Printed Circuit Assembly Prototyping: An Analysis of Customer Requirements and Improvement Initiatives within Hewlett-Packard's Loveland Circuit Assembly Center

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Submitted to the Alfred P. Sloan School of Management and
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Abstract

The microelectronics industry is characterized by aggressive product introduction schedules, intense price based competition, and short product life cycles. Hewlett-Packard's (H-P) Loveland Circuit Assembly Center (LCAC) plays an important role in maintaining H-P's competitive advantage in several segments of the microelectronics market. LCAC provides printed circuit assembly (PCA) manufacturing and prototyping capacity for several business divisions of H-P. This consolidated approach to manufacturing PCAs provides considerable economies of scale, but it also creates difficulties in the integration of functional knowledge during the development of new PCA designs.

This thesis provides recommendations for improving the effectiveness of the PCA prototyping process through utilization of design review methodologies. These recommendations are determined based upon analysis of the customer requirements for PCA prototyping, examination of the current organizational and process structures, and review of the objectives and purposes of prototyping in general. As a manufacturing organization that provides prototyping services, LCAC needs to not only focus on the typical manufacturing metrics of cost, quality, delivery, and flexibility, but also on the design center need for information during the PCA development process. This information must be available to the design centers in a manner that allows it to be readily utilized to improve the competitiveness of the PCA designs.

Information availability and utilization are shown to be critical dimensions for success in providing PCA prototyping services from a consolidated manufacturing center. Therefore, design review methodologies that enhance information availability and utilization during PCA prototyping are recommended to improve the effectiveness of the process. Insights regarding the critical factors of the design review process are provided. The recommendations conclude with implementation guidelines for assuring that the customer needs are being addressed by the new design review initiatives.

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List of Acronyms

DFM/A	Design for Manufacturing/Assembly
EIG	Electronic Instrumentation Group
H-P	Hewlett-Packard
KJ	Kawakita, Jiro
LCAC	Loveland Circuit Assembly Center
LMC	Loveland Manufacturing Center
MIT	Massachusetts Institute of Technology
NPD	New Product Development
NPI	New Product Introduction
PCA	Printed Circuit Assembly
PCB	Printed Circuit Board
SDR	Strategic Design Review
SMT	Surface Mount Technology
TDR	Tactical Design Review

1. Introduction

Hewlett-Packard's (H-P) Loveland Circuit Assembly Center (LCAC) provides printed circuit assembly (PCA) manufacturing and prototyping services to 14 internal H-P business divisions. Economies of scale in technical resources and equipment utilization have led to an H-P organizational structure that requires several business divisions to share manufacturing capacity for capital intensive processes such as surface mount technology (SMT). (Beckman, 1995). LCAC is now the owner of the processes and the process knowledge associated with manufacturing and prototyping PCAs. A set of procedures has been established to satisfy the needs of LCAC's H-P divisions during the sustaining phase of the product life cycle and during the prototyping phase of the product life cycle. LCAC measures its performance based upon the manufacturing objectives of cost, quality, delivery, and flexibility. (Fine, Hax, 1985) The drivers for success in prototyping, however, are not necessarily identical to the drivers for success in sustaining production. Therefore, a separate organization devoted to improving the effectiveness of the PCA prototyping process was formed within LCAC. This organization is called the New Product Development (NPD) group.

1.1. The New Product Development Group Charter

Since its inception, NPD has made several improvements in the PCA prototyping services offered by LCAC. Delivery cycle times have been reduced by over 80%. Critical process steps have been identified and scrutinized for inefficiencies, and flexible, rapid methods for manual assembly have been developed to provide the design center customers with additional assembly options. Even with these improvements, however, there still seems to be a great deal of dissatisfaction among some design center customers regarding the PCA prototyping process. Some customers are sending their prototype designs to "garage" shops for manual assembly using solder wire and soldering irons. The nature of the H-P culture provides the business divisions with the autonomy to accomplish their objectives in the manner that the management of each division deems to be most effective. When the managers of the design projects do not utilize LCAC for PCA prototyping, LCAC misses a valuable opportunity to examine the design and provide manufacturability improvement feedback. Therefore, LCAC needs to improve their PCA prototyping process such that it provides the most value to the design center customers. If the LCAC process is the most valuable prototyping option, it will be the process of choice.

1.2. Requirements for Improving the Printed Circuit Assembly Prototyping Process

Improving the LCAC PCA prototyping process requires an understanding of three separate items:

- the purposes of prototyping,
- the requirements of the customers regarding prototyping,
- and the details of the PCA prototyping process as it currently exists.

Understanding the purposes of prototyping in general establishes basic understanding of the objectives served by the prototyping process. Understanding the requirements of a particular customer base builds upon this basic understanding to reveal the tacit details associated with specific types of product development efforts. Understanding the PCA prototyping process as it exists provides insight into the changes that can be affected to more closely align the process with the objectives and requirements of the customers. Understanding of these three issues allows improvement initiatives to proceed with a high degree of certainty that customer satisfaction will be enhanced.

This research examines these three issues in order to provide recommendations for improving the LCAC PCA prototyping process. The purposes of prototyping are explored through a review of published literature by authorities on the subject of product and process development. Customer requirements are developed and evaluated using established techniques for interviewing, for translating interview data, and for surveying. The details of the PCA prototyping process are presented through an examination of interview data, organizational structures, and the basic process steps and interactions necessary for delivery of the PCA prototype.

The recommendations presented are primarily concerned with improving the availability and utilization of information that is generated by the interaction of the LCAC process experts with each particular PCA design. The design center customers rely on this information to improve the competitiveness of their designs. If it is not widely available and easy to utilize, then it cannot impact the design during the later stages of ramp up and sustaining production. These recommendations are consistent with the notion that prototyping is different from production. In conjunction with the production metrics of cost, quality, delivery, and flexibility, information availability and utilization must be addressed as an area of potential competitive improvement during the PCA prototyping process.

