SUSTAINING COMPETITIVE ADVANTAGE IN PRODUCT DEVELOPMENT: A DFM TOOL FOR PRINTED CIRCUIT ASSEMBLY

by

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Bachelor of Science in Industrial Engineering
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Submitted to the Department of Mechanical Engineering and the Sloan School of Management
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Abstract

Accurate information on the manufacturing cost and quality of product designs is very difficult to provide yet nonetheless vital in a rapidly changing, short product life-cycle environment. Internal manufacturing managers must support the business needs of product designers who increasingly have the option to take their traditional prototyping and manufacturing business outside to contract manufacturing. At the same time, the manufacturing processes used to accommodate new product design features are becoming increasingly complex and there is tremendous benefit to having strong relationships between product design and manufacturing.

This paper will show how a tool can be developed that enables improved communication between design and manufacturing. The research presented here will show how statistics and analysis can be used to turn data into information, which can then be organized in a way that enables manufacturing to communicate the quality and cost of a product design long before it reaches the shop floor. By putting this information into a readily accessible and user-friendly tool, it will be shown that design and manufacturing can have improved communication, stronger relationships, and a faster rate of process improvement and product innovation by making more informed choices earlier in the design process.

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Table of Contents

List of Figures

I. INTRODUCTION

Background

This dissertation addresses the issue of design-for-manufacturability in today's competitive electronics manufacturing environment. Technological advances in the design of printed circuit assemblies and in the manufacturing processes associated with building them have enabled companies such as Hewlett-Packard to bring to market a continual stream of new products each with lower average costs, better features, and better quality than their predecessors.

"How do they do it?" is a question that more than just Digital Equipment Corporation and Apple have been asking lately. This paper will show that one of the essential foundations of this stream of new product introduction successes is good communication between the design community and the manufacturing community during the early prototyping and manufacturing phase of the product development process.

Good communication between design and manufacturing in the early phase of the product development process is critical because it is during this phase that most of the key decisions affecting cost, performance, and manufacturability get made. Studies have shown that that between 50 and 85 percent of a new product's total costs are locked in at the very beginning of the design cycle [7]. Selection of product architecture and manufacturing processes play a significant role in the total cost of the product. In addition, decisions made during this phase also influence several other factors that will play an important role in the success of the product, including:

- **Time to market.** Decisions which change the product architecture or manufacturing process late in the product development process often add significant time to the scheduled delivery of the product.
- **Quality.** Decisions which change the product architecture to increase the functionality can also impact the manufacturing yield. The manufacturing yield is the number of printed circuit assemblies in a production run that meet basic in-circuit test requirements (the number that turn on when placed on a circuit board tester) at the end of the assembly process.
- **Ability to test and repair.** Decisions which change the product architecture can also make the process of repairing assemblies once they are built very difficult.

Quality (yield) and the ability to test and repair are very important parts of the production process because assemblies that do not "turn on" require time and money to fix. Some products cannot be repaired and if they do not pass the test need to be scrapped. Assemblies that have low yields can require several days to repair and re-test, causing delays and cost in the product development schedule, and testing costs typically represent 3 - 6 percent of the total costs of the product. The majority of the remaining product costs are materials (70 - 85 percent), assembly (8 - 16 percent) and inspection (1 - 2 percent). In many cases, the assembly portion of the total cost cannot be controlled, whereas the 3 - 6 percent of cost represented by test and repair can be more effectively controlled through better use of DFM.

As product complexity, the number of leads and parts per square millimeter on a printed circuit board, and manufacturing processes become more complex, yield can decrease, which makes good communication between design and manufacturing even more important. Manufacturing understands assembly and test processes and must share the latest process capability information with design to enable product innovation to continue. In addition, manufacturing can help design make decisions to improve the manufacturability of printed circuit assemblies. Good communication during the early prototyping phase of the product development process enables manufacturing to provide critical feedback on the relative difficulty of a proposed product's features and their importance in terms of the economic value-added of the eventual product.

At the same time, however, increased complexity in design and manufacturing has made good communication harder to achieve. Design rules are changing more rapidly than ever before and what manufacturing can and cannot do is constantly changing. Most importantly, there are few tools available to communicate the process capability information between the design and manufacturing functions of the organization. Lack of tools and formal methods can lead to irregular or sporadic communication between the critical members of the product introduction team which in turn reduces the content and degree of importance of the information that is exchanged. As a result, manufacturing is not able to provide critical and timely feedback to design early enough to influence behavior and as a result total product cost, quality, reliability, and time-to-market often suffer.

This dissertation will introduce a new design-for-manufacturability tool that can be used to communicate process capability early and provide critical feedback to design. The hypothesis of this project is that a DFM Tool based on the current capability can be used in the interactions between manufacturing and design to improve communication about how design decisions impact manufacturing processes. This tool is unique in terms of its focus on the analytical *and* the organizational aspects of the new product introduction process. It is analytical because it uses statistics on existing data to determine the relationships between design features and production results. At the same time, it is organizational because it attempts to change the organizational process currently used to design printed circuit assemblies. Using data inputs which can be quickly and easily calculated by either design or manufacturing personnel, the tool can predict the manufacturing yield of a proposed design long before it was previously possible to do. With this capability, manufacturing can establish effective communication with design much earlier in the product introduction process and enhance its role as a provider not just of assembly operations but also as a provider of process capability information and value-adding design-for-manufacturability guidance.

Based on two observed case studies, the interactions between design and manufacturing in which the DFM Tool for this project was used indicate that the hypothesis is valid. Two cases are described in this paper that involve a new product introduction engineer from the printed circuit assembly area providing specific feedback to design using the tool. In the first case, I observed an interaction firsthand between an NPIE and one of his design customers using the tool. The NPIE used the tool to educate the design customer about the specific, quantitative impacts of alternative design choices on manufacturing processes and process outcomes based on historical data which could not be as easily done without the tool.

In the second case, the observations were derived from notes I made from conversations I had with an NPIE about an interaction he had with one of his design customers using the tool where I was not present. The tool was used by the NPIE to inform the designer about the specific features on a design that will cause it to have a very low yield in the production phase of the project which improved and clarified the customer's understanding of how their design decisions will impact process outcomes.

Research location

The site where the primary research for this paper was collected is Hewlett-Packard's Loveland Circuit Assembly Center (LCAC) in Loveland, Colorado. LCAC provides printed circuit assembly (PCA) manufacturing, prototyping, and test services to 14 internal Hewlett-Packard business divisions. Some of the products produced by these divisions are shown on the following page. The center owns the processes and surface mount assembly process knowledge associated with these manufacturing services, and is responsible for upgrading their capabilities in a way that is consistent with the business needs of their division customers. LCAC specializes on making very hard-to-manufacture designs, and often outsources the less difficult designs to external suppliers. They stretch to the limit many of the existing manufacturing processes to get the difficult-to-make designs built, and are continually pushing the envelope of process capability to more advanced levels over time. On the other hand, they strive to provide feedback to design customers on how designs could be made more manufacturable where possible. New product introductions are an important source of revenue for LCAC.

It is important to recognize that each customer division at H-P is an independent profit-and-loss responsible entity, and LCAC bills each division separately for the services they provide. The LCAC organization has a charter to serve those customers, but it does not get to directly participate in their profit successes. It has separate finances and must constantly strive to reduce its own cost of services to be competitive for the division businesses which increasingly have the opportunity to take more of their printed circuit assembly business to external suppliers. The conclusions of this paper are based on an analysis of data from 60 different new product introductions performed by Loveland since 1990.

Literature Review

Why is good communication between design and manufacturing important?

The importance of good communication between design and manufacturing is emphasized throughout much of the writings of Karl Ulrich and Steve Eppinger of the MIT Sloan School of Management [4]. In a chapter from the book, Product Design and Development, they write:

> Manufacturing cost is a key determinant of the economic success of a product. In simple terms, the economic success of a product depends on the profit margin earned on each sale of the product and on how many units of the product the firm can sell. Profit margin is the difference between the manufacturer's selling price and the cost of making the product. Economically successful design is therefore about ensuring high product quality while minimizing manufacturing cost. DFM is one methodology for achieving this goal; effective DFM practice leads to low manufacturing costs without sacrificing product quality.

And, further:

> For most highly engineered discrete goods the cost of purchased components will be the most significant element of the manufacturing cost. Some component parts may be costly simply because the designers did not understand the capabilities, cost drivers, and constraints of the production process. A designer may specify dimensions with excessively tight tolerances without understanding the difficulty of achieving such accuracy in production. Sometimes these costly part features are not even necessary for the component's intended function; they arise out of lack of knowledge about process guidelines and specifications. It is often possible to redesign the part

> to achieve the same performance while avoiding costly manufacturing steps; however, to do this the designer needs to know what types of operations are difficult in production and what drives their costs.
>
> In some cases, the constraints of a process can be concisely communicated to designers in the form of design rules. However, for processes whose capabilities are not easily described, the best strategy is to work closely with the people who deeply understand the part production process. These manufacturing experts will generally have plenty of ideas about how to redesign components to achieve production objectives (higher quality, reduced costs, etc...).

Eppinger and Ulrich go on to describe their DFM methodology which involves five steps:

⇒ Estimate the manufacturing costs

⇒ Reduce the costs of components

⇒ Reduce the costs of assembly

⇒ Reduce the costs of supporting production

⇒ Consider the impact of DFM on other factors (development time, development cost, quality)

Their work provides thorough evidence documenting the importance of design-for-manufacturability and the potential benefits of having an effective DFM strategy. The general methodology they recommend is a useful framework for understanding the overarching issues; however, they do not provide sufficient specific information on how to actually go about "reducing the costs of assembly or of supporting production" in a low-volume, high-complexity printed circuit assembly shop. In fact, many of their most successful DFM examples come from the auto industry where a successful product design may go into production for several years. In such cases, it may be easier for manufacturing to convince design that good communication on DFM is worthwhile.

The challenge of Hewlett-Packard's Loveland site is to demonstrate the value of the methodology in an environment where the product life cycle may only be six months, not six years. This paper will show that a deeper understanding and examination of the technical and organizational issues related to design and manufacturing process is necessary to drive organizational change and behavior toward more effective use of DFM. The tool developed for Hewlett-Packard's Loveland facility builds on the general framework presented by Ulrich and Eppinger and represents a more tailored, technical template for testing and evaluating proposed designs for their manufacturability.

Most costs "locked in" long before top management pays attention to cost

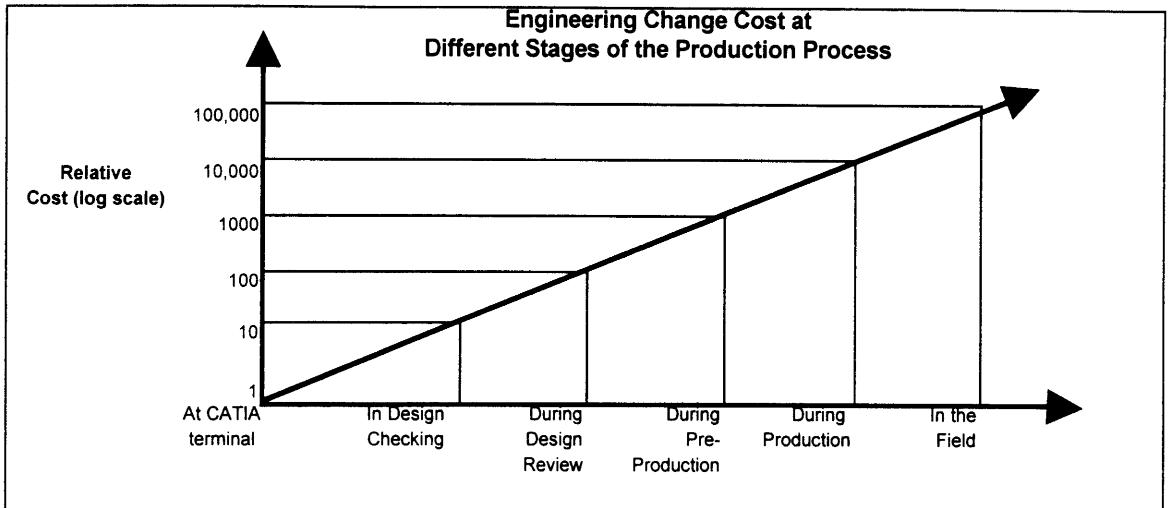
The importance of good communication and effective product development and, conversely, the problems that can arise when these elements are not present was also highlighted in a very important study by Robert Kaplan of the Harvard Business School [7] which showed the great magnitude of costs that are "locked in" during the very earliest phase (design and prototyping) of the product development process. This study also showed that management devotes the greatest degree of attention to product cost at a very mature phase in the product cycle (typically after the product has been developed and is in a volume production phase in the product life cycle).

The organizational dynamics that Kaplan observed are very much at the core of the issues surrounding design-for-manufacturing at Hewlett-Packard. When the future cost savings of a product design change are unpredictable or unknown (because future sales volume can't be forecasted easily), there may be very little incentive to investigate alternative product configurations to accommodate existing, lower-complexity manufacturing processes. Even when the design change could increase the chances of a successful product launch, by improving the time-to-market, quality, or cost, quantifying and predicting the specific impact is difficult and is thus often ignored by management. When individuals responsible for making design changes are not rewarded or penalized for successful or unsuccessful launches, the problems Kaplan describes become even more difficult to isolate and solve.

Difficulty of changing a product design late in the process

Even if there is good communication between design and manufacturing towards the end of the design process, the organizational momentum and costs associated with making a change late will still prevent what could have been a beneficial change earlier from occurring. The costs associated with making design changes late was studied in detail by a previous LFM student, Camilla Denison [3], who found the following relationship in her project with General Motors:

Figure 1-1, Engineering Change Costs Increase at Different Stages of the Production Process

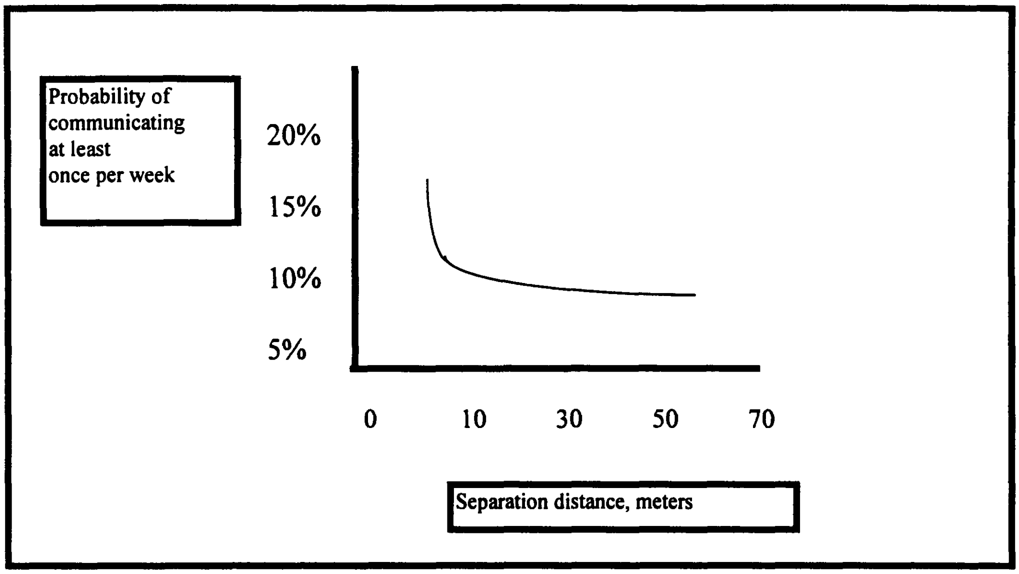


Source: L.Labauve, Martin Marietta Corporation with Camilla Denison. Presented to Manufacturing Executive Conference, San Francisco, June 1991.

Why is good communication so difficult to achieve?

In addition to the managerial incentives and benefits measurement issues that make effective use of DFM more difficult to achieve in the manufacturing organization, there are other challenges to achieving good communication in organizations that are written about extensively by Thomas Allen [1]. In his work, communication frequency is compared with such factors as separation distance and location. He uses empirical data to show that communication frequency is inversely related to physical separation and decreases rapidly when people are located more than a few meters apart.

Figure 1-2, Probability of communication decreases as a function of distance



This finding is relevant to the issues studied at Hewlett-Packard because the core members of the product development teams for most of the test equipment products built in Loveland, Colorado are not just hundreds of meters, but sometimes hundreds of miles apart. If Allen's principle can be extrapolated to such distances, the challenge of establishing communication of any kind becomes clear.

Good communication creates "informed managers" and more effective leadership

This problem also relates to Kim Clark's discussion of high performance teams and so-called "heavyweight team leaders"[2]. These heavyweight team leaders are identified by Clark as being effective product development managers who are well-informed, able to serve as "guardians of the product vision," and can provide "deep functional understanding" of the specific design, manufacturing, and marketing groups which must come together to successfully launch a product. It may be a weakness of the current Test and Measurement Organization's (TMO) new product introduction process that there appears to be very little or no formalized interactions between these so-called heavyweight team leaders (with vision of both design and manufacturing processes) and the various persons responsible for a new product launch. In fact, manufacturing engineers and operators often interact most frequently with non-engineering support staff from the design group who neither care nor have the power to decide among manufacturing process alternatives.

