Proceedings of DETC'03
ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Chicago, Illinois USA, September 2-6, 2003

DETC2003/DFM-48133

APPLYING DESIGN FOR PRODUCTION METHODS FOR IMPROVED PRODUCT DEVELOPMENT

Mandar M. Chincholkar
Department of Mechanical Engineering
University of Maryland
College Park, Maryland 20742.
mmc@eng.umd.edu

Jeffrey W. Herrmann*
Department of Mechanical Engineering
University of Maryland
College Park, Maryland 20742.
jwh2@eng.umd.edu
(301) 405-5433

Yu-Feng Wei
Sigmantra LLC
Boston, MA
yfwei@alum.mit.edu

ABSTRACT

Design for production (DFP) refers to methods that evaluate manufacturing system performance as a function of product design variables. DFP can lead a product development team to consider changing the product design to avoid problems or improve profitability. In addition, DFP can provoke suggestions to improve the manufacturing system.

This paper reviews studies that have successfully applied DFP techniques in a variety of product domains. In addition, the paper discusses how product development teams can create new DFP techniques that will help them create more profitable products. The presentation of these examples and guidelines should encourage the use of DFP and improve product development.

KEYWORDS : design for manufacture, design for production, product design, concurrent engineering

INTRODUCTION

Successful new product development requires the ability to predict, early in the product development process, the life-cycle impacts of a product design. Ignoring downstream issues (or producing poor estimates) leads to product designs that cause unforeseen problems. These have to be redesigned. Accurate prediction allows a product development team to create a superior design that performs satisfactory in all ways. This reduces the number of re-design iterations, the time-to-market, and the development costs. Consequently, manufacturing companies (and solution providers) have developed many design decision support tools that form the class of Design for X (DFX) methodologies. An extremely important, though often overlooked, issue is the performance of the manufacturing system at all levels, from supply chain to production line. The performance of these systems is disregarded because it is considered hard to model and designers don't know much about the manufacturing system. However, practical models are becoming more available. Thilmany [1] reports on the use of virtual manufacturing tools for creating digital factories to study the anticipated performance of factories processing a new product, with emphasis on automobile manufacture. Moreover, the rapid introduction of new products means that existing facilities outlive new products. Instead of designing the manufacturing system around the product, the product must be designed to fit the facility.

This approach goes beyond the traditional concepts of design for manufacturing and design for assembly (DFM/DFA) to become a practice that we call Design for Production (DFP). This approach provides a systematic way to think about manufacturing issues and use such information to develop more profitable products. Design For Production refers to methods that evaluate manufacturing system performance. For example, does the production line have enough capacity to achieve the desired production rate? How long will it take the factory to complete customer orders? How much inventory will be required to maintain superior customer service in an international supply chain? Answering such questions requires information about prod-

*Author to whom all correspondence may be addressed uct design, manufacturing requirements, and production quantities along with information about the manufacturing system that will create the product.

DFP will become more important as product variety increases and product life cycles decrease. Factories will then be faced with an explosion of varying manufacturing cycle times because of the increased product variety, and historical manufacturing cycle times will not be accurate enough for estimating the times for a new product to be manufactured in the future, when the product mix is different. Additionally, since production lines usually outlive individual products, it is prudent to design new products that can be manufactured quickly using existing equipment.

DFP, like Design for Manufacture (DFM) and Design for Assembly (DFA), is related to the product's manufacture. In general, DFM and DFA evaluate the materials, the required manufacturing processes, and the ease of assembly. That is, DFM and DFA study the feasibility and cost of manufacturing the product, primarily from the operation level. On the other hand, DFP evaluates manufacturing system performance at the production line, factory, or supply chain level. Like DFM and DFA, DFP can lead a product development team to consider changing the product design to avoid problems or improve profitability. In addition, DFP can provoke suggestions to improve the manufacturing system.

This paper recommends that manufacturing companies consider, while developing new products, not only the details of the required manufacturing technologies but also a comprehensive view of the entire manufacturing system that will produce and distribute the product. Product development teams must plan how to design new products to exploit the capabilities and capacity that already exist. Suppliers and logistics issues are highly relevant and must be understood as well. The DFP approach can lead a product development team to consider changing the product design to avoid problems and improve profitability.

Research by the authors and others have yielded a number of concrete, feasible techniques that apply the DFP approach. This approach provides the product development team with methods to evaluate the performance of the manufacturing system before production begins. Tools based on the approach may best be applied during the early phases of the new product development process. However, each company must determine how to implement the DFP approach to reflect the particular features of its market and its product development process. In particular, the organization must identify which aspects of the product design most substantially influence manufacturing system performance and develop models and methods for estimating that performance as a function of the relevant design attributes.

The DFP approach uses a system-level perspective of manufacturing activities to guide the product development process. The decision-makers who benefit from this perspective are those leading product development teams, those serving on product design review boards, and those directing product development organizations including managers in firms that continuously envision, design, and develop new products.