1.3. Nature of this Thesis and Thesis Roadmap

This thesis is based on a six plus month internship sponsored by the Leaders for Manufacturing Program at MIT. Research was conducted at the H-P Loveland Manufacturing Center in Loveland, Colorado. At the start of the internship, the NPD group had improved the PCA prototyping process considerably during the previous year. In the face of these improvements, however, several customers were still expressing dissatisfaction with the process. Given the autonomous culture of the H-P business units, it was imperative that LCAC understand the needs of its customers and the areas in which it could make additional improvements to their PCA prototyping process. This understanding and these improvements would help ensure the long term viability of the services that LCAC provides for their customer base.

The purpose of the internship was to assimilate relevant information from several sources and develop a coherent set of recommendations for improvement. Presented in this thesis are the following:

- A literature review of published information relating to manufacturing measurements, objectives of prototyping, methodologies for determining customer requirements, and techniques for sharing functional knowledge across organization and geographical boundaries.

- An overview of the organizational and process structures that influence the delivery of PCA prototypes to the LCAC customer base.

- An explanation and details of the methods utilized to determine the customer requirements for PCA prototyping at LCAC.

- An analysis of the customer requirements and implications for action based upon these requirements and the existing organizational and process structures.

- Recommendations for improving the availability and utilization of LCAC knowledge through a series of design review methodologies. Included in these recommendations is an analysis of the critical factors of the design reviews and corresponding suggestions for implementation.

The information and the recommendations of this thesis provide a foundation for subsequent improvement initiatives to the PCA prototyping processes at LCAC. These results and the corresponding methodologies should be used as a starting point for a continuous process of evaluating customer requirements and changing the process to enhance the competitiveness of the enterprise.

2. Literature Review

This chapter is a review of published information from several sources that is relevant to developing improvement initiatives for PCA prototyping. A review of literature on measurements of performance for manufacturing is presented to provide insight into the dimensions upon which improvements in manufacturing are typically measured. An overview of the literature on the purposes of prototyping is presented to differentiate prototyping efforts from typical manufacturing operations. In conjunction with this information, a review of literature on typical problems encountered during the prototyping process is also presented. A considerable portion of this chapter is devoted to a review of methodologies for developing customer requirements. Finally, a review of literature relating to improving design and development efforts through design review methodologies is presented.

2.1. Performance Criteria in the Manufacturing Organization

Manufacturing has an important role to play in determining and executing plans that are consistent with the corporate strategy. Steven Wheelwright, in his article "Manufacturing Strategy: Defining the Missing Link," addresses the issue of formulating and executing a successful manufacturing strategy. (Wheelwright, 1984) Wheelwright claims that the manufacturing function cannot be considered as a neutral element without any potential to enhance the competitive position of the enterprise. It has an extremely important role to fulfill as a communicator of philosophy and culture. Manufacturing is a "keeper" of the corporate culture in most enterprises because the majority of the workforce is in the manufacturing function. Execution of policies and practices that are consistent with the strategy of the corporation is critical. Good planning and execution on the part of the manufacturing function will help establish sustainable success in the markets in which the firm competes.

Fine and Hax claim that manufacturing objectives can typically be articulated in terms of four major dimensions of performance: cost, quality, delivery, and flexibility. (Fine, Hax 1985) A pattern of decisions regarding these measurements establishes a tone for the efforts of the manufacturing function over time. An examination of the components of these typical performance criteria provides some insight into the tensions that exist among them.

Cost:

Cost drivers for manufacturing include labor, material, capital asset utilization, and inventory turnover. A cost intensive strategy seeks to minimize the labor and material costs of the product while maximizing utilization of equipment. This typically corresponds to a high volume/low diversity product line with long runs and minimal interruptions of production.

Quality

Quality is typically measured in terms of a defect level, product reliability, and an ability to deliver features/performance that is not matched in competing products. A quality intensive strategy will emphasize process capabilities and attention to the characteristics of the product that differentiate it from the competition.

Delivery

Delivery is the ability of manufacturing to produce outputs in a timely fashion that is responsive to the needs of the customer with a minimum of variation. A strategy that emphasizes delivery capability will be characterized by high resource availability and processes for rapid mobilization of those resources.

Flexibility

Flexibility can be measured in terms of the variety of the product mix, the level of production volumes, and the response rate to changes in mix and volume. A high level of flexibility requires highly mobile resources that can be utilized to accomplish a wide variety of processing tasks.

It is impossible to maximize all of these measurements in an absolute sense. Instead, a direction must be established that emphasizes certain dimensions. After these "strategic" dimensions are established as the most important, the others can be optimized within a constraint set that does not compromise the strategy of the corporation. In this manner, the manufacturing function becomes an integral component of the corporation's efforts to sustain its competitiveness through a focused strategy.

2.2. Prototyping Guidelines

Eppinger and Ulrich define a prototype as "an approximation of the product along one or more dimensions of interest." (Eppinger, Ulrich, 1994) Any tool or artifact that approximates some characteristics of the ultimate product and helps the development team understand the impact of these characteristics is a prototype under this definition. Eppinger and Ulrich provide insight into the purposes of prototyping.

2.2.1. Purposes of Prototyping

Prototypes serve as mechanisms for learning, communication, integration, and milestone achievement. (Eppinger, Ulrich, 1994)

Learning

Learning is achieved when the prototype provides information to the design team regarding the functionality of the proposed design relative to the needs of the customer. This information can be used to tune particular design characteristics or add new features to make the design more capable of meeting the customer's needs.

Communication

Prototypes serve as a communication medium based upon the adage that "a picture is worth a thousand words." If the cliché holds true, then hardware, or physical prototypes, are probably worth millions of words. Customers, suppliers, top management, and financial backers can all respond much more explicitly to something that can be held or viewed as opposed to verbal and written descriptions.