Incremental and radical innovation are both needed in today's dynamic manufacturing systems

This problem also relates to Hayes and Wheelwright's discussion of dynamic manufacturing systems [5]. The authors discuss continuous improvement, investment in new process capability, and alignment of manufacturing strategy with corporate strategy as key fundamentals in today's dynamic manufacturing systems. These principles also apply to the product design and development processes at LMC and the TMO divisions that use their services. While the site needs to continuously reevaluate and improve the way it assembles printed circuits, it needs to retain its competency in the entire new product introduction process and all the while make sure that this process is aligned with the goals of the overall Hewlett-Packard organization.

The problem of establishing effective communication between design and manufacturing in printed circuit assembly is similar to the problems discussed by these authors because it involves all of the elements of a cross-functional, time-critical, dynamic new product development process undergoing both radical and incremental change. Incremental technical improvements initiated by persons involved in the design and manufacture of new products can, as has been shown by Henderson and Clark [6] in the case of lithographic alignment equipment, have quite significant competitive consequences over time.

Other DFM Tools that have attempted to improve communication at Loveland

Two alternative DFM approaches have been used at Hewlett-Packard's Loveland printed circuit assembly center to attempt to improve communication. Some of these other approaches, and their strengths and weaknesses are as follows:

- **Complexity Scores.** This is a very simple methodology that was introduced by an NPIE to evaluate product designs along four factors: volume, customer mix, process technology, and functionality. Each of the four factors has levels (1 to 4) with the highest level (4) representing the most-difficult-to-manufacture for that factor. From the sum of the levels of each of the four factors, a total score for each design could be calculated. The tool was intended to be used during informal interactions with design customers to provide them with a rough approximation for how hard their designs would be to manufacture. Comparing measured manufacturing results with what was predicted using the complexity scores method was never done.

The strengths of the Complexity Scores method were its ease-of-use and intuitive inputs. NPIEs and designers could very quickly estimate the relative complexity of their designs using this methodology. The weakness of this approach was that even when the designer knew how complex his or her design was, it was difficult to understand from this methodology, where beneficial changes might occur. The levels along which a designer found him or herself on these four factors used in this methodology were very hard to change and often were dictated by the business need. Thus, the level of detail of the model was at too high a level of abstraction which limited somewhat its usefulness.

- **Spider Diagrams.** This was another attempt at a DFM Tool that was conducted over almost a two-year period. The methodology was similar to the four factor ratings scheme of the Complexity Scores method, however it required over 20 inputs from design, layout, new product introduction engineering, and operations to generate its results. The output of the Spider Diagram tool was a graphical representation of a proposed design along all of the important DFM dimensions.

The strengths of the Spider Diagram DFM tool were its comprehensive, precise representation of the DFM content of a design, and its inclusion of many different inputs from those involved in the product development process. The methodology was not as widely adopted as had been anticipated because the design community refused to take time out of their schedules to complete their share of inputs. The number of inputs that a designer needed to assess to generate one spider diagram took more time than they were often willing to contribute. Finally, there were many special cases and unique designs characteristics in the boards that are produced at Loveland that could not be captured well using the Spider Diagrams.

The DFM Tool developed for this project attempted to address the weaknesses of these attempts in two ways. First, the DFM Tool was designed to allow a single NPIE or single designer to assess all the inputs necessary to run the model and later compare the results of the production run with the model predictions. Second, the model only requires only a few inputs which can be assessed quickly by a designer or NPIE and completed in a short amount of time.

Conclusion

The approach of this project was to design a new DFM Tool for printed circuit assembly and observe its impact on communication in the manufacturing environment. The approach differs from these two preceding attempts in two ways. First, it attempts to apply technical foundations and analytical rigor to the rating methodology where it is not just delivering a "score" but, in fact, a prediction of yield. Second, the DFM Tool developed here attempts to strike a balance between the complexity and unwieldy data input requirements of the Spider Diagrams with the excessively high level of abstraction for the Complexity Scores methodology. The model attempts to capture the most important determinants of manufacturability that enable an NPIE to provide a close approximation for the one-of-a-kind features and special cases. In this way, the tool could be easy-to-use for predicting the majority of board designs and provide a general approximation for the unique designs.

The DFM Tool presented here is novel because it is a practical approach that can be performed by a single NPIE or designer, can be executed quickly, generates a prediction based on actual historical data, and delivers a performance characteristic that can be measured on an ongoing basis. It should enable designers to do what Ulrich and Eppinger recommend in their discussion of DFM [4], which is to "work [more] closely with the people who deeply understand the process" and enable manufacturing, as Kaplan recommends, "to assess costs early, before it's too late to do anything about it" [7].

Chapter Previews

Chapter 2 provides an overview of the circuit assembly operations environment within the test and measurement equipment industry and some of the changes in the demand for products and in the technologies used in the design and manufacture of products there. Next, I focus in Chapter 3 on the specific relationships between design and manufacturing within circuit assembly and discuss some of the critical challenges those two groups face in achieving good communication about how product design decisions affect manufacturing processes in the release of new products. I describe in Chapter 4 the process that I and a small group of engineering personnel at the Loveland Manufacturing Center followed to develop the concept of a new tool that could be used overcome some of these challenges. I present the steps taken to create the tool in Chapter 5. This is followed by a case studies section in Chapter 6 on how the tool has been used. Finally, I summarize in Chapter 7 the impacts that the tool has had so far on the communication between design and manufacturing and outline the next steps that are required for the further implementation and integration of the tool in the organizational processes of the Loveland Manufacturing Center.

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II. CHANGES IN THE TEST AND MEASUREMENT INDUSTRY

Introduction

There have been several changes in the test and measurement equipment industry in the last three years. Many changes have occurred in the general manufacturing environment for test and measurement equipment. Some of these changes have induced changes in the roles of design and manufacturing. Changes in the industry include:

- Surging demand for test equipment products (very high growth for the past 3 years.)
- Increased complexity and density of the parts, components, and manufacturing processes
- Increased importance of design tradeoffs between product features (functionality) and cost, quality, and time-to-market during the new product introduction process

Changes in demand for test equipment

During the period 1993 to 1995, total sales volume grew at a rapid rate. In addition, the average product lifecycle of a test and measurement product decreased. It is not unusual today to see order growth for some products exceeding 50 percent per year. Together, these two changes have put new strains on the manufacturing system at Loveland, because the production lines are already running at full capacity and it is sometimes difficult to source all of the parts necessary to build designs.

In addition, the average life cycle of the products produced is shrinking. According to one NPIE, the products produced at the Loveland manufacturing facilities in 1995 have a life cycle of approximately three to five years, whereas products produced prior to 1990 often had life cycles between 5 and 10 years.

Changes in the parts, components, and manufacturing processes

In addition to the changes in the business environment, there have also been significant changes in product technology and manufacturing processes. Manufacturing at Hewlett-Packard constantly pushes out the envelope of manufacturing process capability, while design at the same time pushes processes to new limits by pushing on that envelope. Some of the changes in manufacturing processes and product technology at Loveland can be seen in the recent shift from through-hole technology to surface mount technology for PCAs .

PCA manufacturing process

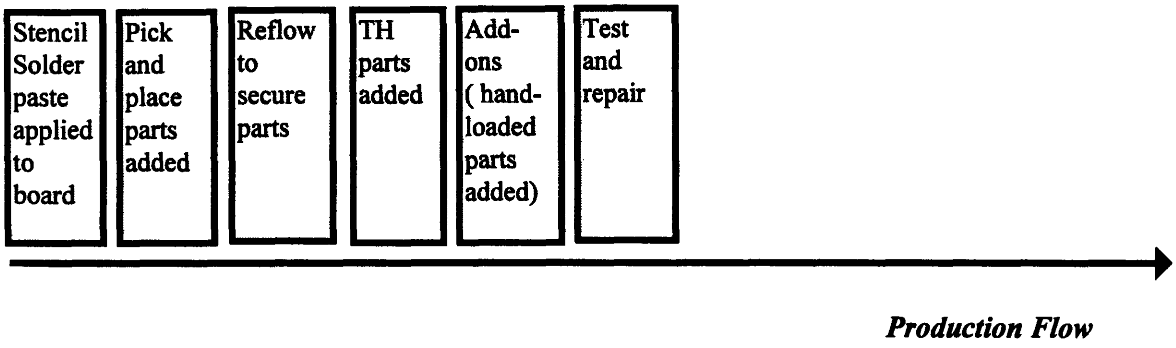
The manufacturing process for printed circuit assemblies was very different ten years ago compared with today. The manufacturing process began with the printed circuit boards which were all made by Hewlett-Packard. Parts were placed only on one side of the printed circuit board. Nearly all of the parts were through-hole and many were inserted by hand onto the board. The highest part-density assemblies made during that period had between 700-800 parts on the printed circuit boards.

In 1995, the manufacturing process has become very different. Manufacturing still begins with printed circuit boards, but these are no longer made internally by H-P, but instead are almost entirely purchased from three different vendors on the outside. Parts can now be placed on both sides of the board. Some parts are still through-hole, but today there is a new technology part that can be placed onto printed circuit boards rapidly, called SMT parts. SMT parts have a low profile and can be made to have the equivalent functionality of through-hole parts but with a smaller size and that can be placed using an automated machine which can place 7200 parts per hour. The cost of auto-inserted SMT parts, is significantly lower than the cost of hand-loaded through-hole parts. One Hewlett-Packard printed circuit assembly site charges ten times as much for the placement of a hand-loaded through-hole part as it does an auto-inserted SMT part. Most of the parts placed on boards today are SMT. The highest part-density assemblies made today have approximately 1,800 components.

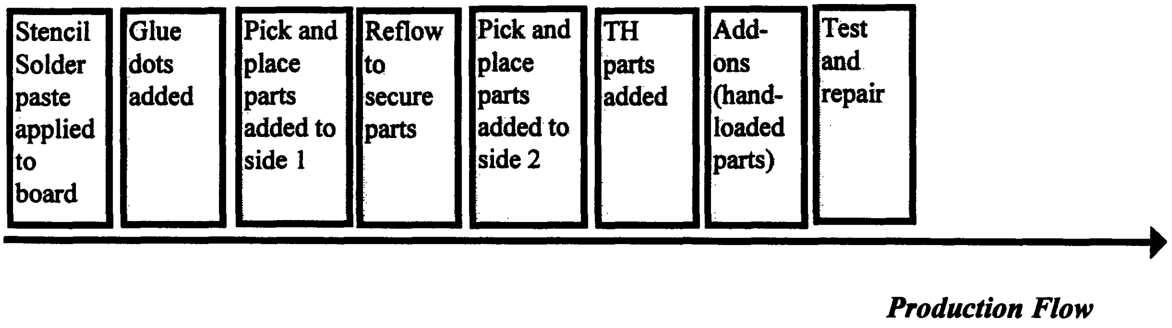
The process of making printed circuit assemblies today is becoming more difficult, though, because the mix of part placement technologies increases the number of process steps used to make the boards and the number of parts that designers would like to fit on printed circuit boards is increasing. In 1985, there were approximately 30-35 process steps that could be used in printed circuit assembly. Today, there are 50-60 process steps (approximately double the old number) that can be used in printed circuit assembly. New processes, such as placement of parts on the second side of the board have increased the part density that printed circuit boards can have but have also made them more difficult to produce. With each additional process step, there is increased risk of defects occurring. For example, when parts are placed on the second side of a board today, there are already parts on the first side; sometimes one or two of the parts which had been placed on the first side of the board can fall off when the second side parts are added. In addition, when parts are too close to each other, pieces of solder can get stuck between two leads and cause bridging across the leads, which can cause the board to later fail the test at the end of the production process. The major process steps of PCA manufacturing are shown in Figure 2-1 below.

Figure 2-1, Printed circuit assembly manufacturing processes

Typical single-sided manufacturing process



Typical double-sided manufacturing process



In addition, as parts get closer together on a board, there is increased likelihood that there will be a placement problems. The automated part placement machine has more difficulty placing two parts extremely close to each other than when there is minimum spacing in between. The machine can also have more difficulty finding certain locater marks on the boards (called fiducials) which help guide the machine during placement. There are also minimum spacing requirements between parts, around parts, and between parts and the edges of the printed circuit board, which, if violated (which sometimes is attempted for very high part density boards), can significantly affect the board's manufacturability and increase the risk that parts fall off during the process.

Today, there are four major processes used at Loveland to produce printed circuit assemblies. The four major processes used are:

- **Process A:** this is a process technique that is used for the application of parts to one side of a printed circuit board.

- **Process B:** this is a process similar to Process A, however it involves placement of parts on a double-sided printed circuit board.

- **Process C:** this is a process technique similar to Process B, but also involves an additional process step involving glue dots; the glue dots process step occurs after the solder paste step, just before parts are placed. The dots are added to better secure parts onto the printed circuit board.

- **Process D:** this is a double-sided process that does not require glue.

Depending on the business need, certain manufacturing processes make more sense than other processes. For example, if the end-use product is small and has minimal enclosure space for internal electronics, the most appropriate printed circuit assembly design may require a manufacturing process that allows very high density of parts, and possibly the placement of parts on both sides of a printed circuit board (Process B, C or Process D). On the other hand, an alternative end-use product may not have a space constraint, relatively few total number of parts, and low functionality requirements. In this case, a Process A manufacturing process may be more appropriate than Process B, C, or D, due to the ease of part placement and lower complexity of the Process A manufacturing process.

Design tradeoffs between feature set, cost, quality, and time-to-market of PCA prototypes

To enable design to take advantage of new trends in the constantly improving product technology, manufacturing must provide feedback to design on the various tradeoffs between new design features and reliability of manufacturing processes as well as frequently make incremental improvements to existing processes to accommodate the latest design features of PCA prototypes. Beyond just cost and quality, design and manufacturing must have fast, accurate communication about the driving characteristics of the product, including desired time-to-market, performance, features, testability, and use. Manufacturing publishes guidelines (rules and recommendations on process specifications such as how close parts should be from each other on a board, how small the parts can be, how parts should be routed, etc...), but these guidelines are necessary but often not fully sufficient to enable design and layout to make the best decisions on the tradeoffs inherent in the development of new products regarding cost, quality, time, and feature set. It can be difficult for the designer to pull the exact information out of the guideline manual. Some of the typical tradeoffs design and manufacturing must design during development are shown on the following page.

Figure 2-2, Typical design tradeoffs for printed circuit assemblies

- **Single-sided designs versus two-sided designs.** The NPIE and the designers from this division often discuss whether a board can be produced using a two-sided technology (Process B, Process C, or Process D) or a single-sided technology (Process A). The single-sided process is simpler, more reliable, and in general requires less processing time. However, the business needs of the customer often dictate that the board not exceed a certain size, and it becomes difficult to place all of the parts on a single-sided board of the required size. In these situations, the prototype will be more manufacturable when more parts are placed on the single-sided design rather than switching to a two-sided design. The NPIE might be able to reduce the spacing between certain parts or rearrange the placement of other parts to enable the designer to fit all of the parts on a single-sided board, but this can affect manufacturability as well.

- **High number of hand-loaded parts versus low number of hand-loaded parts.** The manufacturing process associated with the placement of hand-loaded parts can be a very labor-intensive process, subject to human error, and can negatively impact yield. Thus, having fewer handloads often saves time and increases quality. On the other hand, the designers frequently want to use unique parts that give their board designs a desired functionality. Because many of these unique parts are very large or have unusual shapes, many of them cannot be placed using the automatic part placement machine and must be hand-loaded. Therefore, there is a tradeoff between achieving higher yields by reducing the number of hand-loaded parts and achieving a desired level of functionality using unique parts. The NPIE might be able to suggest using fewer hand-loaded parts or substituting the unique parts for alternative parts that can be placed using the automatic part placement machine since this often reduces the production processing time.

- **High number of fine-pitch parts (parts with < = .05 inch of space in between leads on the part) versus low number of fine-pitch parts.** The NPIE and the designers from this division often discuss how many fine-pitch parts are on the board. "Pitch" is the space between the metal leads coming out of a part. Increased lead density increases the probability that some leads will not have been connected correctly. In addition, the leads of the fine-pitch parts can develop a short or a bridge between the leads which can further decrease yield. Thus, having many fine-pitch parts can have a negative impact on yield. In particular, when there are many fine-pitch parts near each other on a design, adequate parts spacing and adequate routing can become more difficult to accomplish and the manufacturability of the design can decrease. On the other hand, just as with hand-loaded parts, the designers from Division A often want to use fine-pitch to give their board designs a desired functionality.

Figure 2-3, Typical design tradeoffs for printed circuit assemblies (continued)

- **Higher part density versus lower part density.** The NPIE and the designers from this division often discuss whether a simpler manufacturing process at a higher density of parts per square inch is better or worse than a more complex manufacturing process at a lower density of parts. For example, if a designer wishes to add 50 parts to a board that is intended to be produced with the single-sided, Process A, process, the NPIE will often try to find space for the 50 parts on the single side of the board before putting parts on the other side, even if this increases the part density. The reason for this is, the single-sided process requires fewer steps, saves time, and often costs less. Other issues arise, however, when density becomes too high, such as where the parts are located, how close they are to the edge of the board, how close the parts spacing is in certain areas of the board, etc..
- **Through-hole parts on the bottom side versus no through-hole parts on the bottom side.** The NPIE and the designers from this division often discuss whether through-hole parts on the bottom side of the printed circuit board are a necessary feature of the board design. The manufacturing process associated with the placement of through-hole parts on the bottom side, Process D, requires more process steps than boards that do not have parts on the bottom side such as Process A. Through-hole parts placed on the bottom side often have large and unusual shapes and must be soldered in place by hand which often takes more time and can result in lower yields. The tradeoff again, just as with hand-loaded and fine-pitch parts, is that the designers often want to use a particular through-hole part to give their board a desired functionality. The NPIE might be able to suggest using an alternative, SMT part, or removing the parts from the second side altogether and moving to a single-sided process.