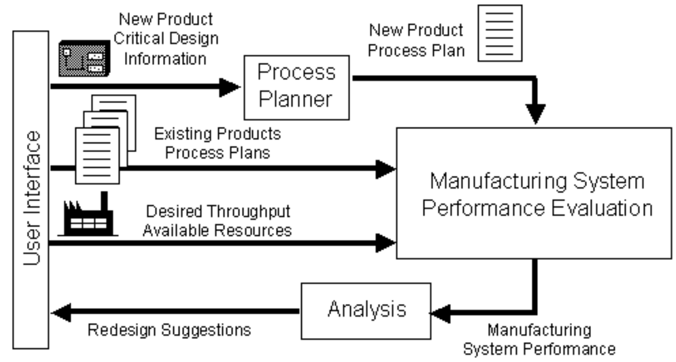

Figure 1: **Schematic for a DFP Tool**

Other researchers have used various names to describe DFP approaches, including design for existing environment [4], design for time-to-market [5, 6], design for localization [7], design for speed [8], design for schedulability [9], and design for manufacturing system performance [10]. Some of these researchers have reported case studies in which product designs were modified to improve production. Most of the work has been in three areas of DFP: design guidelines, capacity analysis, and estimating manufacturing cycle times. See Herrmann and Chincholkar [2, 3] for a more detailed review of DFP approaches and the relative merits of using fixed lead times, mathematical models, discrete-event simulation, and other techniques.

In many cases the DFP approach is implemented as a decision support tool. Figure 1 presents the schematic of a generic DFP tool. The tool consists of an user interface along with a process planning module, a manufacturing system performance evaluation module, and an analysis module. The user interface allows the user to input the product design and the key characteristics for the products being processed in the manufacturing system. The process planning module uses the product design information to find the processing times for the product and its components at the various resources that form a part of the product processing sequence.

An important aspect of the DFP approach is estimating the manufacturing system performance for the product. Different performance measures require different models. This paper presents some applications of the DFP methodology, models developed for such applications, and real-life examples of using the methodology to improve the product development process. Finally the paper presents benefits of the DFP methodology and implementation issues to be researched in order to realize its complete potential.

APPLICATIONS

Following are some applications of DFP to different product domains. Different products are presented here such as mechanical, electrical and electro-mechanical ones. Some results have been derived by the authors while other are presented from relevant work by other researchers.

Printed Circuit Boards

Taylor, English and Graves [4] present a technique that they call "design for existing environment (DFEE)." This DFP methodology can be applied to design products that yield dramatic production rate improvements.

The DFEE techniques are applied to understand the impact of different printed circuit board (PCB) designs on the manufacturing system performance. There are four different types of printed circuit boards. The PCB designs include components mounted on both sides of the PCB along with some through hole components. The design alternatives chiefly focus on varying percentages of surface mounted and through-hole components along with different process routings. The study establishes suitable PCB design rules in order to be able to determine feasibility of switching work away from a bottleneck station, establishes trade-off rules, and determines sensitivity of the design change with respect to performance improvement. To aid in this study, Taylor et al. created a DFP tool.

The printed circuit boards are manufactured in a flow shop manufacturing system. The processing sequence for the boards have 23 processing and assembly operations. Different resources in the manufacturing system have different number of machines. The boards have different component counts resulting in different processing times at different resources.

The study considers the initial product designs and further iterations of these designs. The tool is also employed to analyze various product mixes. The key performance measure is the relative utilization of various resources that form a part of the processing sequence. The paper defines a baseline scenario and compares other design and product mix combinations with the baseline.

The design changes considered include changing the component layout on the PCB, effectively using both sides of the PCB. The choice of a PCB design is constrained by speed, electrical crosstalk and thermal considerations. The changes are aimed at introducing the new product with minimal disruption of the facility. The study shows that one of the four initial designs performs significantly better than the others. The design adopted based on the DFEE suggestions result in an increase in capacity for the product by over 40% without any reduction in component count or any increase in production equipment or personnel. The new designs only involved moving components from one part of the PCB to another to allow for more favorable product routings.

The study concludes by proposing that an hierarchy of DFEE techniques at the strategic, tactical and operational level should be investigated in order to assess its complete impact.