Integration

For complex products, integration becomes a serious issue as the development of a product proceeds closer to actual production. While advanced computer design systems are becoming more capable of evaluating integration issues, it is often the case that integration must be evaluated by building and assembling hardware. This process is a reality check for the validity of the assumptions of all the different members of the product development team regarding tolerances and component interconnection.

Milestones

Finally, prototypes are often used to measure progress of the development project. This is accomplished by establishing the delivery of a prototype as a milestone. Failure to deliver particular prototypes at certain points in the schedule serves as a warning flag that problems have developed that cannot be easily resolved. This "red flag" can be the impetus for management action to determine the future direction for the development efforts.

When planning prototyping efforts, the development team should identify the purposes the prototypes are intended to serve, and what types of prototypes might best meet those purposes. By utilizing this type of planning methodology, the value of the various prototypes to the development effort will be greatly increased. Also, the cost and effort expended on the prototyping process can be greatly reduced.

2.2.3. Prototyping Problems

Clausing identifies a few of the costly traps that can be associated with prototyping. (Clausing, 1994). One "cash drain" associated with prototyping is the "Pretend Design." Designs that strive to be "new and different" without any regard for the actual production processes that must ultimately deliver the product to the customer are "pretend designs." Clausing claims that designs that lack production intent as one of their inputs lead to an attitude, "Oh well, this is just the first design -- we'll fix this later." Designs of this nature tend to lead to excessive prototyping until a design that can be built by manufacturing is prototyped, and this last iteration becomes the final design. Clausing exhorts that "producibility and competitive superiority must be designed in from the beginning."

Slightly different, but closely tied to the "pretend design" concept is the cash drain Clausing labels as "Hardware Swamps." These "swamps" occur when prototypes proliferate without serving any particular purpose to the development team. This trap can be avoided by planning the prototypes with regard to the purpose and type that will best achieve the goals at particular phases of the development effort. By planning the prototypes such that functionality is optimized with accurate information at appropriate points in the project, the occurrence of hardware swamps will be greatly reduced.

2.2.4. Summary of Prototyping Guidelines

The prototyping process can play an extremely important role in determining the success of the product in the market. In order for this objective to be achieved, however, the prototyping process must be carefully thought out and executed to maximize the returns of useful information to the development team. Without this planning and coordination, prototyping can become a drain on the organization that leads to further drains in the form of uncompetitive products being sustained through costly delivery to the market.

2.3. Determining Customer Requirements

Development or improvement of a product should begin with determination of the customer needs. In this context, "product" simply refers to a particular solution. A product can be a material item, a process or service, or a combination of these. Mountains of literature exists on how to determine customer requirements for development of new products. An extensive review of all of the literature is not necessary to develop a usable framework of the main themes important for this research. Only a sample of a few relevant authors is reviewed.

2.3.1. Interaction with Customers

Several authors emphasize the necessity of interaction with a customer group to gain insight into the customer's experience with the product. (Eppinger, Ulrich, 1994) (Clausing, 1994) (Shiba, et. al., 1993) These interactions can take the form of focus groups, interviews, field calls for repairs, or simply watching a customer use the product. This initial set of interactions should lead to an extensive list of customer needs regarding the particular product that is being developed or improved. The amount of interaction required to be confident that no important needs have been overlooked is a function of the complexity of the product and its relationship to the customers. Griffin and Hauser's research proves that a correlation exists between the time spent in interviews with the customer and the percentage of total needs that are revealed to the development group. (Griffin, Hauser, 1993) As a general guideline for most products, 25 to 50 hours of data collection with the customers is probably sufficient to reveal the vast majority of the needs.

2.3.2. Structure of the Interaction with Customers

The structure of the interaction with the customers is critical. It is important to develop an understanding of the use environment for the product while also constructing a clear set of customer needs. In *A New American TQM: Four Practical Revolutions in Management*, Shiba stresses the necessity for the customer to describe images of using the product. An image might not involve the product specifically. Instead, it might be a descriptive corollary that defines the customer's feelings when contemplating interaction with the product. For example, an image that might come to a customer's mind when he contemplates a tap for a keg of beer is one of a group of people at a barbecue. Another less positive image for the same product might be one of a sticky mess on the floor after a particularly raucous party. Beyond gathering images, Shiba recommends that customer voices be gathered with a weakness orientation. Interview questions that focus on the weaknesses of a product reveal more information based upon the theory that customers can often remember unsatisfactory elements of a product much more vividly than positive elements. While this is probably true, it cannot hurt to inquire regarding the strengths of a product as well. In *Product Design and Development*, Eppinger and Ulrich provide a set of potential questions for voice of the customer interviews that include weakness and strength orientations. Other lines of questioning that can prove valuable are those regarding the nature of the purchase decision and postulation about future requirements.

It is important for the interviewer to avoid any bias during the interview regarding particular features or solutions that may be presented by the customer. Eppinger and Ulrich recommend that the interviewer respond to a discussion of features with probing questions that uncover the underlying need that a particular feature addresses. Creativity in satisfying the customer's real needs may be stifled if the needs are not formulated in a manner that is independent of particular features. Eppinger and Ulrich also stress the need to "go with the flow." Let the customer talk about the things that are important to him. The goal of the interview is to discover interesting stuff, not to complete the interview template in a particular amount of time.