The design tradeoffs and PCA prototyping guidelines can change over time as processes improve. This change adds to the communication challenge that design and manufacturing face. Although current specifications are published and updated regularly as NPIEs and design engineers enable processes and products to have greater complexity, the guidelines change so often that it can become unclear to the design community what *is* and *is not* allowed in the product design.

Conclusion

Because product innovation is so tightly linked to process innovation in the creation of an innovative new product in the test and measurement equipment industry, improved communication between manufacturing and design is needed to exchange all of the latest information about design alternatives and manufacturing process specifications. Unfortunately, current interaction between manufacturing and design often happens too quickly, too infrequently, too late, and with too little precision to allow this critical information exchange to take place.

It is within this environment that new organizational processes and tools that facilitate communication must be applied. A new tool must address these specific design tradeoffs between features, quality, cost, and time that design and manufacturing face in bringing new products to market (some of the most important of these are described in Chapter 3). In addition, the tool must also be based on real data, historical experience, and quantitative analysis (which will be described in Chapter 5).

III. CHALLENGES TO COMMUNICATION BETWEEN DESIGN AND MANUFACTURING

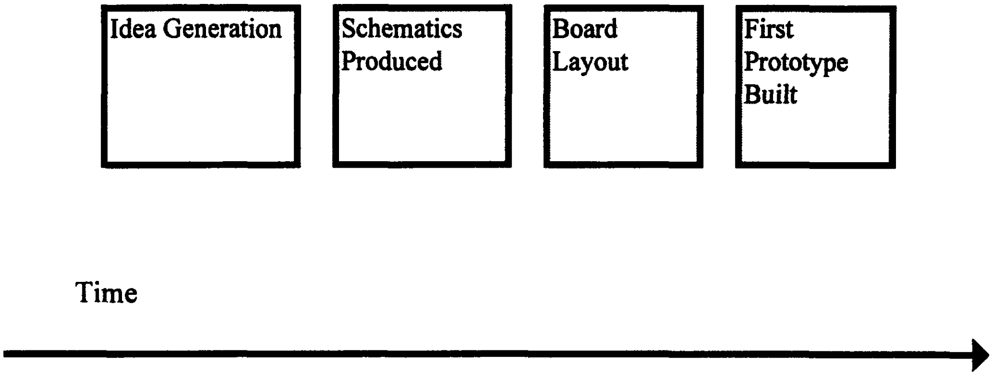
Introduction

Manufacturing can help guide design to the most appropriate manufacturing processes, but it is often unable to do so because of specific challenges to communication that are part of the existing new product introduction process. In this chapter, the new product introduction process and some of the specific obstacles that prevent improved communication about the impact of design features on manufacturing processes are described.

Role of NPIEs and the New Product Introduction Process

The process for introducing new products at Hewlett-Packard consists of several steps. In between each step, information about parts, processes, layout, business needs, and other important details are communicated. Because each step involves a different person (or group of persons) in the organization, there is opportunity for miscommunication, insufficient information, or delay. Below are the major steps that occur in between the origination of a new product concept idea, prototyping, and production.

Figure 3-1, The basic steps in the new product introduction process



There are several persons involved in this new product introduction process. In general, the designers at the customer division are responsible for the first two steps of this process, generating the ideas and the schematics for the printed circuit assembly. They give this information to a member of the layout staff who, in the third step of this process, translates schematics information into actual drawings of printed circuit assemblies, showing how big the printed circuit board is and where the parts might be placed on the board. New product introduction engineers (NPIEs) and coordinators from the prototype assembly area have primary responsibility for the fourth step of the process, which involves reviewing the drawings and data provided by the designer and the layout staff from the division and building the boards.

The NPIEs play a very important role in interacting with the designers and layout personnel in the first two steps of this process. Each design customer is assigned to specific NPIE who they will interact with to get information about manufacturability issues. The NPIEs will spend time with the design customer on a periodic basis to discuss printed circuit assembly designs that are nearing or entering prototype production (for customers who produce many new designs, the frequency may be once each week, for other customers who design fewer new assemblies the frequency may be once each month). Distance between the NPIE and design customers makes the NPIE job more difficult; however the NPIE will usually travel to the customer's location regularly to meet with the layout personnel and the designer at the customer site.

NPIEs provide information during these interactions on how hard or easy the printed circuit assembly design will be to manufacture. Sometimes, an NPIE will make a specific suggestion on how a board could be laid out differently to improve the manufacturability. For example, an NPIE may suggest the relocation of a part from the edge of the board, to an alternative position where it is in less danger of falling off the board during the manufacturing process. On other occasions, the NPIE might suggest a way to rearrange a number of parts such that the board can be produced using a single-sided, rather than a double-sided process.

Feedback for PCA prototype designs and process selection and development

Manufacturing feedback can be helpful to design at several places in this process, in particular during the early part of the layout phase where parts are just getting laid out on the boards. This feedback can significantly enhance the manufacturability, economic viability, and time-to-market of a design. For example, when consulted early about a design, NPIEs can assess whether parts can be placed on the board reliably, whether the boards can be repaired easily, and how to design for better test and design for assembly. In addition, manufacturing can help identify situations where "stretching the rules" is possible, and new processes can be developed to accommodate an innovative product design.

Why this doesn't always happen

Unfortunately, there is still a strong tendency on the part of design to "throw it over the wall" to manufacturing. There are significant obstacles which make it difficult for design and manufacturing to communicate early in the process of developing new products. When there is little communication between design and manufacturing, the benefits of better process selection, design-for-manufacturability, cost, and time-to-market, are diminished.

There are three important reasons why communication is difficult to achieve in the new product introduction process. The primary reasons are:

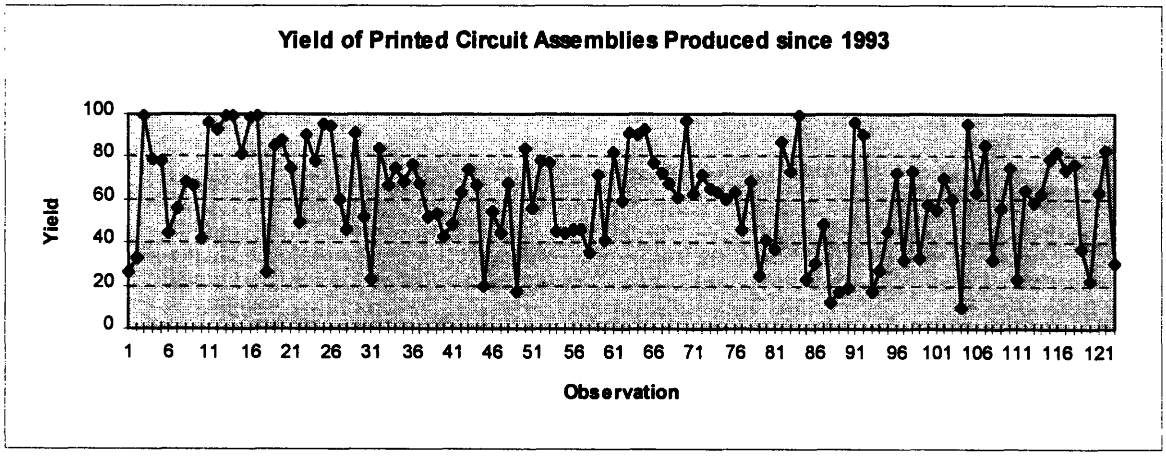
- Significant variation in process output, such as cost, yield, time, and feature set
- Misaligned incentives between NPI stakeholders
- Inadequate quantification of the benefits of DFM

Variation in yield, cost, time, and features of different PCA designs

Part of what makes communication difficult in the new product introduction process is the significant variation in the cost, yield, cycle time, and feature set of the products produced. Over the course of a year, there may be over 40 new, unique printed circuit assemblies released by manufacturing. Because many of the new product designs have features that are unlike anything else that have been previously produced before, predicting what the future cost and quality of these products presents a unique challenge.

Yield is an important metric representing to a significant degree the manufacturability of the assembly and is of interest to both design and manufacturing, as will be shown later in Chapter 4. Higher yielding designs are very strongly correlated to lower test and repair costs. Conversely, lower yielding designs often lead to longer repair times, longer development periods, and higher costs. Therefore, yield is a meaningful and important metric to both design and manufacturing and can serve as an excellent starting point for improved communication and feedback about process capability and design recommendations. Some of the variation in the yield of printed circuit assemblies produced at Loveland can be seen in Figure 3-2 below.

Figure 3-2, Variation in production yield for printed circuit assemblies. This chart shows the observed yield for 123 different PCA designs produced over the last three years.



While design would like to incorporate manufacturing input early in the new product introduction process, without precise, quantifiable, data-driven communication about the impacts of alternative product configurations, they are less likely to act on manufacturing recommendations. Because of the significant variation in the actual cost, yield, cycle time, and feature set of the products produced in the shop, giving precise predictions is extremely difficult early in the process. As a result, design and manufacturing communicate less in the early phases of the design process when the precision is low and communicate more when a product is at the very end of the design process when there is the least flexibility to make any major changes to the product.

There are many sources of variation in the yield of product assemblies. The number of parts and interconnects on the board, for example, are associated with yield. Some products have relatively few parts and high production yields; other products have many parts and low yields. The fact that a product has few parts does not, however, guarantee a high yield. How the parts are placed on the board and how far they are from each other, for instance, can make a huge difference in yield. Thus, for assemblies that have identical numbers of parts, there may be dramatically different yields. This variation in yield and difficulty of part placement will also cause variation in the cost of each board, especially if the board cannot be repaired at the end of the assembly process. For example, consider a board which has a total estimated product cost of $1M and cannot be repaired if it fails the in-circuit test at the end of the production step. According to historical data, if the yield could be improved from just 50 to 60 percent, the cost savings to the designer would be $85,000 in materials alone.

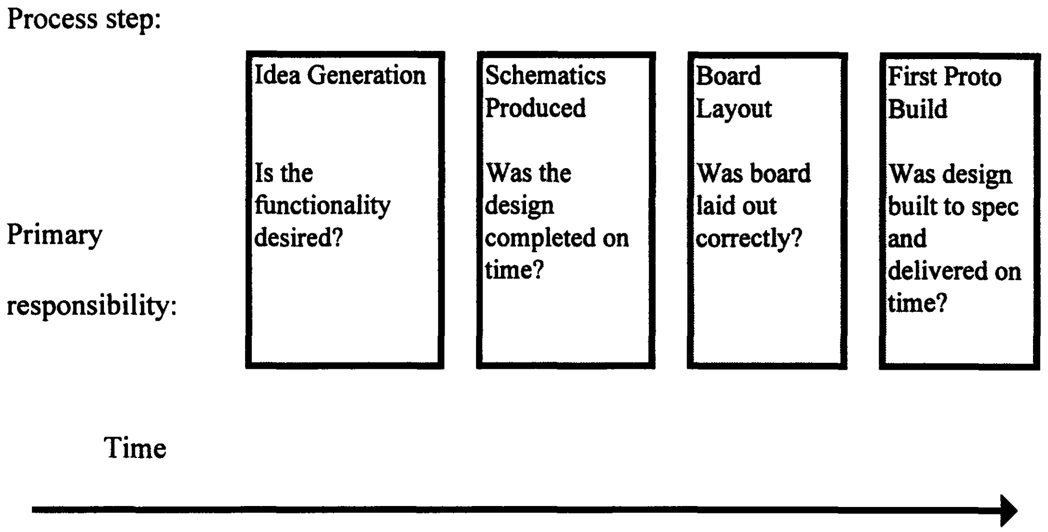
Another important source of variation is the change in process capability over time. In the last several years, there have been several innovations in the manufacturing processes associated with printed circuit assembly. Each time the manufacturing process capability changes, however, the design guidelines associated with printed circuit assembly change. When the frequency of manufacturing process innovations increases (as it has the last several years) the frequency with which the design rules change also increases. This can cause uncertainty and confusion in communication between design and manufacturing, because designers are not always aware of what is or is not allowed in new designs. As a result, some manufacturing processes are attempted before they have been formally described in the process guidelines. This can be a source of competitive advantage for the production shop when it is able to push the processes to new levels of capability, but it can also create confusion in the communication between design and manufacturing.

Misaligned incentives

There are several persons with distinct skills and responsibilities who play a part in the process of bringing a new product from idea generation through to product introduction, and it is very difficult to align all of their incentives to achieve the organization's goals. Ideally, all of the persons involved in the process would be rewarded for the product's success, which could be defined as a product that met its time, cost, quality, and functionality objectives. Unfortunately, though, it is very difficult to measure the impact an upstream person has on the ultimate downstream success of a product in these terms because there can be delays, quality problems, and additional costs introduced later in the process, before the product reaches the market, that make it hard to determine how successful the product *would have been* had those downstream events not occurred..

The Figure 3-3 below illustrates the primary responsibility of the persons responsible for each of the steps in the process by which a product assembly goes from idea generation to production:

Figure 3-3, New product introduction process with representative metrics



Improving communication between some links of this value chain is difficult because the benefits of improved communication do not tie directly to the monetary compensation of those involved. In addition, even when those persons earlier in the chain are sensitive to downstream cost, quality, and reliability issues, there is a tremendous delay in between the time a decision is made and its result can be measured. As a result, it can be a challenge to align the incentives of the various stakeholders in the process.

In addition, some customers care more about some performance metrics than others. For example, some products require minimizing production cost per unit, and designers do everything possible to reduce the cost of assembly. Other designers are interested only in getting designs built quickly and cost is not an issue. This diversity of priorities among customers makes it more difficult to bring into focus exactly which dimensions of performance need to be communicated.

Inadequate quantification of the benefits of DFM

It is very difficult to track and measure the improvement in designs as they move through the new product introduction process. For some products, good communication between manufacturing and design results in a significantly higher-yield assembly. For others, manufacturing input early in the process significantly helps reduce the cost of production. However, because many of the assemblies are unique and have never been built before, it is extremely difficult to estimate what the yield or what the cost *would have been* had the changes not been made. In addition, in the early phases of the design process, it is very difficult to predict what the downstream cost and yield will be anyway, which makes it particularly hard to measure over the course of development of a product.

In some cases, the key value that manufacturing can bring to the development process is to find a way to produce a previously unbuildable design. Here, again, there is a problem of measurement and quantification of this benefit. In those cases where the design really cannot be built, manufacturing can be perceived as insensitive and inflexible to the business needs of the customer. It would be easier to establish good communication between manufacturing and design if there were more trust and understanding of the benefits that manufacturing inputs can provide and the limitations of the manufacturing process capability.

Conclusion

In summary, although manufacturing has the opportunity to add significant value by providing consultative feedback to design during the development process, they are often unable to do so due to the significant variation and imprecision with which they can make predictions early in the process. Misaligned incentives of the major players in the development process and poor quantification of benefits associated with the value manufacturing can provide during the design process present a further challenge to improving communication between design and manufacturing about product design alternatives and manufacturing process impacts. If this communication can be improved, manufacturing can help guide the design community to more appropriate manufacturing processes and provide real-time feedback on the quality or manufacturability of the design which should help customers better meet their business needs and satisfy test equipment customers.

IV. DEFINING SPECIFICATIONS FOR A NEW TOOL

Introduction

There are few tools available to communicate the required process capability information between the design and manufacturing functions of the organization. The two most recent attempts by the new product introduction group at creating a tool that addressed these needs, the four-factor complexity scores model and the spider diagram model, made significant progress at increasing the organization's awareness and attention to these issues and identifying many of the relevant design features. In setting the specifications for the new DFM Tool, it was important to build on the foundations laid by these efforts.

But what should the requirements of the new tool be? In order to answer this question, it was necessary to conduct customer interviews with engineers from manufacturing and new product introduction as well as customer representatives from design and layout. Representatives from these areas were brought together to identify what "tools" and other techniques had been attempted in the past to improve communication. One of the key conclusions from this discussion was that a successful tool would have to have the following characteristics:

- Links decisions to manufacturing processes and impacts
- Enables user to provide quantitative feedback on the manufacturability of product designs
- Enables user to accurately update the tool over time to reflect future process improvements

Specifications of the DFM Tool

I discussed many alternative tools with the NPIEs, the New Product Introduction manager, the head of the engineering section, and two designers from one of the customer divisions. A tool that linked to the existing cost model used to price assemblies was considered but not selected because there was significant variability in the information associated with the total cost of the design of the product, and the information needed to predict cost was available so late in the process that it was usually too late to make major changes.

Another tool that was considered was an analytical model that could link a proposed design to the number of defects incurred per image during the assembly process. It was felt that poor designs often caused defects during the assembly process and that a tool that could analyze proposed designs early and predict the impacts on defects during assembly would be helpful. The difficulty with this proposed tool was that there was no complete set of information available to build such an analytical model. Information on defect repairs was estimated by one NPIE to be recorded approximately three-fourths of the time. For the other repairs, no written record had been kept. As a consequence, a significant proportion of products had defects repaired during the assembly process, but the data might indicate zero defects.

In order to create a tool that would be useful for both design and manufacturing, it had to be based on reliable historical data. Otherwise, the designers would not believe recommendations that might be made based on the tool outputs. After much discussion, a tool that could predict product yield (the percentage of boards at the end of the line that do not require repair) was selected.