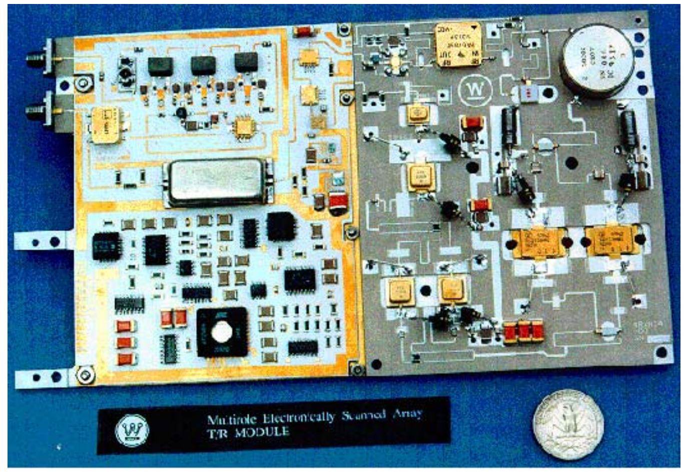

Figure 2: **A microwave module**

Microwave Modules

Herrmann and Chincholkar [2, 11] describe a DFP approach for microwave modules. Modern microwave modules (MWMs) have an artwork layer that includes many functional components of the circuit. See Figure 2. The artwork lies on the dielectric substrate, which is attached to a ground plane that also serves as a heat sink. In addition to the integrated components, MWMs may carry hybrid components, which are assembled separately using techniques such as soldering, wire bonding, and ultrasonic bonding. More details about this domain can be found in Minis et al. [12]. Mounting these components often requires holes, pockets, and other features in the substrate. The facility manufacturing these microwave modules is a batch manufacturing system. There is a CNC machine tool that can machine the required holes and pockets. The facility has an electroless (autocatalytic) plating workstation, an electroplating workstation, an etch workstation, a workstation for automated assembly, and a workstation for manual assembly. The automated assembly workstation has a screen print machine, a pick-and-place machine and a reflow oven. The material handling between these machines is automated. The manual assembly workstation has two employees who can attach other component types. The facility has four technicians who test and tune microwave modules.

Station	Average Cycle Time (mins)	
	Two Products	Three Products
Drill	13.00	14.00
Mill	2.07	2.10
Grinder	2.07	2.28
Plating Machine	5.40	6.00
Etch	63.60	64.80
Insulator	0.00	85.20
Auto Assembly	12.00	12.00
Manual Assembly	34.20	36.00
Test Station	62.40	64.20
Total	194.74	286.60

Table 1: **Cycle Time Estimates**

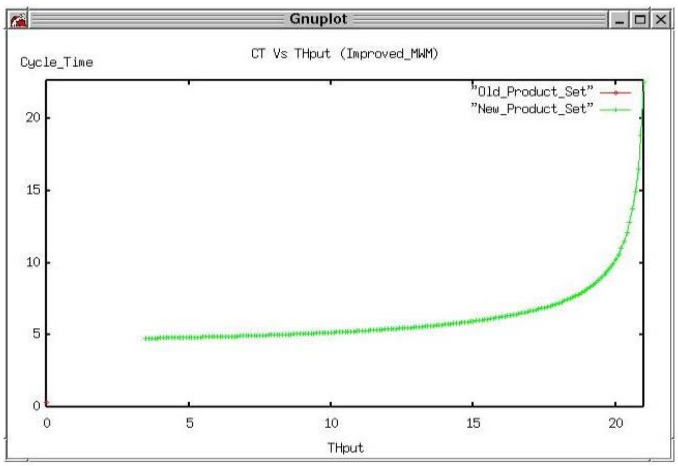

Figure 3: **CT as a function of Throughput for New Product**

In this study, the manufacturing system currently produces two types of microwave modules (which require 8 processing steps) and is developing a third that would require an additional processing step.

The DFP tool developed for this example uses a queuing network model to estimate the average manufacturing cycle time at each workstation. The manufacturing cycle time (also called the throughput time or the flow time) is the interval that elapses as the manufacturing system performs all of the operations necessary to complete a work order. Based on the routing for the new product, the DFP tool estimates the average manufacturing cycle time as the sum of these workstation cycle times. Table 1 summarizes these calculations. The total, when the system is processing the existing products, is 194.74 minutes or 3.25 hours, and 286.60 minutes or 4.78 hours when it is processing the new product set.

Figure 3 shows the plot of manufacturing cycle time for the new product as a function of its throughput. The product development team might consider adding capacity to the resource with the highest utilization as identified by the DFP tool. Alternatively the processing requirements at the resource might be analyzed and optimized so as to reduce its utilization. The team can use the results from Figure 3 to identify the optimal product throughput possible for the current system.

Embedded Passives

In applications such as consumer and industrial electronic products, a printed circuit board (PCB) (or printed wiring board (PWB)) forms the backbone of the device. The PCB substrate supports the discrete components that form part of the circuit along with the wiring requirements for these components. The components may be passive devices (such as resistors and capacitors) or active devices (such as diodes, integrated circuits, and transistors). These components may be mounted on one side of the substrate or on both sides depending on the circuit's requirements and the size of the board. Usually, the substrate is constructed by laminating copper to one or more surfaces of a sheet of plastic reinforced by paper or glass fiber. Single layer, single sided boards have only one circuit layer. Single layer, double sided boards have two circuit layers, one on each side of the board. Multilayer boards have three or more circuit layers made by bonding (or laminating) layers of patterned, pre-etched, undrilled copper-clad laminate together. Layer interconnections are then made by drilling and plating through holes in the non-conducting plastic.

As circuits become more complicated, they require more discrete passives. In addition, smaller electronic devices require smaller PCBs, which requires shrinking the size of the passive components and developing alternative technologies to accommodate the large numbers need for device functionality. Embedded (or integrated) passive components (see Figure 4), which are part of or buried in the PCB substrate and are fabricated along with the substrate [13], may be one way of realizing these goals. The National Electronics Manufacturing Initiative (NEMI) [14] defines embedded passives as functional elements either buried in or incorporated on the surface of an interconnecting substrate. For more information, see, for example [15, 16, 17, 18].