2.3.3. Refining Customer Data for Surveys

In *Total Quality Development: A Step-by-Step Guide to World-Class Concurrent Engineering,* Clausing defines "scrubbing" as the process of developing clarity for the need statements and establishing the correct level of abstraction for these statements. If the interaction data is gathered in a manner consistent with the guidelines above, further refinement or "scrubbing" of the customer voices is a less difficult chore. Eppinger and Ulrich provide some guidelines for establishing clarity that include expressing the need in terms of product performance and avoiding the words "must" and "should" in the need statements. (Eppinger, Ulrich, 1994) Expressing the need in terms of product performance facilitates developing product specifications during later steps in the process. Avoiding "must" and "should" ensures that no bias regarding the importance of particular needs is documented in the need statements. Duplications are removed during this stage, and similar statements are grouped together. Often a higher-level statement that adequately describes the need of these statements can be developed to simplify the logistics of dealing with too many need statements. It is inevitable that too many needs will exist, and some will have to be eliminated to avoid bogging the subsequent processes down. Clausing recommends selecting about 15 to 30 significant needs to carry forward to the next stages of the process. (Clausing, 1994)

2.3.4. Determining Priority of Needs through Surveys

The next step in the process is to understand the relative importance of the needs that have been documented. A customer survey methodology is probably the most accurate way to assess the importance of the needs that remain for further evaluation. Shiba recommends a Kano questionnaire methodology whereby the requirements are assessed as one of four basic types: one dimensional, attractive, must be, and indifferent. (Shiba, et. al., 1993)

One dimensional requirements are characterized by a "more is better" attitude. Gas mileage for a car is a one dimensional customer requirement. Attractive requirements are characterized by a "nice to have, but not necessary" attitude. Power door locks for a car might be an attractive requirement for many car customers. Must be requirements are characterized by a "must be that way" attitude. The requirement that an employee's paycheck consistently arrive on pay day is a "must be" type requirement. "Indifferent" requirements indicate that no additional satisfaction will be obtained by satisfying that particular customer need. By asking respondents to label their feelings if a requirement is satisfied, and by also asking them to label their feelings if that same requirement is not satisfied, the requirement can be classified into one of the above categories. Illustrated below in Figure 2.1 is an example of the Kano question formats and the matrix that is utilized to determine the requirement type based upon the responses. A plot of Kano's hypothesis is presented below in Figure 2.2. This plot illustrates the mapping of customer needs on a perceptual map with product functionality and customer satisfaction as the primary axes.

If the water drains quickly out of the stripping basket, how do you feel?	1. I like it that way. 2. It must be that way. 3. I am neutral. 4. I can live with it that way. 5. I dislike it that way.
If the water drains slowly out of the stripping basket, how do you feel?	1. I like it that way. 2. It must be that way. 3. I am neutral. 4. I can live with it that way. 5. I dislike it that way.

Customer requirements → ↓		Dysfunctional				
		1. like	2. must-be	3. neutral	4. live with	5. dislike
Functional	1. like	Q	A	A	A	O
	2. must-be	R	I	I	I	M
	3. neutral	R	I	I	I	M
	4. live with	R	I	I	I	M
	5. dislike	R	R	R	R	Q

Customer requirement is

A: Attractive O: One-dimensional
M: Must-be Q: Questionable result
R: Reverse I: Indifferent

Figure 2.1: Matrix Analysis Technique for Kano Questionnaire (from Shiba, et. al. 1993)

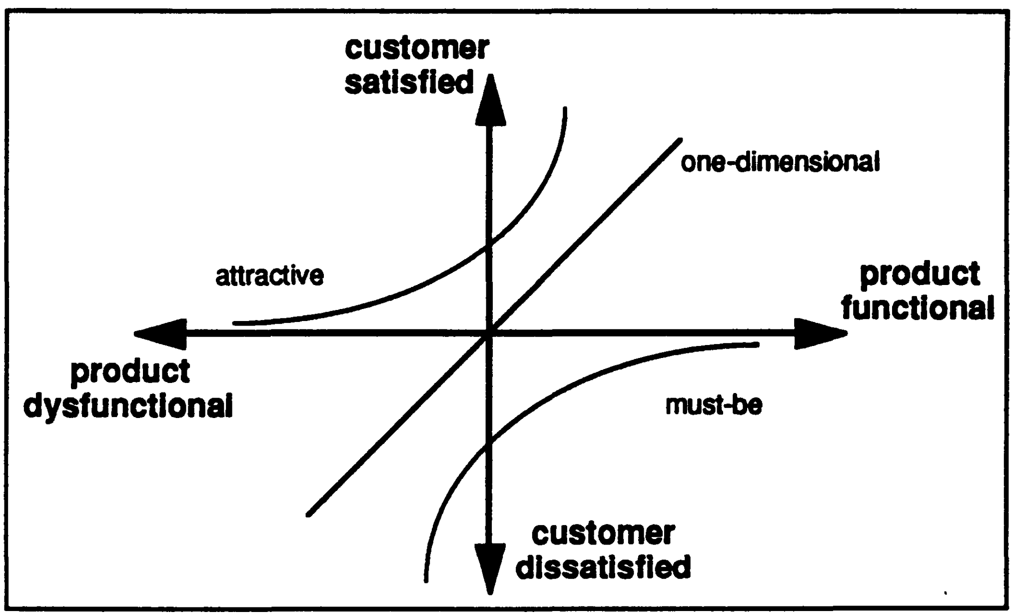

Figure 2.2: Graphical Representation of Kano's Hypothesis (from Shiba, et. al., 1993)

Clausing recommends the use of an importance survey in conjunction with the Kano analysis. (Clausing, 1994) The importance survey provides additional data to the development team regarding the hierarchy that should exist among the various needs. Utilizing the Kano methodology alone, two one dimensional requirements might be given the same amount of attention, when in fact one of the two is significantly more important to the customer. Within the importance survey, customers are simply asked to rank the importance of a particular requirement relative to a given importance scale. In this manner, a importance hierarchy is established among the various requirements.

2.3.5. Summary for Determining Customer Requirements

The main objective of gathering the customer information is to understand and internalize the customer's viewpoint. Once this is accomplished, it is possible to determine project and organizational objectives for the product (or process) that is being developed or improved upon. Without this insight, actions and initiatives within the organization will tend to serve the needs of the organization instead of the needs of the customers. These "organization serving" actions and initiatives will probably not result in any significant increase in customer satisfaction.