Creating a tool that models yield made sense for many reasons:

- **A DFM Tool based on yield can link design features to manufacturing process outcomes.** Production yield reflects to some degree how hard a design is to manufacture and also how well manufacturing process choices were made. It also directly relates to the cost, time, and quality of the design. It is very strongly correlated with the other measure considered (number of defects occurred during assembly) and could reflect many of the same design features that were captured in the defects metric.

- **A DFM Tool based on yield enables manufacturing to provide quantitative feedback on the manufacturability of alternative designs.** There was a significant amount of historical data on the production yields of assemblies that had been built by the shop that reflected a wide variety of design features. This enabled an analysis of many of the potential product characteristics that influenced process outcomes.

- **A DFM Tool based on yield can be updated over time to reflect process improvements.** The nature of the approach taken for the development of the tool--using data, statistics, and regression analysis--lends itself very well to future model enhancements and updates. Once a database on historical yields and critical design features is started, new samples can be easily added later and statistical tests can be run.

Conclusion

A DFM Tool that can meet all of the above requirements provides advantages for the manufacturing organization. NPIEs can use a tool to quantify the benefits of the services they provide, track improvements to product designs as they go through the manufacturing consultation process, and share manufacturing process information with each other and with design and layout. The entire company should benefit. This kind of measurement capability should help the NPIEs overcome some of the challenges to improved communication imposed by the existing significant variation in process, disconnected incentives, and poor quantification of the benefits of DFM.

The next two chapters of the paper will show how the DFM Tool was developed in three distinct phases. In the first phase, a team was assembled to identify design features that might impact production yield. Data on the design features and yields of Process B and Process C boards produced over the last three years were collected. Using the regression analysis statistical technique, the relationships between design features and manufacturing process impacts were explored, and the most statistically significant relationships were included in an analytical model that can predict yield.

In the second phase of development, data from Process A and Process D boards were added to increase the size and completeness of the database, and a regression analysis was used again to correlate design features and manufacturing process impacts. More design features were studied in this second phase and an extensive study of the "outlier" points (board designs whose actual yield far exceeded or fell far short of the predicted yield of the regression model) was conducted.

During the third phase of development, I placed the DFM Tool in the users' environment to gather feedback on implementation and test the hypothesis that such a tool can be used to improve communication about the linkages between design decisions and the manufacturing process. I prepared graphical diagrams using the tool to illustrate the process tradeoff choices of typical design decisions, created a Windows-based interface to enable NPIEs to quickly analyze proposed "What if" designs and predict their manufacturing yields, and produced a step-by-step manual that allows manufacturing to test the statistical significance of new processes for possible inclusion in the DFM Tool over time.

During this phase, I also collected evidence to assess whether the interactions between design and manufacturing using the DFM Tool improved communication on design alternatives and manufacturing processes. These results are described in the form of "Case Studies" in Chapter 6. The next chapter describes phases one and two of model development in greater detail, showing how the DFM Tool was created.

V. CREATING THE NEW DFM TOOL

Introduction

This chapter will present the development of the DFM Tool. The development process began with the formation of a team to identify all of the design variables that might impact yield. I then collected data on Process B and Process C boards and analyzed the impacts of design features on their production yields.

I began the second phase by expanding the data set to include Process A and Process D boards to increase the sample sizes and comprehensiveness of the analysis, and identified design features that are critical drivers of board yields. These characteristics constitute a tool for predicting production yield, as evidenced by the fact that 73% of the total variation in board yield is explained using these design characteristics.

Formation of a group for data collection

A group composed of 12 people from the following groups was assembled to identify all of the possible sources of variation in production yields:

- NPIEs (8)
- Materials engineers (1)
- Purchasing representatives (1)
- Test and repair representatives (2)

I conducted two formal team interviewing sessions with these 12 representatives which lasted approximately 3 hours each to identify possible impact variables. In addition to these meetings, I conducted 11 informal interviews with three additional groups and designers from 3 different divisions. I asked these representatives to identify features that they thought might impact yield. I also interviewed six different production line operators from both the assembly and test and repair areas for approximately one hour each and asked *them* to provide their feedback on possible sources of variation. Finally, I conducted two one-half hour interviews with layout personnel and asked them to identify design features they thought might impact yield.

After these two formal meetings, members from the initial team and the design, operations, and layout groups met with me on an informal basis throughout the first sixteen weeks of the project (June-September) to help guide the data collection process and provide additional information on specific product designs. From the initial team, I formed a smaller core group which consisted of myself, one NPIE, and the engineering head of the NPIE section to meet on a bi-weekly basis to review the data collection and the data analysis activities.

From the initial data collection phase, I put together a list of all of the variables identified from the two brainstorming sessions that could impact yield. These are shown in the Possible Impact Variables table below.

Figure 5-1, Possible Impact Variable Table

Variables that could impact reported yield	**Description**
Process technology	Whether the manufacturing process used was A, B, C, or D
Customer	Which division design and layout group is responsible
Line	Which production line the board was built on (Vendor A or Vendor B)
Six-month board volume	Number of units produced over a 6 month period
# of interconnects	Total number of leads (interconnects) on the board
# of hand-loaded parts	Number of parts that must be placed on the board by hand
Part density	Total number of parts divided by the surface area of the board
Graphics	Whether part placement information silk-screened on board
Total number of parts	Number of SMT and through-hole parts on board (top & bottom)
Total number parts on B side	Number of SMT and through-hole parts on the bottom side
# of fine pitch parts on A side	Number of fine pitch parts on the top side of the board
# of fine pitch parts on B side	Number of fine pitch parts on the bottom side of the board
# of through-hole parts on A side	Number of through-hole parts on the top (A) side
# of through-hole parts on B side	Number of through-hole parts on the bottom (B) side

Control variables considerations

Some of the variables that were identified during this process, however, *could not be changed by the designer*, nor did they specifically have to do with the *design* of the product. Because the primary purpose was to build a tool that could be used to provide feedback on design features that could be changed that impact manufacturing, the subset team (consisting of the engineering section manager, the project intern, and the NPIE) decided to draw a distinction between variables that are the choice of the designers and variables that more or less cannot be changed.

For variables we suspected might have an impact on yield but cannot be changed, there are two options. The first is to include them in the data set during the regression analysis and model development, but not show them in results presented to the design engineers when using the tool to make predictions on future board designs. The second option is to look for other variables in the data set already, or that can be added to the data set, that *can* be changed by the designer and are closely correlated with the variables that cannot be changed. In this case, these closely correlated variables should contribute almost as much to explaining the variation in yield as the other variables would have, and the variables that cannot be changed can be removed from the data set during the regression analysis.

The two variables I identified from the Possible Impact Variables table that I expected might have an impact on yield but could not be easily changed by a designer are “Customer” and “Line.” It was suspected that the “Customer” variable might have some impact on yield because it represented to some degree the level of training and experience of layout personnel, as well as proximity to the manufacturing site—on-site customers had more opportunities for informal interaction with NPIEs which might impact yield. Changing this particular variable, however, was not an option for a designer. It might have also been a challenge for the NPIEs to explain the impact on predicted yield of this particular variable to design customers. The second Possible Impact Variable which could not be easily changed was “Line.” There were several Vendor A lines and one Vendor B line upon which customer boards were built, and it was suspected that differences in the operator personnel and production machinery might have an impact on yield. On the other hand, designers often did not have the foresight to know which production line their board would be built on. For some designs, the board could be built on one production line for one run, and on another line for the next production run. The designer often did not have the knowledge to predict what line his or her board would get built on, nor could the designer necessarily control this decision.

The "Customer" variable was not used in the final model because it meets the option two criteria (it does not appear to contribute to explaining the variation in yield and appeared to be somewhat closely correlated with the total number of parts (see Exhibit 3), for which the correlation coefficient was .57). In addition, the regression output in Exhibit 4 indicates that the addition of this variable to the data set does not appear to contribute much to explaining the variation in yield. Therefore, the contribution to explaining the variation in yield that I expected from this variable appears to be captured and explained by other board design variables included in the model.[1]

The "Line" variable was not used in the final model because most of what this variable could contribute to explaining variation in yield was captured in another design variable that was added to the data set. The variable "Oversize Panel," which was added for the final data set represented an actual design characteristic that described whether designs were so large that they could not be built on a Vendor A line and had to be built using the Vendor B production line. "Line" was very closely correlated with "Oversize Panel" and had a correlation coefficient, as can be seen in Exhibit 3 of .83.

An equation was developed to describe yield in terms of the possible impact variables. The form of the equation used to link design features with manufacturing yields is shown in Figure 5-2 below.

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[1] An additional problem associated with keeping the "Customer" variable in the model and assigning parameter values to each of the existing customers has to do with what happens when the NPIEs interact with a totally new customer. Even if there is no prior data on new customers, something would have to be assumed about them to run the model. A way around this might be to construct separate models for each customer, but this solution would still require NPIEs to create new models for each new customer.

Figure 5-2, Equation for linking design features with manufacturing yield

General form of the equation:			
f	*response variable*	*given the following conditions that generally cannot be changed*	*features that impact yield that designers can change*
Specific form we used:			
f	*yield*	*No control variables were used. (Customer and Line were considered, then removed from the data set)*	*# of parts,* *# of interconnects,* *# of through-hole,* *# of fine pitch,* *# of handloads* ...

Initially, the focus of the tool development efforts was on the most common types of boards that the shop produced. The first phase of model development was focused on boards that had the following characteristics:

- **Maturity:** high (boards have been in production longer than 6 weeks)
- **Volume:** medium to high (approx. 250 boards per six-month period, and no fewer than 50)
- **Technology:** Processes B and C

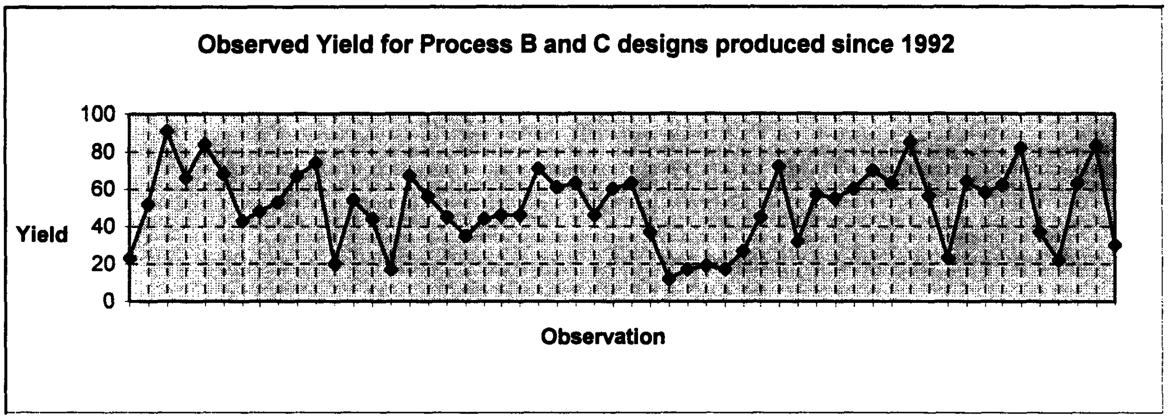
The rationale for restricting the investigation initially to Process B and C boards was that there was sufficient data to do the required analyses and maximize the chances that the right relationships between design parameters and yields would be found.

Data collection for Process B and Process C assemblies

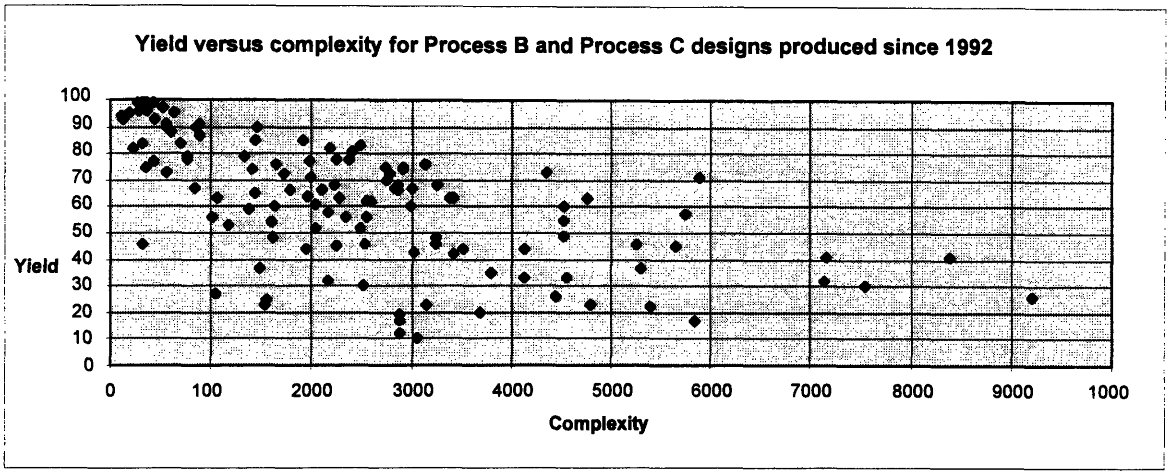
Data on production yields and the possible impact *design* variables were collected for 54 different Process B and Process C products produced at the shop since February, 1993. While there are more samples that could have been drawn from pre-1993 production data, the team decided to restrict the data set to samples only from the last three years. The rationale was that the production processes have that were used more than three years ago were significantly different and may have produced results that would be different today. To some extent the manufacturing process capability is continually changing and setting a cutoff date of any length is somewhat arbitrary. The February, 1993 date was chosen because it struck a good balance between requirements for critical sample size and requirements to model recent production process data.

The 54 samples include all of the Process B and Process C boards produced over that period that underwent some form of test. A small percentage of boards produced at the site do not go through a test step in the production process, and, because there is no production yield data for these designs, could not be included in the data set. The omission of these samples should probably not constitute a serious threat to the integrity of the data set because the samples *within* the data set represent a broad range of design features and customers of the manufacturing site. Boards that do not go through a test step typically are tested at the customer site or at some process step closer to finally assembly and shipping. They probably *do not* represent a particularly hard- or easy-to-produce sample whose inclusion would dramatically bias the results of the analysis.

Data on the design features and production yields appear to be reliable and sound because they were drawn directly from Hewlett-Packard's proprietary information systems. Collection of yield information is a standard procedure in the test area and is collected for every assembly that goes through the test process. In some cases, data collection involved a manual transcription of data from hardcopy drawings of product designs, but even for this information, the collection procedure was not subjective, it was a direct transfer of data from the drawing to the database. The chart below shows the production yields of Process B and C boards made the last 3 years:



As can be seen from this data, there is a significant degree of variation in historical yields. This demonstration of the historical variation in yields validated the conventional wisdom in the shop that different product designs, although going through similar manufacturing processes, could have dramatically different results in terms of yield. The other way this could be validated was by plotting the production yield of the Process B and Process C boards versus the complexity (number of parts + number of leads) of the boards:



The conclusion drawn from this chart is that for the same total number of parts and leads, yields for two alternative designs can vary substantially. The remainder of the first phase of the DFM Tool development process was a period of exploration of which variables from the Possible Impact Variables might be responsible for these tremendous swings in yield.

Descriptive statistics on design variable data

The descriptive statistics on the design variable data explored during the regression analysis are shown in Exhibit 3. As can be seen from this table, some of the variables show much a much larger range of values and variance than others. For these variables, I expected the differences might not appear statistically significant when analyzed as linear variables, but to possibly appear more significant when transformed to become nonlinear variables. I expected this because some of these variables, namely total number of parts, total number of interconnects, six month board volume, and total number of parts on the bottom side have a very large range of values. For example, the number of interconnects on the boards in the data set varies from 618 to 6204. This variable may not appear to have a statistically significant impact on yield if changed by just a small number of interconnects. However, when the number becomes *very* high, the differences in yield might be more easily observed. In other words, the effects on yield total number of interconnects might be more easily detected at the very high or the very low ends of the range. When this was the case, I expected that using a log transformed variable might increase the likelihood that the statistical significance of the design variables would be detected by the analysis.[2]

Some of the other variables shown in the descriptive statistics section of Exhibit 3 have a much more narrow range and standard deviation. I expected that these variables might be better analyzed without logarithmic transformations, since such transformations might diminish the impact that could be observed by these variables on yield. Furthermore, a narrow band of variation around a design variable does not imply that the variable will not likely contribute much to explaining the total variation in yield, since for some of the variables we might expect the addition of only one or two parts to have a tremendous impact on the yield of the board.

Building a regression model from the original data set

To identify the relationships between design features and yields, I used the statistical technique known as regression analysis. The point of using this technique was to test the statistical

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[2] Other forms of transformation were explored. For example scalar transformations were attempted and square roots were taken; squares, cubes, and exponential transformations of the variables were also explored. The best results did come from the logarithmic transformations, which were included in the final model.

significance of the impact on yield that certain design parameters might have. By finding statistically significant parameters for the Possible Impact Variables, I could begin to explain the variance in the response variable (yield) in terms of design characteristics. I transformed the response variable (yield) from a directly reported number: y, to become the transformed variable: $\ln [(y) / (1 - y)]$. The reason the response variable was changed was to generate parameters for the design variables that would not, when recombined, lead to a predicted negative (< 0) or over 100 percent yield.[3]

There are some important pitfalls I tried to avoid in using the regression analysis technique. The first important pitfall that the team attempted to avoid was "data mining," or "overfitting the data." This can occur when too many predictive variables are used to explain the response variable variation. Another potential pitfall was parameter estimation using too few observations. During the analysis, I followed a rule of thumb that there had to be at least three observations (independent data points) for every one design variable that I was trying to estimate.