Chincholkar and Herrmann [19, 20] created a DFP tool for evaluating how embedding passives affects manufacturing system performance. Their study analyzed the PCB that serves as the central processing unit for the AS900 controller. The company makes two kinds of products, a conventional CPU board and a new CPU board that contains embedded passive components. The key characteristics for the conventional CPU board are: length of board

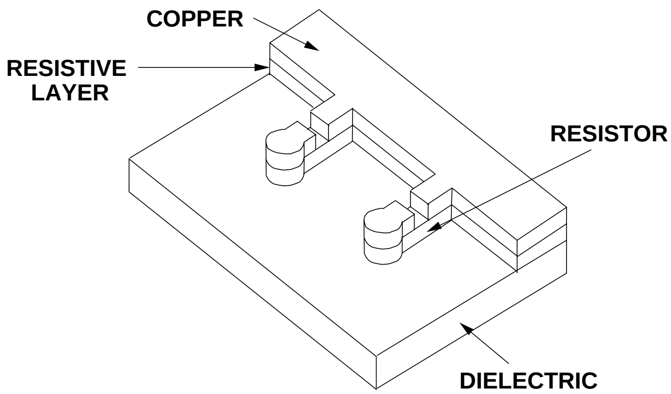

Figure 4: **Embedded Resistor [21]**

= 18 inches, breadth of board = 12 inches, 627 discrete resistors, 54 discrete capacitors, 53 bypass capacitors, 71 network parts, 53 diodes, 17 zeners, 64 transistors, 28 inductors, 12 transformers, 108 ICs, 12 layers, 2 sided board. The manufacturing system, which makes only these two products, is a job shop. The two products follow different processing sequences. As a result of embedding passive components in the substrate, the assembly requirements for the new CPU board are lower than the conventional CPU board. However, certain processing operations associated with embedding passives are added to the PCB processing sequence.

For this scenario, as the percentage of embedded passives in the new CPU board change, the performance of the manufacturing system also changes. The system performance measures considered were resource utilization and machine and product manufacturing cycle time [19]. Figure 5 shows how the manufacturing cycle time for the products changes as the percentage of embedded passives components in the new CPU board increases.

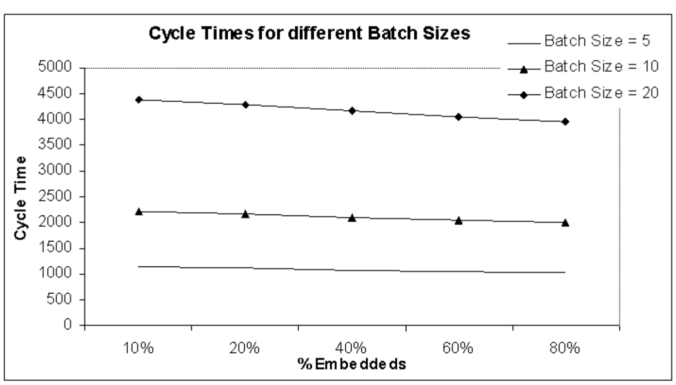

Figure 5: **Manufacturing cycle time with increasing percentage of embeddeds**

Across a range of manufacturing scenarios, the DFP tool recommended improving manufacturing system performance by either reducing the number of layers in a panel or increasing the number of boards that can be cut from a panel (i.e. reducing the size of the board).

Aircraft Tubes

Wei and Thornton [22, 23] describe a three-step DFP methodology that that enables the concurrent optimization of decision variables at the product, process and system levels. They first model the quality variations and yield rate in each of the manufacturing processes and then use them along with the queuing model to predict the system performance in terms of manufacturing cycle time, inventory level, and production cost. Finally, these performance measures are used to simultaneously optimize the product design, tolerances, and lot-sizes. The methodology has been applied to assist tube design and production by a major aerospace manufacturer.

Tubes are widely used in an aircraft for various purposes, such as hydraulic control, waste transport, and ventilation. The complete production system for aircraft tubes is shown in Figure 6. The manufacturing plant makes a number of different types of tubes in batches to replenish the finished-good inventory controlled by the reordering point, then the assemblers pick up the tubes to install onto the aircraft. Gauges are used to inspect the tube geometry after the tube bending process.

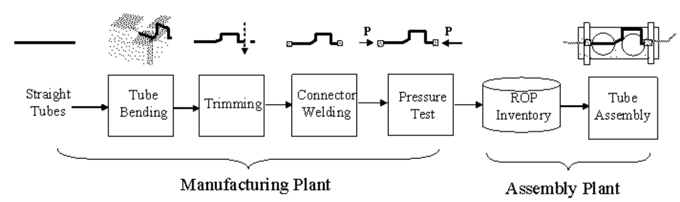

Figure 6: **A tube production system consisting of manufacturing and assembly plants with a ROP inventory**

There are three major challenges for the tube design and production. First, the tube geometry design (number of bends and shape) should provide ample compliance to absorb the aircraft variation during the assembly, without adding excessive variations during the manufacturing. For example, increasing the number of bends introduces more bending process variations into the tube geometry. Secondly, the gauge tolerance setting for the tube geometry needs to balance the yield rates at the manufacturing and the assembly. Lastly, the lot-size for each replenishment order shall minimize the manufacturing cycle-time and inventory. An example is used to illustrate the methodology. There are four tube designs to be evaluated along with the corresponding optimal tolerance for the inspection gauge and the reordering lot-size. After obtaining the yield information through the quality model, a design engineer can further predict the system performance measures and convert them into production cost using the queuing and cost models described in [23]. The cost curves for the four tube designs are shown in Figure 7. Note that at each data point, the lot-sizes for the manufacturing plant have been optimized. In addition, the solid dot indicates the minimum cost point for each design. From the result, we can see that B3 is the optimal design with the optimal gauge tolerance of 0.07 inches.