2.4. PCA Prototyping Strategic Design Reviews

The literature reviewed below on the development of design review procedures[1] addresses four main issues that dictate the nature and the necessity of the review process. These four issues are:

- lack of definition and structure for knowledge
- benefits of sharing process knowledge in a design review
- development of tools for effective knowledge sharing during the review
- timing of the review

The literature regarding the lack of definition and structure for knowledge is common to all development efforts. The literature on the benefits of knowledge sharing, on development of tools for knowledge sharing, and on timing of the knowledge review are all particular to the development process for PCAs.

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[1]A design review is any structured interaction among designers and downstream functions or customers that occurs as a milestone in the development of a new product or system. The review typically serves to ensure that the characteristics of the design are aligned with the needs of the downstream functions or the customers.

2.4.1. Lack of Definition and Structure for Knowledge

Thomas A. Stewart, in a cover story for *Fortune* magazine entitled "Your Company's Most Valuable Asset: Intellectual Capital," provides many compelling examples of the unmeasurable but highly valuable nature of knowledge within the corporation. (Stewart, 1994) Stewart refers to this knowledge as "intellectual capital," and he solicits many opinions and frameworks from experts in knowledge intensive industries. These experts comment on the qualities and characteristics of intellectual capital. Managers within corporations such as Dow Chemical and Hughes Space & Communications are striving to develop systems and procedures that will extract maximum value from company knowledge in the form of more competitive processes and products. The forms that the impending systems and procedures take is highly dependent on the characteristics of the intellectual capital that is to be utilized within the corporation.

Within the Stewart article, Arian Ward, a business engineering leader at Hughes, provides a useful framework for understanding the characteristics of knowledge within the organization. Ward claims that "islands of knowledge" are developed as a result of studies and projects. These islands do not necessarily contribute to an optimum corporate solution for many recurring or similar problems because no "bridges" are readily available to link the islands together. These bridges can take several forms. However, for the bridge to be optimal for sharing and utilizing knowledge, the nature, or type of the knowledge to be shared must be considered. While noting that several types of knowledge probably exist, Ward describes two of these: rules based and unstructured.

Rules based knowledge yields an algorithm for generating the correct answer by following a set of procedures that are accepted as optimum for a specific problem. Knowledge of this type is subject to automation through computer hardware and software. The fields of computer aided engineering and manufacturing rely heavily on structured knowledge for delivering productivity solutions to designers and development teams.

Unstructured knowledge, by contrast, is much more difficult to quantify into expert systems of hardware and software because the correct answer varies based upon the context of the problem. Ward explains that this knowledge takes the form of "wisdom, experience, and stories, not rules." This unstructured knowledge can deliver tangible improvements when applied. However, formalized tools for exploiting the advantages to be yielded by this knowledge are difficult to develop. The primary concern for the managers seeking to benefit from this knowledge sharing is dealing with the relationships that must exist for the intellectual content of the corporation to flow in a timely and effective manner into the areas that are in need of it. This flow can be inhibited by the culture and structure of the organization. Getting people to talk and to share effectively across projects and functions is essential if benefits of unstructured knowledge are to be realized. As Ward explains, "People think in terms of stories, not facts."

2.4.2. Benefits of Sharing Process Knowledge in Design Reviews

The primary benefits of sharing manufacturing process knowledge in the form of a design review are improved communication and lower costs. These are described separately rather than in a relational manner because communication has competitive dimensions beyond the implications of definable cost structures. All of the economics of cost, such as the cost of sub-optimal creativity and delays in product introductions, cannot be easily quantified. Therefore, cost and communication issues are examined as separate, but related, opportunities for improvement by utilizing a design review procedure.

2.4.2.1. Improvements in Communication

The design review addresses the issue of communication of unstructured knowledge across the various functions of the organization that must interact to deliver a competitive PCA product. Tucker Garrison and John Stobaugh of IBM-Austin provide a framework related to PCA assembly processes similar to Ward's more general framework. (Garrison, Stobaugh, 1992) Garrison and Stobaugh explain that SMT and PCA assembly technologies and microelectronic designs are so dynamic that it is impossible to develop a comprehensive set of rules that can be embedded into a usable, automated software algorithm. By the time such an algorithm could be developed and encoded, the assumptions and technologies that it would be based upon would be obsolete. They further claim that developing and using this type of rigid, rule based system would result in a "going out of business plan." A system is needed that can respond quickly to new information, but still provides valuable insights into design and manufacturability tradeoffs during the design process. This system or set of procedures would have as its primary goal the achievement of highly manufacturable PCA designs through communication of manufacturability issues to the design community early in the design cycle. Some of the formats and mechanisms that Garrison, Stobaugh, and others at IBM recommend for this communication are reviewed below in section 2.4.3., Developing Tools for Effective Knowledge Sharing.

2.4.2.2. Improvements in Costs

The nature of the costs of PCAs also provides a convincing argument for developing an effective design review procedure. Happy Holden of Hewlett-Packard Co. and Larry Kenyon of Mitron Corp. provide some cost estimates that indicate a healthy potential payback for establishing procedures that effectively leverage manufacturing knowledge early in the design process. (Holden, Kenyon, 1994) Holden and Kenyon reference benchmarking and case studies that indicate a potential 35% improvement in assembly costs when Design for Manufacturing/Assembly (DFM/A) methods are utilized in development of PCA designs. Holden and Kenyon further claim that 75% of the manufacturing costs of any product are determined when the design drawings and specifications for the product are complete. For PCAs, the vast portion of the costs are determined even earlier than the release of the drawings and specifications. When only 35% of the design budget for a PCA has been expended, 60% of the manufacturing costs of that PCA design have already been determined. Therefore, it is imperative that manufacturing knowledge for PCAs be injected early and effectively into the design process. Without this early involvement, the potential for delivering a lower cost PCA product to the market is reduced considerably.