To better understand the impacts of individual design variables on the yield variation, and to avoid some of the pitfalls mentioned above, I tested variables incrementally and added them to the model one at a time. In this way, I could observe the direction of the impact each design variable has on yield according to the regression analysis and compare that with the NPIEs assumptions of what, based on actual shop-floor experience and intuition was expected.

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[3] When the regression analysis is performed on an untransformed response variable, the results are quite similar. All three variables, total # of interconnects, part density, and # of through-hole parts on the bottom side of the board are significant at the 90 percent confidence level.

At the beginning of the analysis, I expected some of the Possible Impact Variables to have a very strong *negative* impact on yield, others to have a weak and negative impact on yield, and still others to have a *positive* impact on yield. The expectations I had for the Possible Impact Variables were derived from interviews with other NPIEs and from direct observation of printed circuit assemblies at the shop. There was widespread consensus of expectation for each of the six Possible Impact Variables explored during the first phase of the DFM Tool development.

At the outset, I expected some design variables would have a large impact on yield. In particular, I expected the Process C process, the number of through-hole parts on the bottom side of the board, and the total number of interconnects to have strong *negative* impacts on yield. I expected this result for the Process C process because it is only required when the placement of more complex, fine pitch parts is part of the design. These fine pitch parts are held in place using a special glue which the Process B process does not require, and the reliability of the glue adds some variation to the process. I expected number of through-hole parts on the bottom side to also have a strong negative impact because the placement for these parts is a very difficult, manual labor-intensive procedure. Many of the through-hole parts must be hand-placed and hand-soldered, and this introduces some variation in yield into the process. Almost all of the unusually-shaped parts in the printed circuit assembly area have a through-hole style, and when these parts must be placed on the bottom side of the board, there is a higher chance that the parts will not be placed correctly than if they were standard parts.

I also expected that designs with a high number of interconnects would have lower yields because there can be bridging between leads. One of the critical sources of variation preventing boards from "turning on" is a short in the circuit, caused when solder is accidentally stuck between two leads (interconnects), called bridging. When there are more joints to solder, the likelihood that two will be bridged increases, and when the leads are not correctly connected on a board, the board often fails to pass the yield test at the end of the production line. When there are more leads that can fail, generally we expect there will be more boards that fail.

I expected three additional design variables to have a smaller, but still significant impact on yield. Total number of parts and the total number of parts on the bottom side of the board I expected would have a small *negative* impact on yield and I expected six-month board volume would have a *positive* impact. Total number of parts is similar to total interconnects in that a higher number of parts means a higher chance of bridging which would negatively impact yield. However, since many parts have only two interconnects (leads), the impact I expect on yield will be relatively small. Similarly, total number of parts on the bottom side can negatively impact yield when there are a lot of interconnects for a small area or when the parts are difficult to place. However, when there is adequate spacing and parts do not significantly increase the number of leads, placement is a highly reliable process. I expected higher six-month board volumes would have a small, positive impacts on yield because of learning effects. When many boards of the same design are produced within a six-month period at the shop, operators tend to get better at building a particular board and also find ways to improve the reliability of the process. For example, in some cases the consistency of the glue can be changed or the documentation of hard-to-place parts can be enhanced over time which enables operators on different shifts to have greater success building a particular design.

Suspected correlation between variables - original data set

There were several variables which I expected might be strongly correlated with each other and have similar impacts on yield. This was an issue of concern because inclusion of two variables that are almost exactly correlated in the same regression model is undesirable. There is a risk that when the two variables are strongly correlated, each might show up as statistically significant when treated separately in two different regression models, but neither will show up as statistically significant in regression results when both are included simultaneously.

I suspected that total # of parts and total # of interconnects design variables might show a very close correlation. I expected this because each part has at least two interconnects; some fine-pitch parts have even more interconnects, often over 50 leads for per part. When the number of parts on the board increases, I expected there to be not only more interconnects from each part, but I also expected there to be a greater chance that some of the parts would be fine-pitch parts, adding significantly to the number of interconnects. From the correlation table shown in Exhibit 3, it can be seen that the correlation coefficient between these two variables for the original data set is .64, which is somewhat high. Another interesting result from this correlation analysis is that the correlation is not entirely linear. Based on conversations with the engineering section manager, I concluded that a possible reason for why the relationship is not entirely linear is because every part does not have the same number of interconnects. Thus, for some boards, there may be many parts, but because the parts have only two interconnects each, the total number of leads may still be low. In general, the trend is upward and more parts tends to indicate more interconnects; however, due to this variation in the number of leads per part, the relationship is not entirely linear.

After discussing the issue with the NPIE supervising the project, it was decided that the regression analysis for the original data set would continue with both variables, but there would be a review of the regression results to determine whether having both variables added any benefits in terms of explaining variation in overall yield. One of the variables could always be removed later after reviewing the results, even though the regression analysis would have to be re-done without the variable that is removed from the data set. A discussion of the regression results with regards to this suspected correlation can be found in the section below called "Correlation results - original data set."

A summary of the names, descriptions, and expectations for all of the Possible Impact Variables is shown in the table in Figure 5-3 below.

Figure 5-3, Summary of possible impact variables and their expected impact on yield

Variables that could impact yield	**Description**	**Expected direction and impact on yield**
Process technology	Whether the manufacturing process was Process C, not Process B	**Negative; strong impact.** Boards with Process C were not expected to always be worse, but in general, boards produced using Process C were more complex.
Number of TH parts on B side	Number of through-hole parts on the bottom side of the board.	**Negative; strong impact.** Because through-hole parts on the bottom side of the board almost always require hand-placement and hand-soldering, they are very susceptible to error, falling off the board during process, etc....
Number of interconnects (log)	Number of leads on the board.	**Negative; strong impact.** When there is a lot of space available on the board, the number of leads is less critical; however, more leads and greater density create more opportunity for failure, bridging, etc...
Number of parts on B side (log)	Total number of parts on the bottom side of the board.	**Negative; weak impact.** Depending on the situation; putting parts on the bottom side of the board could be easily done, or in some cases very difficult.
Total number of parts (log)	Total number of SMT and through-hole parts on the board	**Negative; weak impact.** It was not expected to be worse all the time; in general, however, more parts increased complexity and the chance of bridging errors, etc.
6-month board volume (log)	Total number of boards of this particular design in last 6 mos.	**Positive impact.** In general, higher production volumes provided more opportunity for learning and refinement during production.

In Exhibit 1, the results from the six independent runs are shown.

The regression tables show that as more design variables are added to the data set, the fraction of the total variance in yield that can be explained increases. It should be observed that the design variables added in models 4, 5, and 6 (# of parts on the bottom side, six-month board volume, and total # of parts) appear to make smaller and smaller contributions to explaining the total variance in yield. The R-square values for these three runs are .39, .41, and .41, respectively. These contributions contrast noticeably with those made by two variables added earlier in Models 2 and 3 (# of through-hole parts on the bottom side and # of interconnects) which appear to contribute greatly to explaining the yield variance. The R-square values for these two runs are .23 (from .05), and .37, respectively.

From the regression table results, it is clear that the directions on all six of the design variables are in line with expectations. Two of the variables appear to have a statistically significant impact on yield at the 90 percent confidence level. The negative parameter value for Process C (-.11) is in the expected direction. The baseline case in this statistical model is a Process B board, and it appears from this result that boards designed for the Process C process have lower mean yields, but not to the extent that I expected before the regression. It can also be seen from the table that the number of interconnects and number of through-hole parts on the bottom side (the two variables that appear to have a statistically significant impact on yield at the 90 percent confidence level) impact yield in the directions that were expected. The results show that the information provided by total number of parts does not appear to be statistically significant, nor does it help explain much additional amount of variation in the response variable. This is likely because the useful explanatory information provided by this variable is already largely captured by the total number of interconnects variable (as can be seen from Exhibit 3, the correlation coefficient between these two variables is .70).

Another important result on the regression table is the R-square value (called the coefficient of determination) which reflects the percentage of the total variation in yield that can be explained by the design variables in the model. The percentage of the total variation in yield that is explained with these six variables is 41 percent. The adjusted R-square value in the regression table, which is basically an adjusted R-square value which takes into consideration the number of design variables used to explain the yield, is 34 percent. In general, monitoring the adjusted R-square value is a way to check whether the analysis is falling into one of the pitfalls of "overfitting" the data (cited earlier at the beginning of this chapter), using too many design variables to explain a small data set. This could be the case if the adjusted R-square is significantly lower than the R-square.

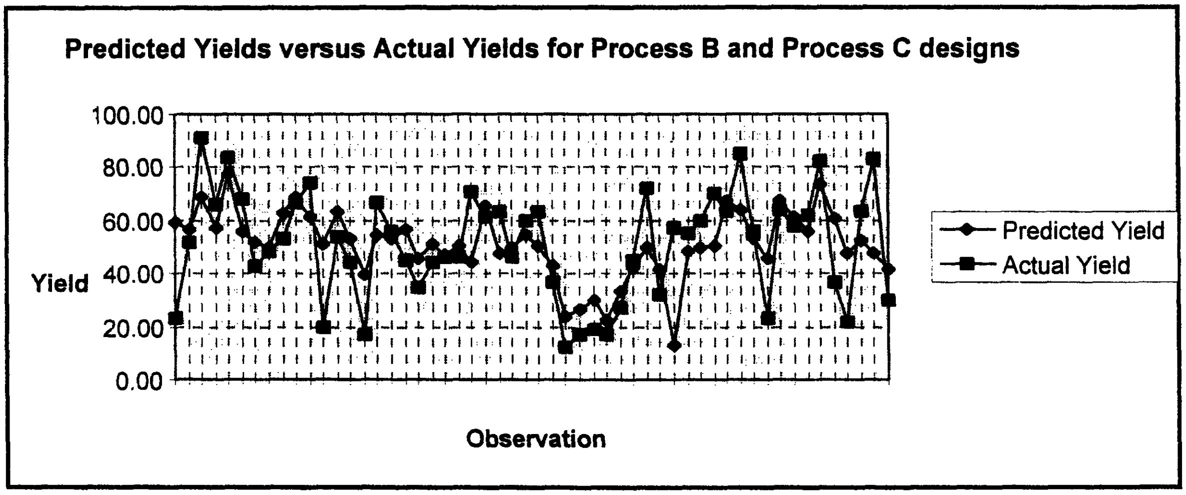
Correlation result - original data set

As might be expected from the overall strong correlation result between total # of parts and total # of interconnects, the results from models 5 and 6 show that the additional contribution to explaining variance in yield by adding the total # of parts variable is near nil. The R-square value remained unchanged at 41 percent.

Because the total parts design variable appeared to be strongly correlated with another variable in the model and did not appear to add significant additional explanatory benefit, it was not included in the model developed for the second phase of the DFM Tool. If the statistical model developed for the first phase had been the only model for the project, it might not have been appropriate to include both the total number of parts and total # of interconnects in the model. One of the two should have been removed. Discussion on the correlation issues surrounding variables in the final data set and which variables were removed for the final model is presented in the "Correlated variables - final data set" section of this document.

Using the information generated from the regression analysis of the original data set, a list of predicted yields was generated for each of the assemblies in the data set. These predicted yields were plotted against actual yields in Figure 5-4 to graphically compare how well the model at this point could estimate yield impact using design information.

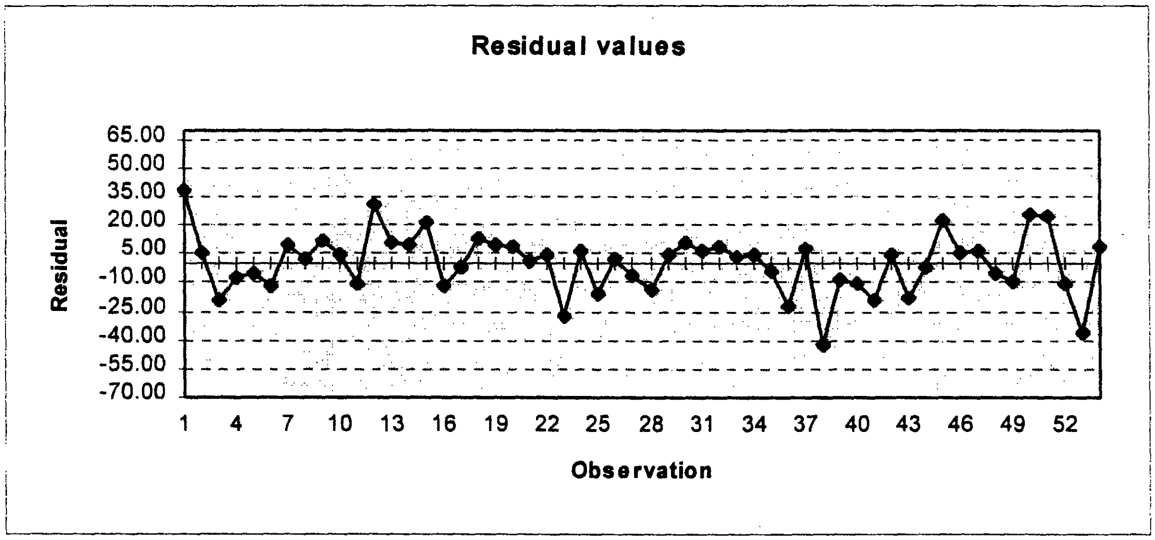
Figure 5-4, Predicted yields versus actual yields for Process B and Process C designs



From this diagram, the engineering head of the NPIE section concluded that some progress had been made, but there were quite a few outlier points that were not predicted well by the model. I inspected several of the boards that had shown a significant discrepancy between the predicted yield from the regression model and the actual observed yield. One of the boards featured a very large, very high part density design. The model had failed to predict this board's actual yield well probably because the design variables representing Oversize Panel and Part Density were not yet added to the model. These variables were added for the final model. For some of the other outlier boards, however, there were other reasons; one outlier board, for example, had been designed for another Hewlett-Packard manufacturing shop, and had been very quickly modified to enable it to be built at the Loveland printed circuit assembly center.

A better way to see the differences between predicted and actual yields is to look at the residuals. The residual is the difference between the predicted and actual values for these board designs. These are shown in Figure 5-5 below.

Figure 5-5, Residual values plot



It is important to recognize that there were other design features—not yet captured in the final model—that were probably impacting yield, and this might explain why 59 percent of the total variation in yields is not yet explained by the data. With additional observations, design variables, transformation variables, and interaction terms, I hypothesized that the relationships might become even more clear. I collected data on more assemblies (including the Process A and Process D assemblies) and more detailed data on the outlier boards from the original data set to come up with possible reasons why the resulting yields were in some cases far from the predictions. The next section describes the addition of these variables and second phase of development of the DFM Tool.

Second phase of DFM Tool development

At the beginning of the second phase of the DFM Tool development, I listed the additional design variables I wanted to explore and began to look for more observations to increase the size of the data set. At this time, there was some concern that the number of observations within the original database available for testing the additional design features was small.

In addition, several NPIEs expressed a very strong interest in having the tool capture all of the major manufacturing process changes that are available to designers. To avoid overfitting the relatively small, original data set (54 observations) and explore the impacts of the additional design variables, I began the second phase of the DFM Tool development process using a larger data set that included yield and design information for all of the assemblies for Process A, Process B, Process C, and Process D boards that had undergone some form of testing at the end of the production process.

Data collection for Process A, B, C, and D assemblies

Data on production yields and the possible impact design variables were collected for an additional 69 board designs, increasing the total sample size 123 observations. There was some concern that the variation in yield for this data set was even greater than the original data set. The mean yield for the new data set was 62 percent and the standard deviation was 24 percent, whereas for the original data set the mean was 51 percent and standard deviation 20. The rationale for including the additional observations, as stated previously, was to increase the sample sizes for some of the design variables and provide a more comprehensive framework for analyzing the entire range of process tradeoffs which might be available to a design customer.

Building a regression model from the new data set

Just as in the original data analysis, I expected some of the Possible Impact Variables to have a *strong negative* impact on yield, others to have a *weak negative* impact on yield, and others to have a *positive* impact. In this second model, I included both those variables that I could collect information for the first model and a number of new additional variables. The expectations I had for the variables from the original data set were unchanged. Expectations for the new variables were again derived from interviews with other NPIEs and from direct observation of printed circuit assemblies at the shop. There was widespread consensus of expectation for each of the design variables.

The new design variables I expected to have a *strong negative* impact on yield were process technology D and part density. I expected Processes D to have a negative impact because it is a more complex assembly processes than the baseline assembly process in the model (Process B). Process D involves the attachment of complex parts on the bottom side of the board. I expected part density to have a negative impact on yield because generally an increased population of parts on a small board leads to tighter spacing between parts. When parts are too close together, they may not get placed correctly, some not at all, which would reduce yield.

The new variable I thought would have a *weak negative* impact on yield was the number of hand-loaded parts. I expected the number of hand-loaded parts to have a negative impact on yield because these parts are put on by hand and they are subject to human error and variation. When parts are hand-placed, sometimes they can be inserted using the wrong orientation.

I expected one of the new design variables to have a *positive* impact on yield, the Process A variable. The Process A variable indicates the simplest manufacturing process where the boards do not have to go through as many process steps as Process B, C, or D. It is not used to produce two-sided board designs; only single-sided board designs are produced using the Process A manufacturing process.