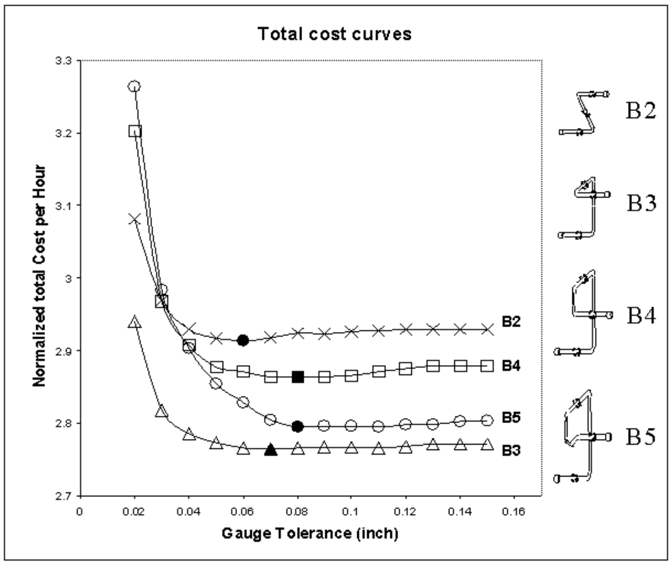

Figure 7: **Total costs for the four design alternatives under varying gauge tolerance**

This case study not only demonstrates the benefits of concurrent engineering but also provides an interesting contrast to the industrial practice in quality management: most industrial practitioner deem tightening tolerance as a means for quality improvement, without knowing the negative impact on the production performance. For example, it can be seen from Figure 7 that overly tight tolerances can lead to disastrously high production cost, while loose tolerance just increases the cost marginally. This is because inspection only controls the consequence, not the root of the problem, which is often times the non-optimal product design.

Absorption Chillers

Hernandez et al. [24] apply the DFP approach to implement component standardization in the early stages of the product design stage with emphasis on production system evaluation. The models developed are used to analyze preliminary designs of an absorber-evaporator module for a family of absorption chillers. The product under scrutiny is expensive and highly-customized with very low production volumes. In that it differs from all the earlier reported high production volume products. The design variations are a result of the manufacturer's need to make different capacity chillers. As a result, various component combinations are possible with different tube types and lengths in the absorber and evaporator portions of the chillers. This increases physical inventory and complicates purchasing, material handling and storage. The evaporator tube design has six design characteristics: outer diameter, wall thickness, fin density, fin height, fin thickness and material. The absorber tubes have four design characteristics: outer diameter, wall thickness, fin density and material. The chiller designs are combinations of the number and types of these tubes.

The manufacturing system for the chillers is a simple production line with an assembly station and three processing stations for post-assembly processing. The authors propose a product family approach to generate alternative designs for the product. The key manufacturing system performance measures are the production time and its variance. The goals for the synthesis are to achieve these production performance targets while simultaneously minimizing the associated costs. The paper identifies a product design that optimally combines tube lengths and tube types to form the baseline model for the entire family. The associated reduction in component variety results in a reduction of physical inventory and associated investment with savings of more than 1.25 million dollars.

Therefore, the results from the example product domain show that using the production system performance as an evaluation metric helps the product development team significantly reduce component variety and identify a single standard and robust combination of design parameters that are beneficial for the entire product family.

Deskjet Printers

Lee, Billington and Carter [7] report on Hewlett Packard's "design for localization" scheme that takes into account the operational and delivery service considerations for multiple market segments. The approach included developing an inventory model to evaluate alternative product and process designs and was applied at HP's Deskjet-Plus Printer Division. The paper presents an approach to understanding the relationship between design and the eventual customization, distribution and delivery of the product to multiple market segments. The Deskjet Printer used for the example is one of a set of printers produced by HP. The manufacturing process for the printer has two stages, printed circuit board assembly and final assembly & test. The product is manufactured in a network of manufacturing and distribution sites that form a part of the supply chain. The distribution centers operate as inventory stocking points and operate in a make-to-stock mode with large safety stocks. The manufacturing system operates as a pull system with smaller incoming material safety stocks and replenishes the distribution centers.

The aim of the localization exercise for HP was to reduce the safety stock for finished goods at the distribution centers. The product design changes needed to facilitate localization included creating a generic printer version (like a product platform) and adding modules to create product variants for different portions of the global market. The replenishment lead time for the distribution centers is a sum of the transportation times, manufacturing flow time in the factory and delays due to other contingencies.