2.4.3. Developing Tools for Effective Knowledge Sharing

In developing a design review procedure, two issues should be considered: translation of manufacturing knowledge into metrics and presentation of these metrics in a useful framework for communication. The drivers of manufacturing cost should be determined and related to the design features of the PCAs in the form of manufacturability metrics. These metric's impact on a particular PCA design should then be presented to the design team in a methodical, effective manner.

2.4.3.1. Translating Knowledge into Manufacturability Metrics

Hume, Komm, and Garrison describe a system at IBM-Austin that incorporates existing quality and process data into a set of metrics for evaluating PCA designs for manufacturability. (Hume, et. al, 1992) They present ten areas that significantly affect the manufacturing quality and cost of a PCA design. These ten areas were determined by failure analysis of field failures and downstream subassembly failures. Assembly and test process information from the PCA assembly and test areas was also utilized. The PCA design is "graded" in the ten areas. These "grades" can be considered as the manufacturability metrics that form a basis for estimating the quality and cost of a PCA design prior to actually assembling the design and measuring the resulting quality and cost. Hume, Komm, and Garrison stress that the basis for these metrics should continually be examined and updated based upon new information that is generated by ongoing failure analysis and process evaluation.

2.4.3.2. Developing Communication Tools

The second issue that must be considered when developing a design review procedure is the form of the communication tools. The information that determines the basis of the design review has been assembled, but it must be incorporated into a useful format for review with the design community. Holden and Kenyon indicate that traditional concurrent engineering efforts that co-locate experienced manufacturing personnel with the design team often fail. (Holden, Kenyon, 1994) The failure of these efforts is driven by the increasing rarity of experienced manufacturing personnel, by the distances that often separate manufacturing facilities from design team locations, and by the delivery of manufacturing knowledge in an informal, opinionated manner that is difficult to defend.

Holden and Kenyon further claim that multiple functional experts are needed for PCA design reviews because designer suspicion of functional sub-optimization can undermine the best intentions of the various manufacturing experts. If optimizing for assembly sub-optimizes the manufacture of the bare printed circuit board (PCB) substrate, then the total system cost might be higher than if no review took place at all. The design review procedure must incorporate communication from all manufacturing areas that are involved in delivery of the PCA. All areas of the manufacturing community must converge upon a useful framework that incorporates and prioritizes all of the manufacturing issues. This framework should be explicit in the nature of the underlying assumptions so that the design community will recognize the thoroughness of the effort that was utilized to develop it.

Finally, the form that the framework takes should facilitate discussion of alternatives for the PCA design relative to a scoring system. This scoring system should be based upon the above mentioned prioritization of manufacturing issues. Hume, Komm, and Garrison recommend a matrix format that multiplies a rating or "grade" for the design in a particular area by the prioritized importance of that area. (Hume, et. al., 1992) These multiples are then summed to determine a final score for the PCA design. In this manner, several scenarios can be evaluated within the matrix utilizing a set of non-dimensional scores.

2.4.4. Timing of the Review

As indicated by the work of Holden and Kenyon, the timing of the design review for PCA designs is critical. (Holden, Kenyon, 1994) Further documentation of the necessity for early assessment of manufacturability for PCA designs is provided by Glen Davis of Hayes Microcomputer Products and by Judy Hume, Richard Komm, and Tucker Garrison of IBM-Austin. In an article in *Printed Circuit Design* entitled "Concurrent Engineering: Teamwork Eases a Product's Journey from Concept to Manufacture," Davis establishes some guidelines for effective PCA design reviews. (Davis, 1993)

The first guideline that Davis stresses is conducting the design review prior to the upload of the circuitry information into a CAD system. Design changes that occur after CAD interconnection of components are expensive and time consuming to incorporate. Also, budget and schedule constraints become much more pronounced during the later phases of the design process when actual expenditures of time and money are hovering very near their planned amounts. Hume, Komm, and Tucker echo this advice in their paper entitled "Design Report Card: A Method for Measuring Design For Manufacturability." They recommend that the PCA design be reviewed prior to the development of an exact or frozen bill of materials. In this manner, key tradeoffs involving the component selection and the physical layout of these components within the PCA design are addressed when changes can be incorporated at a minimum of cost in time and money. Manufacturing issues become secondary to designers when schedule constraints begin to squeeze the team for completion of a particular project.

2.5. Printed Circuit Assembly Prototyping Tactical Design Reviews

Richard F. Dominach of AT&T Bell Laboratories provides an example of how late stage tactical issues can be resolved quickly and effectively utilizing design for manufacture and conferencing software. (Dominach, 1994) The issues discussed above for inclusion in the early design review are strategic manufacturing issues. Issues that arise after the design has been uploaded into a CAD format are tactical manufacturing issues. These issues include discrepancies in the part definitions for new parts, mismatches between component footprint and printed circuit pads due to rotation or pin discrepancies, or other interferences that were not taken into account during the automated rule checking stages. Resolving these tactical issues quickly and effectively is extremely important. As mentioned previously, the later stages of the development process are characterized by high levels of budget and schedule pressure.

In an *IEEE Spectrum* article entitled "Design Reviews at a Distance," Dominach describes a situation where geographically dispersed PCA designers and manufacturers can share information and resolve problems in a real time manner. With the component layout and

CAD design determined, the participants in the design review share a common file image on their screens and work through the design difficulties utilizing standard phone lines for communication. Because the system uses low bandwidth communication transmission, only the host station can make alterations to the file. However, a mirror image of all changes appears on the remote station's screen. Problems can be resolved quickly because the visual nature of the description process enhances understanding for both parties. If the problem cannot be fully solved during the initial conference, action items and follow up conferences can be scheduled to finalize a solution. This type of on-line, interactive problem solving is much more effective than mailing drawings and notes between the affected parties and hoping that the problem was understood well enough to obtain resolution. On-line conferencing with shared visual files improves the level of teamwork, and it reduces the design cycle and the number of problem solving iterations. A graphical representation of the process is provided in Figure 2.3 below.