Correlated variables - final data set

There were several variables in the final data set which I expected might be very closely correlated with each other. I was once again concerned, as I had been in the original data analysis, that there might be a problem where design variables, when treated separately, would have appeared to have a statistically significant impact on yield, but together simultaneously would *not* appear so. In particular, I suspected that the total # of interconnects and total number of parts were closely correlated (since they had been in the original data set); I also suspected part density and total # of interconnects might be closely correlated, as well as part density and total number of parts.

To determine whether these expectations were correct and avoid the aforementioned problems, I explored suspected relationships between the design variables before doing the regression analysis. I first prepared a correlation table (see Exhibit 3) showing all of the correlation relationships between the design variables considered in the final data set. I investigated the coefficients for the pairs of variables I expected to be very closely correlated as well as those of all of the other design variables in the data set to see if there were any unexpected pairs that were closely correlated.

From the correlation table in Exhibit 3, I concluded that the correlation coefficient between the total # of interconnects and the total number of parts was high (.70) and one of the two variables should be excluded from the data set used for the regression analysis. Of the two, I expected the total # of interconnects variable to be more important because it better reflects the difficulty of the manufacturing process and should be a better determinant of yield. It is possible, for example, to have a board that has a significant number of parts that is relatively easy to build because most of the parts are two-leaded parts (parts with only two interconnects each). Similarly, it is possible to have a board with few parts, but many that are fine-pitch, that is difficult to build. Because the interconnect data was expected to be a slightly better predictor of yield, it was selected over total number of parts.

It is also possible to see from the correlation table that the coefficients for the other suspected pairs, part density and total # of interconnects and part density and total # of parts, were low.

The correlation coefficient for part density and total # of interconnects is .40, which indicates that the part density and total # of interconnects is loosely correlated. A possible reason why these two variables are not more closely correlated is that the former reflects to some extent the surface area of the board (in addition to the total number of parts) while the latter is not directly affected by surface area. The presence of a loose correlation between these variables gave me some concern that there was some similarity between the two variables; however the correlation was not so high as to justify removing part density from the data set.

There is a loose physical relation between the total # of interconnects and part density, since an increase in one often indicates an increase in the other. However, these variables reflect different things. The former represents the number of leads which must be connected properly between the part and the board and the latter represents more the spacing between parts and the space available to put them on a board. There is also a relation between the part density and total number of parts. The correlation coefficient between these two variables is .40, which, by itself, might not justify removal of one of the two variables from the data set. It was found through the analysis that the addition of the total number of parts variable to the data set did not contribute much to explaining the total variance in yield once the other variables, total # of interconnects and part density were included.

Overall, choosing which variables to include in the data set and which to remove was a difficult part of the data collection process. In addition to the desirable properties of having low correlations with other variables as described above, the variables selected for the final regression model also had to be based on reliable data that could be collected (as mentioned at the beginning of this chapter) from a representative sample boards that underwent the yield test step at the end of the assembly process. Finally, they had to improve the degree to which the variation in yield could be explained. A summary of the names, descriptions, and expectations for the Possible Impact Variables that were new for the second phase of the DFM Tool development is shown in the table in below.

Figure 5-6 below.

Figure 5-6, New Possible Impact Variables used in the final regression model

Variables that could impact yield	**Description**	**Expected direction and impact on yield**
Process technology	Whether the manufacturing process was Process A, Process C, or Process D	**Depends on process.** Boards with Process D were expected to be worse; with Process A slightly better; with Process C, slightly worse.
# of hand-loaded parts	Number of parts that must be placed on the board by hand	**Negative; weak impact.** This is a manual, sometimes difficult process that introduces the chance for operator error.
Part density	The total number of parts for a board divided by the total surface area (top) for **one side** of the board	**Negative; strong impact.** Increased population of parts on a board reduces part spacing and makes placement more difficult.

Exploring potential interaction terms

For part of the analysis in the second phase of the DFM Tool development, I explored potential interaction terms between the design variables already identified. I conducted a brief interview session with two new product introduction managers and an NPIE to identify places to look for possible interactions *only where this engineering group suspected there might be some.* It was possible to have two variables that, independently had no serious impact on yield, yet—when put together in the same design—could have potentially dramatic effects. I created the matrix below from the discussion on the potential interactions among the design variables with the engineering and management staff members.

Figure 5-7, matrix of suspected interactions among design variables[*]

	Proc. C	Proc. D	Proc. A	# hl pts.	pt. dens	tot. int.	6 mo	grph	#th A side	#th B side	# fp A side	# fp B side	trace cut req.
Process C	■												
Process D	X	■											
Process A	X	X	■										
# hand-loaded parts	X	X	X	■									
part density	+	+	+	X	■								
total # of interconnects	+	+	+	X	+	■							
six-month board volume	X	X	X	+	X	X	■						
graphics	X	X	X	+	X	X	X	■					
# of through-hole parts on A side	+	+	X	X	X	X	X	X	■				
# of through-hole parts on B side	X	+	X	X	X	X	X	X	X	■			
# of fine pitch parts on A side	+	+	X	X	X	X	X	X	X	X	■		
# of fine pitch parts on B side	X	+	X	X	X	X	X	X	X	X	X	■	
trace cutting required	X	X	X	X	+	+	+	X	X	X	X	X	■

X = Strong interaction not suspected + = Strong interaction suspected

From an analysis of the proposed interaction terms, however, no additional significant terms emerged as statistically significant. The closest potentially significant term was an interaction between part density and the number of fine-pitch parts on the top side of the board; however, as can be seen from Exhibit 5, inclusion of this term did not significantly improve the R-square and the variable does not have a t-statistic which indicates significance at the 90 percent confidence level. The engineering reason for this suspected interaction was that placing large multi-lead parts on an already crowded board may create more bridging and part placement defects which would create a more significant negative impact on yield than either variable would independently. However, from the results of the additional regression run, it does not appear that the interaction is statistically significant.

While it was somewhat surprising that none of the eighteen suspected potential interactions appeared significant, one possible reason is that most of the explanatory capabilities of the statistically significant variables are captured in their individual parameter estimations. Another possibility is that there are some combinations of *more than two* variables that have an impact on yield, but that these would go undetected in a pairwise correlation analysis. Because the data analysis for this project only looked for interactions between two variables at a time, if there existed in the Possible Impact Variables data set interactions that only occurred between more than two variables, they would not have been detected in this analysis.

Regression results

The results from the regression analysis on the new data set can be seen in Exhibit 1. As can be seen from the table, all six of the design variables, process D, process A, the number of through-hole parts on the bottom side, the total number of interconnects, the number of hand-loaded parts, and the part density appear to have a significant impact on yield at the 90 percent confidence level with the expected signs across a wide range of board designs and yields.[4]

The impact of the constraint placed on the model using the transformed response variable keeps predicted values for yield between 0 and 100, however the "true" impact on the model is that the impact of the design parameter values depend on where the base case predicted yield for the board is. In other words, if the predicted yield for a base case board is already 93 percent, the impact of reducing the part density and total # of interconnects by half will show only a maximum impact of 7 percent. If the base case board had been at 13 percent, the predicted impact may appear much greater.

Take, for example, a hypothetical Process D board that has 400 parts, 2,400 total interconnects, one *through-hole* part on the bottom side all on a 142K square millimeter surface area with a predicted yield of 29 percent. Doubling the number of through-hole parts on this design reduces the predicted yield to 11 percent. Similarly, doubling the number of interconnections for a board with a predicted yield of 29 percent lowers the expectation to 21 percent. Reducing the surface area by one-half lowers the expectation on a board with a predicted yield of 29 percent to 24 percent. Doing all three at the same time results in a predicted yield of 5 percent. Below is a

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[4] The additional design variables, through-hole parts on A side, fine-pitch parts on the A side, six month board volume, number of parts on the B side, fine-pitch parts on the B side, oversize panel, trace cutting required were explored during the regression analysis, but were not found to have a statistically significant impact on yield. An important warning label was attached to the model at distribution which explained that some of the variables have significant distributions around their mean predicted parameter values. The phrase "your mileage may vary" was used to describe the yield predictions made by the model, since the t-statistics for many of the variables were lower than was desired.

table summarizing these potential changes to a board design and their impacts on yield. The variables that do not change in this example were set to their mean values.

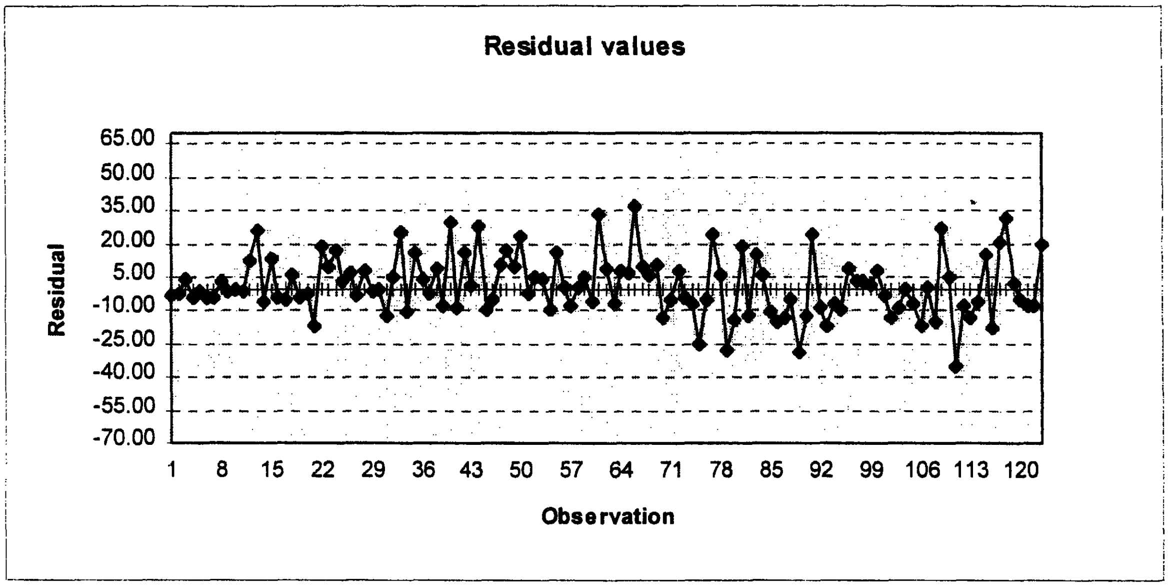
Summary Table of key "What ifs..." and predicted impacts on yield

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Design features	*Design features*	*Design features*	*Design features*	*Design features*
• Production process = D • # of through-hole parts on B side = 1 • Total # of interconnects = 2,400 • Sfc. area = 142K sq mm	• Production process = D • **# of through-hole parts on B side = 2** • Total # of interconnects = 2,400 • Sfc. Area = 142K sq mm	• Production process = D • # of through-hole parts on B side = 1 • **Total # of interconnects = 4,800** • Sfc. area = 142K sq mm	• Production process = D • # of through-hole parts on B side = 1 • Total # of interconnects = 2,400 • **Sfc. area = 71K sq mm**	• Production process = D • **# of through-hole parts on B side = 2** • **Total # of interconnects = 4,800** • **Sfc. area = 71K sq mm**
Predicted yield = 29%	Predicted yield = 11%	Predicted yield = 21%	Predicted yield = 24%	Predicted yield = 5%

Given the difficulty of the Process D manufacturing process, the reliability of placing through-hole-in-paste parts on the bottom side of the board, and the tremendous lead density associated with 4,800 interconnects on a relatively small, 71K surface area board, this proposed design was estimated by myself and by the NPIEs I discussed it with to be approximately zero. The lowest actual yield board in the data set I could compare with this hypothetical example is a board that had a similar density, only one through-hole part on the bottom side, and an actual yield of 10 percent. Considering the model predicts a yield of 5 percent for this design, I conclude therefore that the model prediction is reasonable. The relatively smaller impact on yield resulting from doubling the density compared with the impact on yield resulting from the through-hole parts change is very much in line with what the NPIEs told me that they tell their customers, which is that "increasing the density, by itself, is not necessarily a problem; but putting through-hole parts on the bottom side almost always is."

The R-square value is higher (73 percent of the total variation in yield is explained), which is almost certainly the result of the increased data sample size. The degree to which the final model can predict yield can be seen in the plot of the residuals plot for the final model in below.

Figure 5-8, Residuals plot for final model



Conclusion

From this analysis, I concluded that a DFM Tool that predicted yield could be created from the database of design features and yields. The relatively high R-square value and the intuitive consistency between the design variables results and expectations gave me sufficient confidence to proceed to the third phase of model development--putting the tool in the user's environment to observe it in use. A user-interface was constructed and installed on the new product introduction engineer's computers to increase the user-friendliness of the statistical model. I gathered observations from several interactions between design and engineering using the model. An analysis of these interactions and the degree to which they validated the hypothesis is presented in the next chapter.

VI. USING THE DFM TOOL: CASE STUDIES

Introduction

This chapter consists of two parts. The first is a summary of my hypothesis when I began the DFM Tool project. This part also reviews what kind of observations I attempted to collect that might prove or disprove the validity of the hypothesis. The second part of this chapter is a summary of the observations. The observations are presented in the form of two case studies. This part also reflects on how well the observations validates the hypothesis.

Data collection methods

As was stated in the introduction, the hypothesis of the project at Hewlett-Packard's Loveland Manufacturing Center was that a DFM Tool that predicted yield could lead to improved communication between design and manufacturing about the manufacturability of proposed designs. Educating design customers about how their decisions impact manufacturing processes and process outcomes, specifically process yields, was a high priority for the printed circuit assembly group, and it was hypothesized that having a DFM Tool would enable them to do this better. The previous two chapters have shown how a DFM Tool was built to predict yield based on design characteristics. This section describes how I collected observations of the tool in use, to try to determine whether using the DFM Tool in interactions between designers and manufacturing representatives improves communication about the manufacturability of proposed designs.

I used two different methods of observation in collecting the data for the two case studies that are presented below. For the first case, I went with an NPIE to the design customer location and observed the customer's reaction to a graphical diagram which showed how typical design decisions impact manufacturing processes and process outcomes. The customer was located on-site, at the Loveland facility. I was able to first watch the NPIE and the customer interact, and later asked the customer questions directly about the diagram which was produced using outputs from the DFM Tool.

For the second case, the observations were derived from the notes I made from a conversation I had with an NPIE about an interaction he had with a design customer using a windows-based application of the DFM Tool on his laptop personal computer. The NPIE had traveled to the customer location, which in this case was off-site, in Colorado Springs, and used the tool to show how the designer's decisions on one particular board were going to impact yield. As a next step in the data collection process for the case studies, I came up with a criteria to use to determine whether the observations made from these cases might validate or disprove the hypothesis.

Validation criteria

Measuring the manufacturability of a product design or the impact that a DFM Tool has on the interactions between designers and manufacturing representatives is difficult. Just as there are significant time delays between the time a child receives an education at primary school and the time you can observe him or her working in his or her company or community, there are delays between the time a designer receives better education from manufacturing and the time he or she begins producing better designs. However, the project needed some guiding principles by which a preliminary estimation of whether the DFM Tool developed for the project appeared to validate the hypothesis.

A direct method for assessing the validity of the hypothesis might be to measure and compare the cost, yield , cycle time, and functionality of printed circuit assemblies designed over time by customers who interact with NPIEs using the DFM Tool with the cost, yield, cycle time, and functionality of printed circuit assemblies made by customers who do not use the tool. This method several problems, however. First, most of the printed circuit assemblies made at Loveland are one-of-a-kind products that cannot be easily compared with other products within the division let alone across divisions or across time. Second, different design customers have different needs, different priorities, and a simple metric, such as cost per assembly, may not reflect the increase in the manufacturability of a product made possible through the use of a DFM Tool

In addition, exact measurements in terms of time or cost savings from these interactions will be hard to achieve in future because the net impact of using the tool in this kind of interaction *may not be* a net reduction of meeting time, but in fact a net increase in the quality of how that time is spent. It is very difficult to measure what a board design would have cost or what kind of manufacturing process yield it would have had if the NPIE had not provided this information. Instead, the meeting time will be used more effectively on the process development activities (helping think up ways for getting their customers' innovative designs built) and *increasing the quality* of the communication between design and manufacturing.

I created the three criteria below to serve as first order approximations to use instead of the direct method to assess the validity of the hypothesis. These questions to a significant extent reflect the aspects of cost, time, yield, and functionality from the direct method, but are easier to measure and objectively assess in the short period of time I had available to collect information on the tool in use at Loveland. The answer to how well the hypothesis was validated depends on the answers to the following three questions:

1. **Did the interaction with the tool improve the design customer's knowledge of how design decisions impact manufacturing processes?** This questions links back to cycle time and yield because when designers know more about manufacturing processes, they should be less likely to make bad decisions that lead to non-manufacturable designs, product development delays, and designs which are very difficult to make reliably. More knowledgeable customers should be able to make better, more informed choices about product designs early, therefore assessing whether their knowledge of manufacturing processes is increasing is a good first order approximation to the direct measures.

2. **Did the interaction(s) in which the tool was used generate cost savings opportunities that could improve the manufacturability of printed circuit assembly designs?** This question relates relates very well to the metrics of cost, yield, and functionality because it does not require the physical change of the product design. It measures the size of the cost savings opportunity identified during the interaction which is very useful information to the designer even if he/she does not used in a particular design.

3. **Did the interaction(s) in which the tool was used improve customer satisfaction?** This measure is a good overall approximation for how well the printed circuit assembly shop is meeting *all* of the customer's required metrics. It is a superior metric to direct measures because it encompasses aspects of cost, time, yield, and especially functionality.