The inventory model developed was used to analyze HP's global supply chain. It incorporated the target stock levels, the supplier lead times and the demand. The localization of various distribution centers and factories was used to create design alternatives for the supply chain with the finished goods inventory levels as the measure of performance. The alternatives were evaluated in terms of the dollar investment. They considered a range of material shortage and downtime profiles for sensitivity analysis. Further, changing localizations would require changing the product design. The reduction in the total dollar value of the finished goods inventory investment from factory-localization to distribution center-localization was found to be 21 percent while the corresponding increase in localization materials worldwide was 24 percent. The resultant impact was that the distribution center-localization led to an 18 percent reduction in total inventory investment in the supply chain.

BMW 7-Series Project

Pisano [25, 26] reports on BMW's attempts to use the prototyping phase of product development to bridge the gap between anticipated product design quality and the quality of the final production vehicle. BMW realized there were significant differences in its prototype vehicles and the final vehicle sent to the market. The old prototype process gave poor estimates of production issues such as production rate and product quality. In order to identify errors in expected design performance early in the development cycle, it was necessary to build prototypes under conditions similar to actual production.

The BMW 7-Series vehicle was dissected into component modules. Interfunctional teams were setup of people from design, product engineering, vehicle testing, procurement, manufacturing and other phases. A team was responsible for each module of the car from start to launch. During the development phase, the production engineers specified numerous new fabrication and assembly processes and designed expensive, complex production tools.

The BMW teams felt that their present prototyping schemes masked many of the design, manufacturing and production problems which only surfaced later. The present scheme utilized the services of highly skilled technicians who were able to hand-craft the complex shapes. The 7-Series Project attempted to build prototypes with the technology, equipment and workers typically found in a factory environment. Another significant change was to bring in the expertise of production phase suppliers into the design and prototyping phases. Such suppliers were able to foresee problems from the production phase related to the production rate and product quality when supply is in high volumes and at regular delivery schedules. With the emphasis of prototyping similar to production, the teams minimized use of sophisticated tooling and production process during prototyping that would likely constrain the production phase. The craftsmen who built the prototypes were also replaced by workers from production lines. They were able to provide valuable inputs. The teams found that design mistakes were immediately discovered in the prototype phase and rectified thus eliminating inaccurate or incomplete designs. The objective of the prototype became to surface mistakes rather than to just represent designer intent, in some sense serving as a quality control check on the designs themselves. In addition to improving design quality, the project led to improved communications between various development phases.

Unlike the other applications mentioned earlier, which relied on mathematical models, the DFP approach adopted for the BMW 7-Series project used a physical model (the new prototyping process) and the experience of a multidisciplinary team to evaluate manufacturing system performance and identify design problems.

With the new approach, the teams identified, during the prototyping phase itself, production rate and quality problems that would otherwise have manifested themselves in production. BMW found that, with the new approach, their engineers were involved in the designs three years before production and production workers were involved in the last batch of prototype production. With the successful implementation of the 7-Series Project, BMW was able to introduce a completely re-designed 7-Series luxury automobile in the market and received unanimous praise from automobile reviewers for its performance, styling and technical enhancements. The new approach reduced the rework on the vehicle from 15% to about 2% to 3%. With the new designs, the company expected to attract 20% of the luxury car market.

SUMMARY AND CONCLUSIONS

It is important that the product development team understand how their design decisions affect the manufacturing system performance. Having this feedback early in the design process avoids rework loops needed to solve problems of manufacturing capacity or cycle time. The results shown

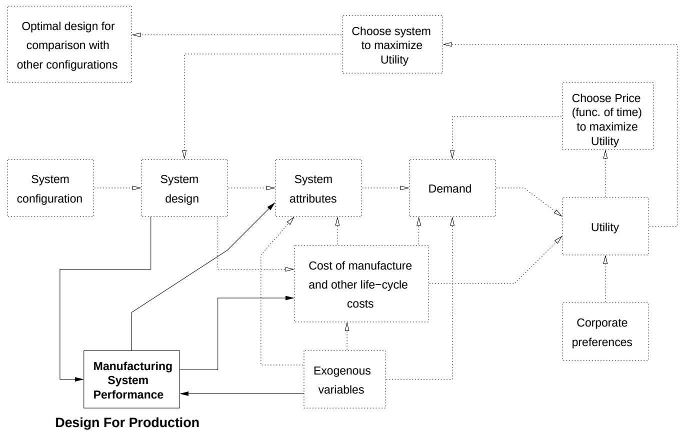

Figure 8: **Contributions of DFP to Hazelrigg's decision-based design framework [28]**

here illustrate how DFP techniques can be used to improve the product development process.

Benefits of DFP

Much effort is spent trying to improve manufacturing system performance by improving manufacturing planning and control systems and developing more sophisticated scheduling procedures, and these efforts have shown success. However, it is clear that the product design, which requires a specific set of manufacturing operations, has a huge impact on the manufacturing system performance. Hence, understanding the relationship between the two is important to the effort of improving the manufacturing system performance for the product.

Improving the manufacturing system performance has multiple impacts. An important metric for the system performance is the manufacturing cycle time for the product. Reducing the non-processing components of the manufacturing cycle time significantly reduces total time. This would have a significant positive impact on the economic returns from new product introduction, including reduced product costs, increased product sales and increased revenue [27]. These benefits, in turn, increase profits.