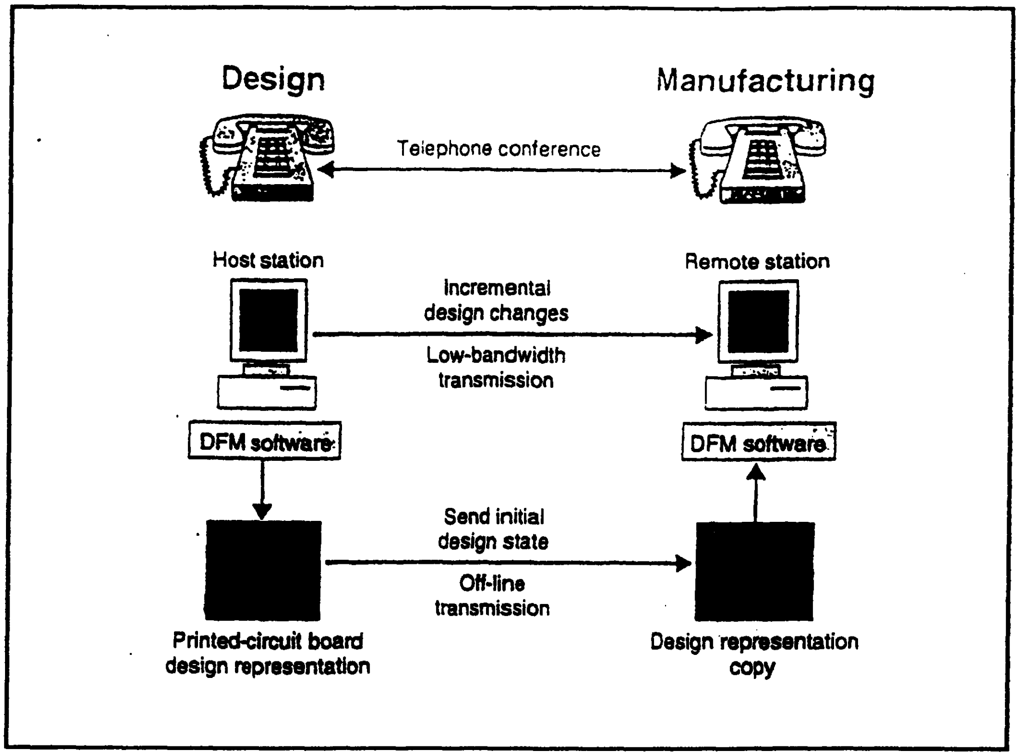

Figure 2.3: Graphical Representation of PCA Tactical Design Review System (Dominach, 1994)

2.6. Summary of Key Items from Literature Review

A review of literature regarding improving the effectiveness of prototyping describes several key items. First, the strategies of the corporation require the manufacturing function to evaluate and execute plans for production and prototyping that serve the customers of these services effectively. For production efforts, tradeoffs among cost, quality, delivery, and flexibility are established in a manner that is consistent with the needs of the corporation and its customers. Similarly, prototyping efforts should address the purposes to be served by building prototypes. At a high level, these purposes include learning, communication, integration, and milestone achievement.

Second, to determine more specific needs for particular prototyping efforts, the customers of the process should be solicited for information regarding their specific needs. Interactions with the customers to determine customer requirements is a topic that has received a great deal of attention by many authors. The steps for effective establishment of customer requirements are well documented within the literature.

Finally, the design review is described as a method for integrating knowledge across geographical and organizational boundaries. Techniques, methodologies, and computer systems are presented as potential solutions for integrating the expertise of several functional groups operating at separate locations. These design reviews are shown to facilitate improvements in the cost competitiveness of new designs while improving the communication ties among the various participants in the process.

3. Organization and Process Structures

This chapter provides an overview of the H-P organization and the process structures for PCA prototyping. Information is provided on the evolution of the organization and process structures, and the economic and cultural influences that continue to shape the organization and the PCA prototyping process are described. A design structure matrix is utilized to describe the interactions that must occur during PCA prototyping efforts, and a brief description of SMT processes is provided to establish the nature of the production technologies at LCAC. Finally, an image KJ entitled "What are the Images of PCA Prototyping" provides a graphical description of the operating environment in which PCA prototyping occurs. These details highlight the challenge of integrating knowledge and effort across geographical and organizational boundaries.

3.1. Hewlett-Packard Corporate Organization Structure

Figure 3.1 is a representation of the organization structure of H-P during the latter half of 1994. Figure 3.1 is not complete in detail for all of the H-P organization, but it is representative of all of the relationships that exist among the Loveland Manufacturing Center (LMC) and its H-P customer base.

At the highest level, H-P is divided into *organizations* such as the Test and Measurement Organization and the Computer Systems Organization. These are organized to capitalize on synergies among the products, customers, strategies, and functions of the member entities. Additional segregation occurs at the *group* level of H-P. Within each *organization* there exists several *groups* whose members have even closer ties among customers and products than at the *organization* level. Examples of these *groups* include the Electronic Instruments Group (EIG) and the Analytical Products Group. Within these *groups* are various business divisions and functional centers that perform the majority of the business and functional tasks required to serve a particular market segment. LMC is a functional center for manufacturing within the EIG. Each of the other divisions that are listed is served by LMC with printed circuit assembly and other manufacturing services for their products. These PCA assembly services include both production and prototyping capacity. This consolidation of manufacturing capacity within LMC is a result of economic factors associated with SMT processes. The high capital and technical support cost of SMT processes requires high utilization of the equipment and technical resources for an

