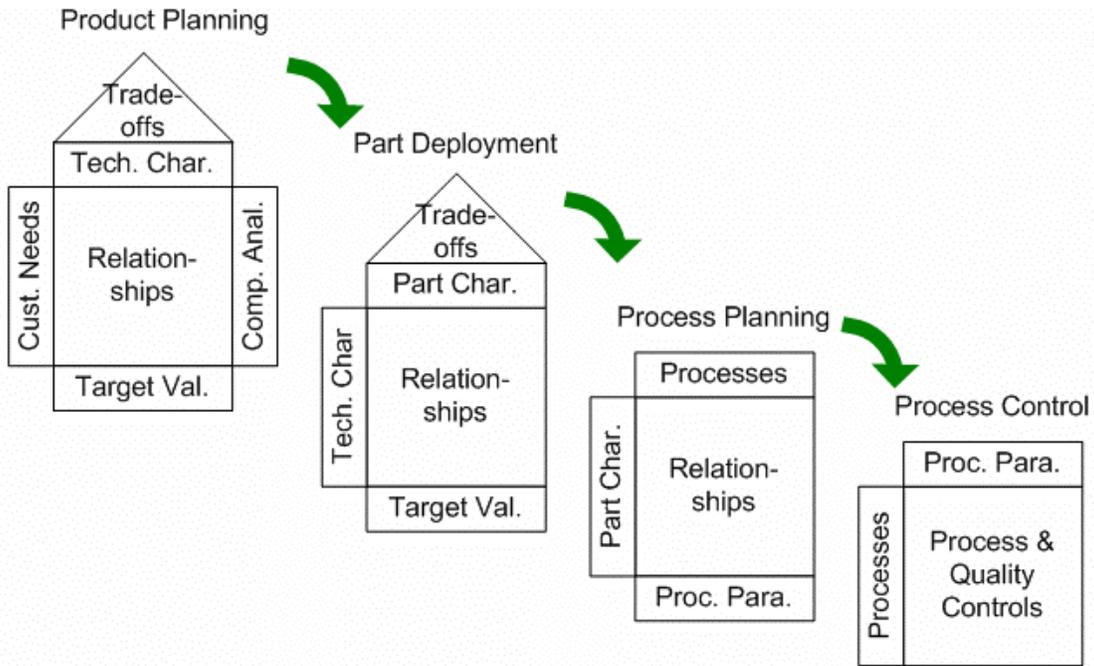
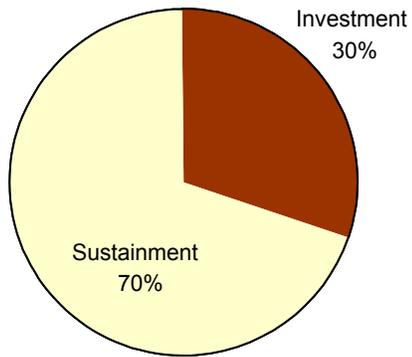


Figure 2: The Phases of Quality Function Deployment

Business Jet



Office PC Network (including system administrator)

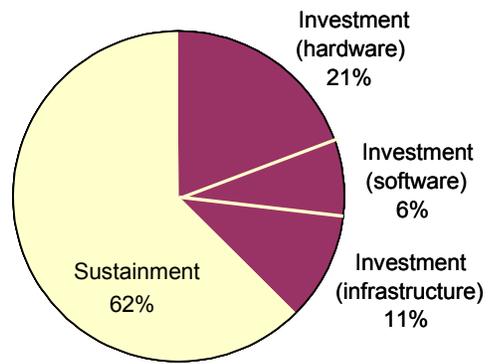


Figure 3. Life cycle cost breakdowns for a private jet (OmniJet) and a PC network (Shields, 2001).