Need to Integrate DFP with Other Metrics

DFP research has studied the impact of a product design on manufacturing system performance and highlighted the economic impact of reducing manufacturing cycle time for a product. Overall product economics can be used to create better and more profitable products using the ideas in decision-based design.

Hazelrigg [28] proposed a framework for decision-based design. The purpose for the framework is to enable the assessment of a value for every design option in a set of design alternatives so that options can be rationally compared and a preferred choice identified. The goal is to maximize profit, considering costs and revenues associated with the product. The framework incorporates the effects of things that the designer can control (system design or product design) as well as those the designer cannot control (exogenous variables). These exogenous variables are usually random variables and can be estimated as distributions. All aspects of the design have associated costs. Demand and revenue are functions of the price and the product's attributes. Thus the problem includes deciding the price for the product while maximizing product utility. Since the revenues and costs are distributed over the entire product life cycle, the decision-based design framework views the design process from a systems context.

Figure 8 illustrates a modified version of this framework that makes explicit the role of manufacturing system performance (indicated by the solid box and arrows in the figure) in this framework. The references to "system" in the figure will point to the product when applying the framework to product design. Manufacturing system performance is significantly influenced by the product design among other factors. This system performance affects product attributes including total product development time, product platform design decisions and inventory levels. This was demonstrated by the DFP approaches illustrated throughout this paper. This product performance measure must be considered when making important product design decisions. Further, there are certain uncertainties associated with estimating the manufacturing system performance. Some of these uncertainties were modeled in the approaches, but more work needs to be done to include others. The economic impact of manufacturing system performance and the models developed to quantify this impact can be added to the product life-cycle costs.

Implementation Issues

The design for production methodology advocated throughout this paper has focussed on analyzing the relationship between a product design and a given manufacturing system using performance metrics such as manufacturing cycle time and throughput. There exist a wide variety of products and manufacturing systems and all can benefit from the design for production methodology. The requirements for the DFP approach will vary depending on the type of product being designed and the manufacturing system characteristics.

Tools based on the DFP approach must be designed based on the specific class of target products and manufacturing systems. This in turn requires understanding specific factory or supply chain performance metrics. The product development team must identify how different design decisions affect these performance metrics and to what extent. Design phases that have larger impacts on manufacturing system performance should include DFP techniques. This analysis will help the team develop and validate models that relate the critical design information for the associated design phase to these performance metrics. Identifying key product design characteristics would involve suitably decomposing the design into components and developing modular product architectures.

The development of DFP tools must also take into account the data available about the product and the manufacturing system, the effort involved in making that data accessible to the development team, and the time constraints that limit the amount of analysis that can be done. Herrmann and Schmidt [29] discuss a technique for modeling product development organizations and propose that such models can improve the implementation of design tools.

Current DFP tools focus on the business environment where the production facility is known by the product design team. However, with outsourcing becoming a common business practice, product design and production might be conducted by different and unknown business entities. For example, a company designing its product may outsource the production to external contract manufacturers through its supplier network or e-marketplace auctions. In such cases, product design needs to be robust against the outsourcing decision and to enable procurement and supply-chain optimization. To achieve this goal, more sophisticated DFP tools need to be developed in conjunction with other techniques such as robust design and option-based decision-making. Minis et al. [12] have done some preliminary work towards developing such a DFP tool that includes automatic subcontractor selection.

It must be remembered, however, that the final goal for the product development team is to design a profitable product. Applying independent DFX methodologies that target different aspects of the product life cycle will likely lead to conflicting design improvement suggestions. Therefore, successfully applying the DFP approach requires coordination with other product design assessment measures, all of which finally contribute towards the ultimate aim of designing a more profitable product.

ACKNOWLEDGMENTS: Research into developing DFP tools for microwave modules and PCBs with embedded passives was supported by the National Science Foundation under grant DMI 97-13718, and was conducted in the facilities of the Computer Integrated Manufacturing Laboratory, a constituent lab of the Institute for Systems Research at the University of Maryland. Work towards applying DFP principles to aircraft tubing was supported by Boeing Co. and the National Science Foundation under grant 9702662. Jeffrey W. Herrmann has a joint appointment with the Institute for Systems Research.

References

[1] Thilmany, Jean, 2003, "Planning a Plant: A digital factory runs just like a real one, only on a computer," Mechanical Engineering, 125, no.2, pp 42-45.

[2] Herrmann, J.W. and M.M. Chincholkar, 2001/2002, "Reducing Throughput Time During Product Design," Journal of Manufacturing Systems, 20, no.6, pp 416-428.

[3] Herrmann, J.W., and M.M. Chincholkar, 2000a, "Models for estimating manufacturing cycle time during product design," Proceedings of 10^{th} International Conference on Flexible Automation and Intelligent Manufacturing, vol 1, pp 576-585, College Park, Maryland.

[4] Taylor, D.G., J.R. English, and R.J. Graves, 1994, "Designing new products: Compatibility with existing product facilities and anticipated product mix," Integrated Manufacturing Systems 5, no.4/5, pp 13-21.

[5] Govil, Manish, 1999, "Integrating product design and production : Designing for time-to-market," PhD Dissertation, University of Maryland, College Park, USA.