The answers to these questions will help reveal whether the DFM Tool developed for this project enables NPIEs to provide feedback on the manufacturability of designs. Information to help answer these questions can be gathered in a two ways. The first method, the one used in this dissertation, involves the collection of qualitative information from direct interactions between design customers and NPIEs using the DFM Tool and summarizes the information in the form of case studies and conclusions based on those qualitative observations. A second method that uses a more formal and rigorous data collection process and can be used to quantitatively analyze information that might help validate or disprove the hypothesis is presented at the end of the chapter.

In the next chapter, two case studies of the DFM Tool's application and use are presented and analyzed. The cases document interactions between NPIEs and design customers, and illustrate improvements in communication of manufacturing process information that can occur between manufacturing and design when a quantitative tool is applied to the situation. The methods for data collection used in the case studies and an outline of how more data can be collected in future to investigate the impact of the tool at Loveland is presented at the end of the chapter.

Case study 1

Context

This case study describes an interaction between an NPIE and a design customer from one of the HP divisions on-site at Loveland in which an output from the DFM Tool was used to improve communication about product design alternatives and manufacturing process capability.

The NPIE had worked with this division for three years and provided two basic services. The first service was to educate and inform the designers and layout personnel at the division about the existing manufacturing process capability. The second was to make small, incremental adjustments to existing processes to get his customer's designs built. According to the NPIE, approximately one third of his time was allocated to this second service, which he called tweaking the processes. The remainder of his time was spent either monitoring specific production issues for prototype PCAs or performing general overhead tasks, which included periodic meetings with his customers. While the first service is necessary, the incremental process adjustment task is also important because the printed circuit assembly shop often has to tweak existing manufacturing processes to get the latest test and measurement products built.

Adequate time for incremental process adjustment is essential because product innovation increasingly requires process adjustment to ensure that the new product designs, parts styles, and components can be built reliably. An application of the DFM Tool that more clearly communicates alternative design tradeoffs in order to reduce the time required for educating customers about existing processes and to make more time available for tweaking and incrementally adjusting processes is described below.

Application of the DFM Tool to make Tradeoff Arrow Diagrams

In order to more clearly communicate design tradeoffs (described in Ch. 2), I used the DFM Tool to prepare a Tradeoff Arrow Diagram (see Exhibit 2) demonstrating the manufacturing process choices and likely process impacts on yield. I collected information from the new product introduction engineer about typical process choice tradeoffs for this customer, processed the information using the DFM Tool and prepared the graphical diagram displaying different impacts of the alternative manufacturing processes and product design features. The diagram shows the likely manufacturing impacts that the tool predicts for each design feature if the changed.

I used the tool to present information about manufacturing process tradeoffs and yield impacts in a graphical, easy-to-interpret form using tradeoff arrows. The arrows enabled me to show not only the direction, but also the predicted impact of the change from an assumed base case scenario. The base case scenario is a Process D board design that has 200 parts, 1,200 interconnects, 20 hand-loaded parts, 2 through-hole parts on the bottom side, 50 parts on the bottom side, a 142K sq. mm. surface area, and a projected volume of 250 units over a six-month period. The base case yield is only 18 percent. As can be seen from Exhibit 2, some of the changes to the design improve yield, others lower the predicted yield. For example, the designer can see from this diagram that adding two through-hole-in-paste parts to the bottom side of the board has potentially significant, negative consequences (a potential decrease in yield of 13 percent) whereas reducing the number of hand-loaded parts has potentially significant positive benefits (a potential increase in yield of 3 percent), and switching to a less complex manufacturing process, which might also require removing the through-hole parts from the bottom side has potentially higher impacts on yield. From this diagram, the designer can very quickly develop a more clear understanding of the size of the impact of some of the changes considered.

The Tradeoff Arrow Diagram also displays each of the major process choices available at the printed circuit assembly shop, arranged in order of positive impact from left to right. This arrangement can be helpful for educating new designers who are not yet familiar with some of the major processes in the printed circuit assembly shop. It provides a quick reference and an intuitive structure that might help them remember manufacturing process tradeoffs more easily.

Results

The Tradeoff Arrow Diagram was used by the NPIE with his division customer during the first week of December, 1996. The NPIE presented a color transparency of the diagram to a group of designers at a customer division who were trying to balance a manufacturing process choice decision with the functionality requirements of their product design. The NPIE was able to use the Tradeoff Arrow Diagram to initiate discussion with the customer about the degree to which manufacturing process choice impacted yield. Based on the length and depth of the discussion, summarized below, it appears that at least the first and third criteria regarding validation of the hypothesis were met. The customer's knowledge about manufacturing processes and how design decisions impact process outcomes was higher after the interaction with the DFM Tool than it was before the meeting. Because the customer appeared very happy to see the NPIE provide information about the manufacturing process in this way, it appears that the third criteria of customer satisfaction was met as well.

During the customer interaction, the NPIE used the diagram to display the yield impacts of alternative process choices and discuss the costs and benefits of some of alternatives displayed. He showed the designer how switching from double-sided manufacturing processes to single-sided had a very large impact on predicted yield. He also used the diagram show how designers could make adjustments to the board without switching the manufacturing process that might improve the future process yields almost as much as switching to a single-sided process. For example, he showed the designer that yield could be improved significantly simply by reducing the number of hand-loaded parts on the board from 20 to 2.

The design customer appeared very satisfied with the diagram. The customer said that this kind of graphical representation of design tradeoffs would be useful to him two ways. First, he believed he could keep the diagram as a quick reference in his work area that would help him develop a more solid, conceptual understanding of the manufacturing process choice tradeoffs, and the impact of some of the design decisions on yield. Second, he believed that he could show the diagram to some of his newer, less-experienced colleagues in design who did not yet have any understanding of the impacts of their design decisions on manufacturing process choices and potential yield impact.

There were already references that contained DFM and manufacturing process information, such as a very large process guidelines manual, but the customers was interested in having something that was easier to access than the guidelines manual and could represent the current, most important process tradeoffs. He thought the manual was a little too large and hard to navigate for specific, critical process information. If manufacturing could routinely provide a kind of "hot sheet," displaying the latest guidelines and tradeoffs of the manufacturing processes, he thought the designers would need less time with the NPIE getting educated on manufacturing process choices, thus freeing up more NPIE time to tweak existing processes to get innovative designs built.

The NPIE also reacted very favorably to the interaction where the output from the DFM Tool was used. He said the diagram had "had its desired effect" on the customer and described the use of the Tradeoff Arrow Diagrams during this interaction as successful. Presenting the information this way enabled him to communicate manufacturing process knowledge more quickly than he could have without it. The statistical analyses used to generate the yield impact predictions on the diagram may have added to his credibility with the customer because they were providing historical data and analysis to back up what he had been telling his design customers based on intuitive knowledge.

A possible way to collect more quantitative observations to monitor the impact of improved customer education and communication over time might be to record the amount of time an NPIE spends developing new processes and the time for educating and informing customers about existing processes and specifications. Although the dividing line between these two services is at times blurred, some kind of rough distinction could be drawn in the future that would enable this information to be collected and measured.

Conclusions from Case 1

The observations from this case indicates that the hypothesis was validated at least against the first and third criteria. Manufacturing process knowledge was more clearly conveyed using the Tradeoff Arrow Diagram made from the DFM Tool than it could have been without the tool. While neither the Tradeoff Arrow Diagrams nor the DFM Tool itself capture all of the design details important to manufacturing, they do represent some of the most important decisions designers make and show how the impact manufacturing processes. In the words of one NPIE, the tool enables manufacturing to point out "what neighborhood of the yield world the designer might be going to live in," which does not necessarily mean that the NPIE can't make some minor adjustments to manufacturing processes to make yield slightly better. It only means that within certain manufacturing process worlds, there are some constraints and limits to yield.

The observations from this interaction also indicate that the design customers are comfortable and satisfied receiving this information. The fact that the customer expressed an interest in having a "hot sheet" in the future indicates that they are interest in receiving more diagrams like the Tradeoff Arrow Diagram prepared for that interaction. The customer commented that the identification and ordering of the key process choices would help his junior designers develop an understanding of which processes were in general better than other processes and how their design decisions impacted process outcomes more quickly than they would have without the diagrams. The NPIE was also able to build credibility through communication with the customer by bringing models based on quantifiable, data-driven, analyses of historical manufacturing process outcomes.

Case Study 2

Context

This case study will describe an interaction between an NPIE and an off-site design customer in which a Windows-based application of the DFM Tool running on a laptop was used to improve communication about product design alternatives and manufacturing process capability for a specific product that the design customer was developing. After using the tool in the interaction with the customer, the NPIE said that the customer had a more clear understanding of how the particular design decisions they had made on the product would impact manufacturing and the future production yield.

This design customer was located more than one hour from the printed circuit assembly shop, which poses some small communications challenges. Meeting every day is difficult, however face-to-face meetings are still possible on a regular basis. Because face-to-face contact is one of the most effective ways to communicate about designs, the NPIE visited this off-site customer regularly to discuss how the product design was developing.

Approximately six months into the product development process, this customer changed the design from a configuration that could be produced using Process C to one that had to be produced using Process D, which (as can be seen from the results derived in Chapter 5) has negative yield implications. The change was driven by a business need--the product had to achieve a greater degree of functionality; but achieving this functionality required more parts and more density than could be accommodated using the Process C manufacturing process.

The product was already extremely complex. The design had 560 parts, 15 hand-loaded parts, 25 fine-pitch parts, over 5,000 interconnections, 226 parts on the bottom side, and only 72K square millimeters of surface area. The change in manufacturing process and concurrent change in some of the other product design features, including the number of through-hole parts on the bottom side, would make the future yield even worse.

Some of the recent changes in product design features caused the NPIE to be concerned that the board would not have a very high yield; however, the NPIE understood that the design needed to be that complex to attain the critical functionality requirements of the product. Another concern of the NPIE was that the customer (in this case, there were four designers responsible for the hardware, or printed circuit assembly) did not fully appreciate or understand the negative consequences on manufacturing yield that would be introduced by the design change. The purpose of the NPIE then was to inform the design customer of the likely manufacturing impacts of this design and suggest any alternatives that might be pursued that could attain the same functionality requirements with a more manufacturable configuration.

Application of the DFM Tool by creating a Windows-based interface

I created a Windows-based interface for the DFM tool that can run yield prediction analyses in real time using a portable computer. It has an easy-to-use interface written in Visual Basic that runs from Excel and accepts as input from the user the values of the different design characteristics of a board. The NPIE loaded the tool onto his laptop and brought it with him on his next visit to the customer. While at the customer site, the NPIE analyzed the impacts of the new design and presented a yield prediction to the customer within minutes.

Results

The NPIE was able to use the DFM Tool at the customer site during his consultation visit on the proposed new design. He provided a real-time assessment on the predicted yield of the design (which was zero) using the tool after getting from the customer the design drivers needed to run the model. The NPIE generated a potentially significantly negative impacts of the division customer's design decision and was able to show to the customer that the design under consideration had a yield prediction of zero. This implication of this very low yield is that more time and costs must be spent by get the product for the repair process, the assembly processes and test..

While the presence of the DFM Tool did not in this case reverse the decision of the division, it played a role in improving the communication between design and manufacturing. The NPIE was able to construct the yield prediction for the board design in front of the customer and the customer could clearly see the negative impacts of his decision to switch to manufacturing Process D from Process C.

Conclusion from Case 2

The primary purpose of the tool is *not* to reverse design decisions when manufacturing wants them to be reversed, but to in fact create a more clear understanding and level of communication with designers by providing them with better information on how their design decisions will impact manufacturing processes and process outcomes. In this case, the NPIE was able to show using historical data that the design proposed by the division was clearly "out of bounds" and would have a zero percent yield in the production phase. From this demonstration alone, and from the NPIE building the yield production in front of the customer it is clear from the observations made from the case that the first criteria from the validation criteria was met during this interaction. This number was documented, the meeting was recorded, and, the designer and manufacturing community were fully informed as to what the likely impact would be. Because most design customers like to know what their future manufacturing process yields will be, even when they will not be very high, it appears from this interaction that the third criteria on the validation list was also met.

The observations from this case indicates that the hypothesis was validated by the observed interaction. The NPIE was able to use the tool to communicate manufacturing process information more clearly than just providing a "gut level" feedback and a recommendation to the designer on his opinion about the product. The process information was conveyed using a tool that was built using historical data and statistical analyses and could deliver more precise information than was possible to do before. Through additional data collection, not only on the design variables used in this model, but also on additional variables that could be identified in the future, some of which are described at the end of this chapter, the impact of the model and its ability to improve communication should increase further.

Based on the observations from this interaction, the customer now has a much clearer expectation for what will happen to the board when it gets to the production step. Prior to the application of a quantitative tool to the design consultation with this customer, the NPIE was only able to predict a bad result for the board design, without being able to display graphically and numerically the specific negative impacts of each of the design characteristics that were difficult to manufacture on the board. Using the DFM Tool, the NPIE could show that the predicted yield was zero, and demonstrate using the graphical capabilities built into the Windows-based tool a visual model for what particular design features were the "heavy hitters" causing the most damage to the predicted yield of the board.

Conclusions from the entire case study data collection process

Comparing the observations made from each case study, it can be seen that some aspects of the interactions were similar, others were different. In both of the cases, the design customers were receptive to the idea of the NPIE using a tool to try to communicate how the design decisions had an impact on manufacturing processes. The cases were also similar in that no particular design decision was reversed or changed as a result of the interaction. However, in both cases the NPIE felt that the use of the tool had been very effective at clarifying the understanding and expectation of the designer on how certain design decisions impacted process outcomes.

On the other hand, there were some differences between the cases. In the second case, for example, the NPIE had much more flexibility to attempt "What if" analyses on the data using the Windows-based application of the tool. In the first case, the NPIE was restricted to displaying a single graphical chart which did not have reflect all of the design customers specific questions. On the other hand, in the first case, the NPIE was able to leave with the designer the diagram, which could then be used by the designer as a quick reference guide for himself and for some of the new designers in his group.

Overall, there were positive aspects to each approach to using the DFM Tool, but the observations from the second case indicate that the Windows-based application method was the superior approach. The degree to which the NPIE could customize his prediction and interaction with the customer was much higher in the second case. The Windows-based approach also enables the NPIE to bring an interactive aspect to the consultation, where he could foreseeably work with the customer to generate ideas for the "What if" case.

Proposed future method for data collection and validation of hypothesis

One of the shortcomings of the validation steps taken for the DFM Tool project was a lack of more formal data collection and experimental design to check the validity of the hypothesis. With more time and a rigorous approach, more extensive data collection on actual interactions could reveal new insights to how the DFM Tool improves communication between design and manufacturing. What follows is a proposed outline of the key metrics, experiment design, and guidelines for analysis that a more rigorous validation procedure should follow to answer the three questions put forward as validation criteria at the beginning of this chapter.

Key Metrics

The validation criteria questions and proposed key metrics for a more formal data collection process are as follows:

Validation criteria	Proposed key metrics
Did the interaction(s) in which the tool was used improve the design customer's knowledge of how design decisions impact manufacturing processes?	• Average score on general manufacturing process knowledge quiz
Did the interaction(s) in which the tool was used generate cost savings opportunities that could improve the manufacturability of printed circuit assembly designs?	• Potential repair time savings identified • Potential cost savings identified • Differences in yield across iterations • Differences in yield within design process
Did the interaction(s) in which the tool was used improve customer satisfaction?	• Average ratings on semi-annual customer satisfaction survey

For each of the validation criteria, key metrics could be used to determine whether a sample of customers and NPIEs working with the DFM Tool perform better, the same, or worse than the control sample not using the tool. For the first criteria, the metric could be the design customer's score on a general manufacturing processes quiz. The idea of creating a quiz came up during the early brainstorming sessions for the DFM Tool project. Similar to a "driver's test," it could ask basic questions of the designer about manufacturing processes and could be graded confidentially. The scores from the quiz could be used in the data collection for the model validation. For the second criteria, there are four potential metrics which could be recorded over a six month period. Potential cost and repair time savings could be recorded for board design recommendations that are or are not acted upon. Yield could be collected over design iterations for certain boards or within the design process for a single board. For the third criteria, a simple customer satisfaction survey would suffice, and the baseline ratings would not be as important as the changes in ratings over time. A sample question could be: "How satisfied with your current knowledge manufacturing processes and services?" Other questions could be added.

Using information collected in each of these metrics, trends could be plotted, statistical tests run to look for disparities, and it may become more clear whether the hypothesis for this project is validated.

Experiment Design

There could be four groups in the experiment, one group for each of the three places the tool was envisioned to be used, and one group which does not use the tool at all. The first group of NPIEs and design customers would never use the DFM Tool, a second group could use the tool at the very earliest step in the design process (just after idea generation, see NPIE process in Chapter 2), a third group could use the tool somewhere after idea generation but before first prototype production, and a fourth group could use the tool at the end of the design and layout process just during the release of the boards. Data would have to be collected during each interaction in a consistent, formal way, so that there is little discrepancy among the NPIEs within one of the experimental design groups.

Guidelines for analysis

By looking across the measured results for each of these groups, and watching how the measures change over time, some indication of not just how but also when the tool can be used effectively will be more clear. The analysis would simply plot trends and calculate averages for potential repair time savings, potential cost savings, customer satisfaction, and general manufacturing process knowledge. Determination of whether one group's results are statistically significantly different from another's could be done using statistics.