[6] Govil, M and E. Magrab, 2000, "Incorporating production concerns in conceptual product design," International Journal of Production Research, 38, no.16, pp 3823-3843.

[7] Lee, Hau L., C. Billington, and B. Carter, 1993, "Hewlett-Packard gains control of inventory and service through design for localization," Interfaces, 23, no.4, pp 1-11.

[8] Nielsen, N., P. Heeser and J. Holmstrom, 1995, "Design for speed: a supply chain perspective on design for manufacturability," Computer Integrated Manufacturing Systems, 8, no.3, pp 223-228.

[9] Kusiak, A., and Weihua He, 1994, "Design of components for schedulability," European Journal of Operational Research, 76, pp 49-59.

[10] Soundar, P., and Han P. Bao, 1994, "Concurrent design of products for manufacturing system performance," Proceedings of the IEEE 1994 International Engineering Management Conference, pp 233-240, Dayton, Ohio.

[11] Herrmann, J.W., and M.M. Chincholkar, 2000b, "Design for Production: A tool for reducing manufacturing cycle time," CD-ROM Proceedings of DETC2000: 2000 ASME Design Engineering Technical Conference, Baltimore, Maryland.

[12] Minis, I., J.W. Herrmann, G. Lam, and E. Lin, 1999, "A generative approach for concurrent manufacturability evaluation and subcontractor selection," Journal of Manufacturing Systems, 18, no. 6, pp 383-395.

[13] Scheffler, M., G.Tröster, J.L. Contreras, J. Hartung, and M. Menard, 2000, "Assessing the cost-effectiveness of integrated passives," Microelectronics International, 17, no.3, pp 11-15.

[14] Marcanti, L., 2000, NEMI Technology Roadmaps, NEMI, Boston.

[15] Power, C., M.Realff, and S.Bhattacharya, 1999, "A Decision Tool for Design of Manufacturing Systems for Integrated Passive Substrates," Proceedings of the IMAPS 4^{th} Advanced Technology Workshop on Integrated Passives Technology, Denver, CO, April.

[16] Rector, J., 1998, "Economic and Technical Viability of Integral Passives," Proceedings: 4^{th} International Symposium on Advanced Packaging Materials: processes, properties and interfaces, Braselton, GA, USA.

[17] Sandborn, P.A, B.Etienne, and G.Subramanium, 2001, "Application-Specific Economic Analysis of Integral Passives in Printed Circuit Boards," IEEE Trans. on Electronics Packaging Manufacturing, 24, no.3, pp 203-213.

[18] http://www.circuitree.com/CDA/ArticleInformation/coverstory/BNPCoverStoryItem/0,2135,21373,00.html.

[19] Chincholkar, Mandar, 2002, "Design for Production: Using Manufacturing Cycle Time Information to Improve Product Development," PhD Dissertation, University of Maryland, College Park, USA.

[20] Chincholkar, M.M., and J.W. Herrmann, 2002, "Modeling the Impact of Embedding Passives on Manufacturing System Performance," CD-ROM Proceedings of DETC2002: 2002 ASME Design Engineering Technical Conference, DFM-34174, Montreal, Canada.

[21] Mahler, Bruce P.,Integral Resistors in High Frequency Printed Wiring Boards, TECHNICAL FEATURE, Ohmega Technologies, Inc., Culver City, CA, USA.

[22] Wei, Y.-F. and A.C. Thornton, 2000, "Tube Production and Assembly Systems: The Impact of Compliance and Variability on Yield," CD-ROM Proceedings of DETC2000: ASME Design Engineering Technical Conference, DAC-14271, Baltimore, Maryland.

[23] Wei, Y.-F. and A.C.Thornton, 2002 "Concurrent Design for Optimal Production Performance" CD-ROM Proceedings of DETC2002: ASME Design Engineering Technical Conference, DFM-34163, Montreal, Canada.

[24] Hernandez, G., J.K.Allen, T.W.Simpson, E.Bascaran, L.F.Avila, F.Salinas, 2001, "Robust Design of Families of Products with Production Modeling and Evaluation," Journal of Mechanical Design, 123, pp 183-190.

[25] Pisano, Gary, 2002, "BMW: The 7-Series Project (A)," Case Study 9-692-083, Harvard Business School Publishing, Boston, MA.

[26] Pisano, Gary, 2002, "BMW: The 7-Series Project (B)," Case Study 9-695-013, Harvard Business School Publishing, Boston, MA.

[27] Chincholkar, M.M., and J.W. Herrmann, 2001, "Incorporating manufacturing cycle time cost in new product development," CD-ROM Proceedings of DETC2001: 2001 ASME Design Engineering Technical Conference, Pittsburgh, Pennsylvania.

[28] Hazelrigg, G.A., 1998, "A Framework for Decision-Based Engineering Design," Journal of Mechanical Design, 120, pp 653-658.

[29] Herrmann, J.W.., and L.C. Schmidt, 2002, "Viewing Product Development as a Decision Production System," CD-ROM Proceedings of DETC2002: 2002 ASME Design Engineering Technical Conference, DTM-34030, Montreal, Canada.