From taking this next step in the validation procedure, greater insights will be derived as to how well the DFM Tool can improve communication between design and manufacturing and also how the tool itself might be improved over time to continue to serve this purpose. .

VII. CONCLUSIONS

Introduction

The objective of the project was to develop a DFM Tool that would enable NPIEs to provide feedback to customers about the relative manufacturability of their designs. Through the data collection, model development, and regression analysis tasks described in this document, this objective was accomplished. It has been shown through this work that data from design variables can be used to explain seventy-five percent of the variance in the response variable, manufacturing process yield for printed circuit assemblies produced at the Loveland Circuit Assembly Center.

During the end of the project, observations were made on two interactions between NPIEs and design customers that provided additional insight on the DFM Tool's impact on communication between design and manufacturing. From the analysis of these early observations, there is a solid indication that the tool should achieve improvements in the communication between design and manufacturing about the manufacturability of designs and the process capability of the printed circuit assembly shop. The conclusion that must be drawn from the data collected thus far is that further integration of the DFM Tool into the organizational process will continue to improve communication about manufacturing processes between design and manufacturing.

Summary of what was done

To summarize, the three main accomplishments of the project and the conclusions that can be drawn from an analysis of the data that was collected are:

- **It is possible to build a DFM Tool that explains variation in yield.** The data collection and analysis demonstrate that the tool development was successful.

- **Data indicate clear benefits of improved communication within the manufacturing community and also improved communication between manufacturing and design.** From the interactions that could be observed, the observations indicate that communication was increased and improved as a result of the use of the tool.

- **Future enhancements of integrating the tool with cost and existing management systems will deepen the impact and effectiveness of communication about manufacturability and process capability between design and manufacturing.** From discussions with several NPIEs, their customers, and the division managers, it was clear that integration of the tool with the organizational processes was desirable, and could be achieved with future enhancements to the basic model.

Shortcomings

There are four shortcomings of this work. The first is that there was very little evidence and data available at the end of the project that could be used to prove or disprove the hypothesis that the DFM Tool developed for the project has improved communication about the manufacturability of designs and process capability between design and manufacturing. The second major shortcoming is that the work does not have a direct tie-in with the cost of alternative board designs. The DFM Tool team very early in the project decided to focus on yield rather than cost because the data availability and data quality were very high and the it was possible to get a fairly precise estimate of yield very early in the development process. The third is that there still remains some unexplained variation in the response variable, yield. The possible reason for this is that there still remain many unique design characteristics and special cases that are not fully captured in the list of Possible Impact Variables during the model development phase. This should be addressed in the future by continual data exploration and inclusion of new variables into the regression model. Finally, there has been inadequate attention to the issues of integration with the existing organizational processes that would be very desirable and beneficial to the design and manufacturing community. One of the things the DFM Tool does not provide is a clear way for NPIEs to integrate the use of the tool with the new product introduction process, and this need should be addressed to achieve greater utilization and benefit of the tool.

Of the four shortcomings, the most important is data collection for how the DFM Tool is improving communication. There was significant focus on the tangible deliverable, the DFM Tool, and less attention given to the intangible, communications *improvement,* during the project. As a result, assessing the current and future impact of the DFM Tool will require more research and analysis on how the model is used in the organization. In the Next Steps section below are some of the ways that HP Loveland can begin to collect more evidence and ongoing measurements for this purpose.

Next Steps: Future enhancements for the DFM Tool

Despite the preliminary evidence which indicates that the DFM Tool created for this project is improving communication at the site, there are more steps which can be taken that will further leverage the potential that the tool possesses.

One of the important first steps that should be taken, and should be easily accomplished given that the data already exists for doing this, is to link the DFM Tool outputs more directly to repair costs. This might be accomplished by running the regression analysis using the same design input variables but with total repair time as the response variable. Because the finance department has price information for repair, a direct translation might be made to the 3 - 6 percent of total manufacturing cost that is represented by test and repair. Considering that test and repair is a controllable expense, and 6 percent of $300 million in manufacturing cost per year is $18M, better identification of test and repair costs should be an area that merits continued attention.

As the tool becomes more widely used and enables improved communication early in the design process, it should help drive the behavior of the designers towards value-added decisions that better meet the business needs of their customers and more successful new product launches.

Designers and layout persons are now able to attempt “what if” configurations of designs for “turn on rate” predictions long before the products reach manufacturing.

Applications for other organizations

The general framework and approach employed in this project thesis is applicable to wide range of organizations, particularly those companies that produce a wide range of highly-customized products. By attempting to link known, controllable design variables, with uncertain manufacturing process outcomes and yields, we have demonstrated here a systematic process for understanding and capturing much of the variation in the design process. Without a database, statistical model, or summary diagram to illustrate the historical impact of design decisions on manufacturing processes, communication can be a much less-precise, less-efficient process.

Conclusion

Improved understanding and ability to communicate process capability will change the way design managers and manufacturing managers interact and the way they see their role in the business. Enabling innovation is critical to maintaining strong relationships between these constituencies, but as we have seen from this analysis, it is a two-way street. In order to have strong relationships, design must be convinced that manufacturing understands its critical business needs. And, in order to understand design’s critical business needs, manufacturing needs to have a way to provide feedback and education to the layout and design managers. This project has shown how a knowledge-based tool can be an excellent step to making this happen.

By bridging the gap between design features and manufacturing processes, Hewlett-Packard Loveland has taken an important step towards leveraging the manufacturing process knowledge it possesses and the new, deeper understanding that this will create between the design community and the manufacturing community should sustain Hewlett-Packard's competitive advantage in product development for many years to come.

Exhibit 1 - Regression Results

SUMMARY RESULTS - ORIGINAL DATA

	Model 1 - Process C			Model 2 - Process C TH Parts on B Side			Model 3 - Process C TH Parts on B Side # of Interconnects (log)			Model 4 - Process C TH Parts on B Side # of Interconnects (log) # of parts on B side (log)			Model 5 - Process C TH Parts on B Side # of Interconnects (log) # of parts on B side (log) 6 mo. board volume			Model 6 - Process C TH Parts on B Side # of Interconnects (log) # of parts on B side (log) 6 mo. board volume Total # of parts (log)		
Regression Statistics																		
R Square	0.05			0.23			0.37			0.39			0.41			0.41		
Adjusted R Square	0.03			0.20			0.33			0.34			0.35			0.34		
	Coeff.	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*
Intercept	0.18	1.15	0.26	0.21	1.52	0.13	5.27	3.45	0.00	4.99	3.28	0.00	4.01	2.37	0.02	3.99	2.33	0.02
Process C	-0.43	-1.57	0.12	-0.06	-0.22	0.83	-0.12	-0.50	0.62	-0.09	-0.38	0.71	-0.11	-0.44	0.66	-0.11	-0.44	0.66
#TH B Side				-1.38	-3.46	0.00	-1.39	-3.81	0.00	-1.39	-3.85	0.00	-1.39	-3.87	0.00	-1.37	-3.62	0.00
# of Interconnects (log)							-1.50	-3.32	0.00	-1.18	-2.37	0.02	-1.12	-2.25	0.03	-1.04	-1.74	0.09
# Parts on B Side (log)										-0.35	-1.44	0.15	-0.43	-1.72	0.09	-0.40	-1.42	0.16
6mo Bd Vol (log)													0.37	1.30	0.20	0.37	1.29	0.20
Total # parts (log)																-0.12	-0.23	0.82

SUMMARY OUTPUT - ALL DATA

	Model 1 - Process D, C, A			Model 2 - Process D, C, A total Interconnects (log)			Model 3 - Process D, C, A total Interconnects (log) #HL/Image			Model 4 - Process D, C, A total Interconnects (log) #HL/Image # TH B side			Model 5 - Process D, C, A total Interconnects (log) #HL/Image # TH B side, part dens. (log)		
Regression Statistics															
R Square	0.30			0.58			0.68			0.71			0.73		
Adjusted R Square	0.28			0.56			0.67			0.69			0.71		
	Coeff.	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*	*Coeff.*	*t Stat*	*P-value*
Intercept	0.18	0.65	0.52	6.79	8.74	0.00	6.13	8.95	0.00	6.39	9.64	0.00	6.48	10.02	0.00
Process D	-0.46	-1.02	0.31	-0.61	-1.74	0.09	-0.92	-2.97	0.00	-0.61	-1.95	0.05	-0.51	-1.67	0.10
Process C	-0.22	-0.63	0.53	0.03	0.12	0.91	-0.11	-0.46	0.65	0.00	0.01	1.00	-0.01	-0.05	0.96
Process A	1.35	4.16	0.00	0.74	2.81	0.01	0.70	3.06	0.00	0.64	2.91	0.00	0.48	2.18	0.03
Total # of Interconnects (LOG)				-2.02	-8.87	0.00	-1.62	-7.81	0.00	-1.72	-8.50	0.00	-1.54	-7.44	0.00
# HL/image							-0.01	-6.22	0.00	-0.01	-5.37	0.00	-0.01	-5.80	0.00
#TH B Side										-0.96	-3.25	0.00	-1.26	-4.09	0.00
Part Density (LOG)													-0.84	-2.74	0.01

SUMMARY OUTPUT - ALL DATA, FINAL MODEL

	Model 6 - Process D, A, total Interconnects (log) #HL/Image # TH B side, part dens. (log)		
Regression Statistics			
R Square	0.73		
Adjusted R Square	0.71		
	Coeff.	*t Stat*	*P-value*
Intercept	6.47	10.10	0.00
Process D	-0.50	-1.91	0.06
Process A	0.49	2.79	0.01
Total # of Interconnects (LOG)	-1.54	-7.56	0.00
# HL/image	-0.01	-5.87	0.00
#TH B Side	-1.26	-4.15	0.00
Part Density (LOG)	-0.84	-2.76	0.01

Exhibit 2 - Tradeoff Arrow Diagram

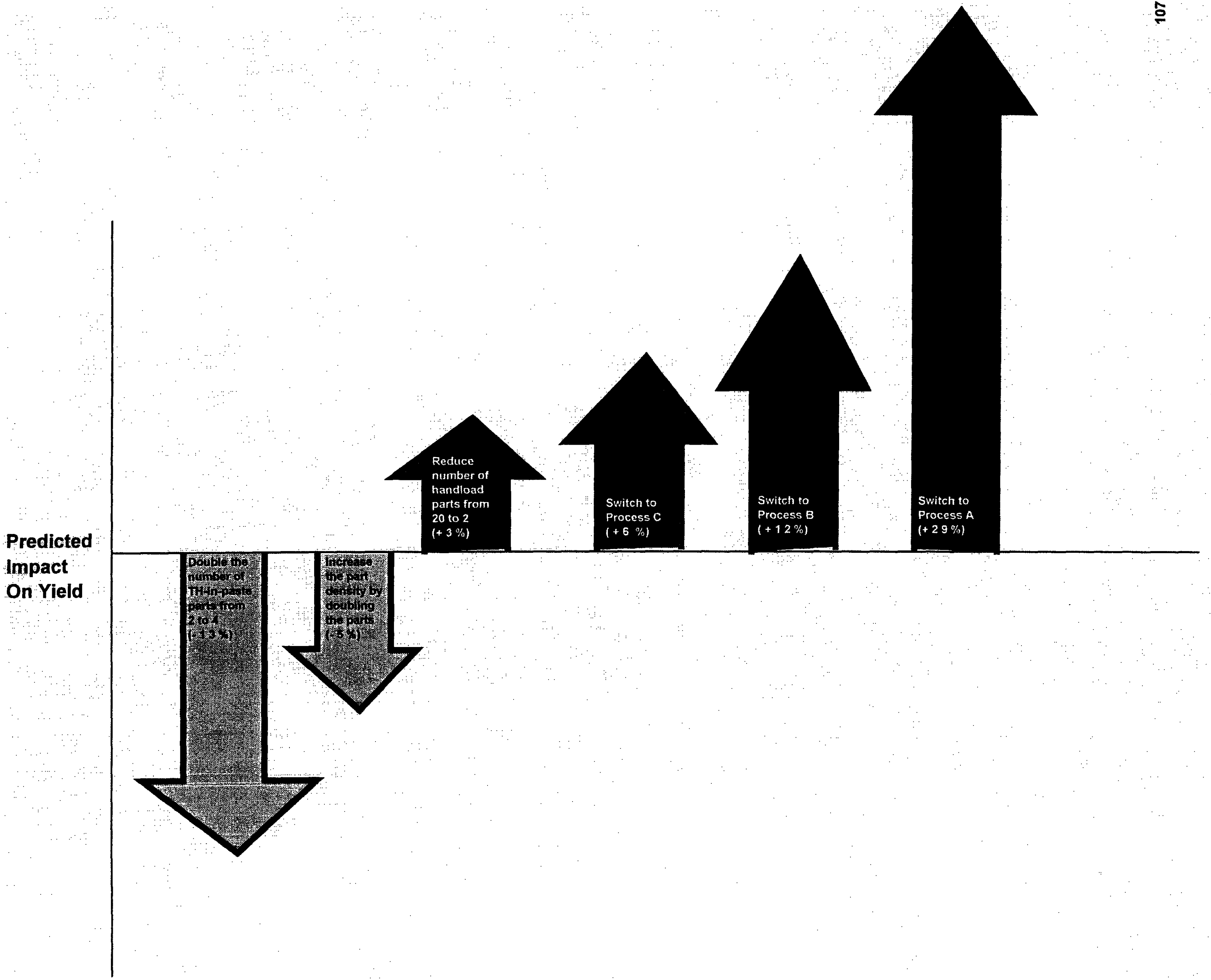


Exhibit 3 - Correlation table for Final Model Design Variables and Descriptive Statistics

CORRELATION TABLE

	Proc. D	Proc. C	Proc. A	Total # of Intercon. (log)	# HL/image	#TH B Side	Part Density (log)	#TH A Side	#FP A Side	6mo Bd Vol (log)	# parts on B side (log)	#FP B Side	Oversize Panel	Trace cutting	Part density / # FP A Side	Total number of parts	Customer	Line
Process D																		
Process C																		
Process A																		
# of Interconnects (LOG)																		
# HL/image				0.30														
#TH B Side				0.05	0.19													
Part Density (LOG)				0.40	-0.08	-0.22												
#TH A Side				0.28	0.39	0.18	-0.11											
#FP A Side				0.24	-0.09	0.03	-0.01	-0.13										
6mo Bd Vol (log)				-0.04	-0.13	-0.08	0.17	-0.12	-0.15									
# Parts B Side (LOG)				0.49	0.09	0.24	0.42	0.04	0.13	0.14								
#FP B Side				0.06	-0.04	0.30	0.12	-0.06	-0.04	-0.11	0.09							
Oversize Panel																		
Trace cutting required																		
Part density/#FP A Side				0.28	-0.09	0.04	0.08	-0.14	0.36	-0.12	0.21	-0.04	-0.18	0.07				
Total # of parts				0.70	0.45	0.04	0.40	0.46	-0.09	0.13	0.41	-0.02	0.13	0.00	-0.05			
Customer				0.09	-0.23	-0.09	-0.03	-0.20	0.13	0.11	0.06	-0.03	-0.12	-0.03	0.13	0.57		
Line				-0.20	0.21	0.21	-0.46	0.24	-0.13	0.01	-0.28	-0.02	0.83	-0.21	-0.13	-0.12	-0.11	

DESCRIPTIVE STATISTICS

	# of HL parts	part density	mo. Board Vol.	#FP A side
Average	43	5	587.89	1.67
Median	36	4	288.00	2.00
Minimum	1	1	60	0
Maximum	120	15	3374	28
Std. Dev.	30	3	674.84	5

	#TH A Side	#TH B Side	trace-cutting	oversize panel
Average	39	0.51	n/a	n/a
Median	30	0	n/a	n/a
Minimum	3	0	0	0
Maximum	118	4	1	1
Std. Dev.	28.22	0.617	n/a	n/a

	# interconnects	# parts B side	total # of parts	yield
Average	2588	148	395	61
Median	2279	51	287	63
Minimum	618	1	22	10
Maximum	6204	878	1346	99
Std. Dev.	1344.42	213.33	340	23.76

Exhibit 4 - Regression Results (with Customer variable)

SUMMARY RESULTS - ORIGINAL DATA PLUS CUSTOMER

Regression Statistics	
R Square	0.42
Adjusted R Square	0.33

	Coefficients	*t Stat*	*P-value*
Intercept	4.17	2.38	0.02
Process C	-0.14	-0.54	0.59
#TH B Side	-1.35	-3.55	0.00
# of Interconnects (log)	-1.21	-1.78	0.08
# Parts on B Side (log)	-0.40	-1.39	0.17
6mo Bd Vol (log)	0.34	1.14	0.26
Total # parts (log)	0.05	0.08	0.94
Customer	0.21	0.54	0.59

Exhibit 5 - Results with suspected interaction term

SUMMARY OUTPUT - INCLUDING SUSPECTED INTERACTION TERM

Regression Statistics	
R Square	0.73
Adjusted R Square	0.71

	Coeff.	*t Stat*	*P-value*
Intercept	6.58	10.15	0.00
Process D	-0.50	-1.91	0.06
Process A	0.52	2.91	0.00
Total # of Interconnects (LOG)	-1.60	-7.56	0.00
# HL/image	-0.01	-5.56	0.00
#TH B Side	-1.26	-4.15	0.00
Part Density (LOG)	-0.81	-2.63	0.01
Part density/#FP A Side	0.04	1.03	0.30

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