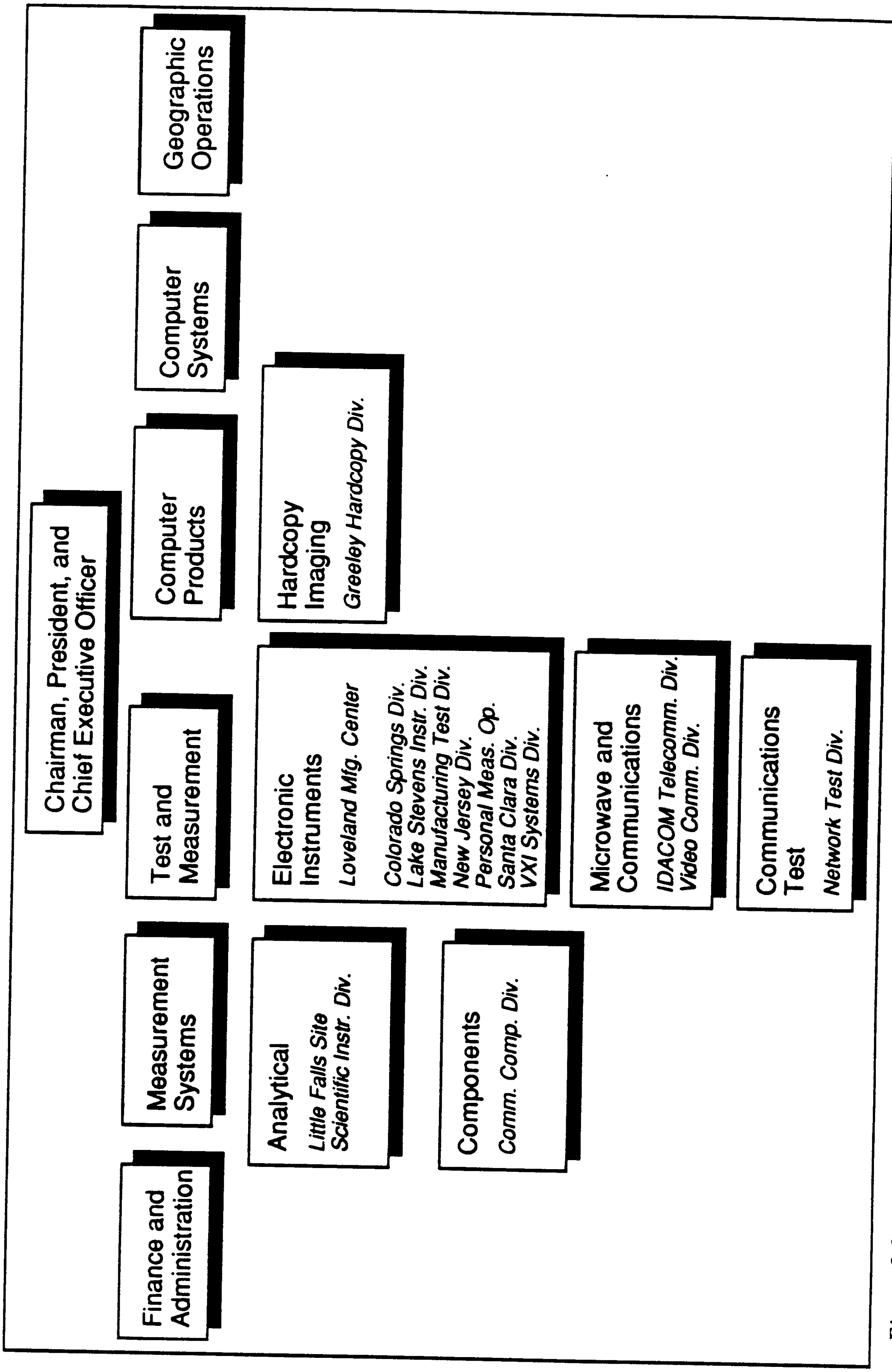

Figure 3.1: Hewlett-Packard Corporate Organization, 1994

acceptable return on investment to be achieved. (Beckman, 1995) Prior to SMT, most divisions within H-P had through hole assembly operations. For the corporation to realize acceptable returns on SMT, these divisions now have to share SMT assembly capacity.

3.1.1. Hewlett-Packard Loveland Manufacturing Center Organization Structure

Figure 3.2 represents the structure within LMC for providing printed circuit assembly services to the customer base. LCAC is the entity within LMC that has responsibility for all PCA assembly. It consists of four primary functional groups: New Product Development, LCAC Engineering, LCAC Production, and Materials Engineering.

The NPD group is responsible for coordinating the logistics of delivery and performing the actual assembly for prototype PCAs. This group consists of various technicians, assembly operators, and logistics coordinators. The technicians are responsible for programming the SMT equipment, and they also provide support to the operators for problem resolution. The assembly operators are responsible for the assembly of the PCA prototypes. The coordinators are the focal point for all information that travels between LCAC and the design center customers. The NPD group was formed in 1993 to address the trend in PCA proliferation among LMC's customer base. Many of LMC's customers market custom and semi-custom systems. Each time a sale is made, there is a high probability that a new PCA will be introduced to accommodate the needs of that customer. The number of prototypes that LCAC was required to deliver in the period from 1992 - 1993 grew exponentially. The NPD group was formed to address the increasingly complex logistics of coordinating this large number of prototyping cycles. By providing dedicated resources and a focal point for interaction with the customers, the NPD group has had good success in streamlining the process and improving delivery performance for PCA prototypes.

LCAC Engineering is responsible for technical support of the assembly processes for PCAs. The engineers in this group also serve as consultants for manufacturing issues during new product introductions. These engineers are process and new product introduction (NPI) engineers. This dual role is necessary in order to maintain effectiveness in both process development and NPI consulting. Through their NPI consulting efforts, the engineers at LCAC develop understanding of designer needs for new process capabilities. This allows them to target their process development efforts in a manner consistent with the projected needs of the customers. Similarly, active participation in assembly process development and support enables the LCAC engineers to communicate

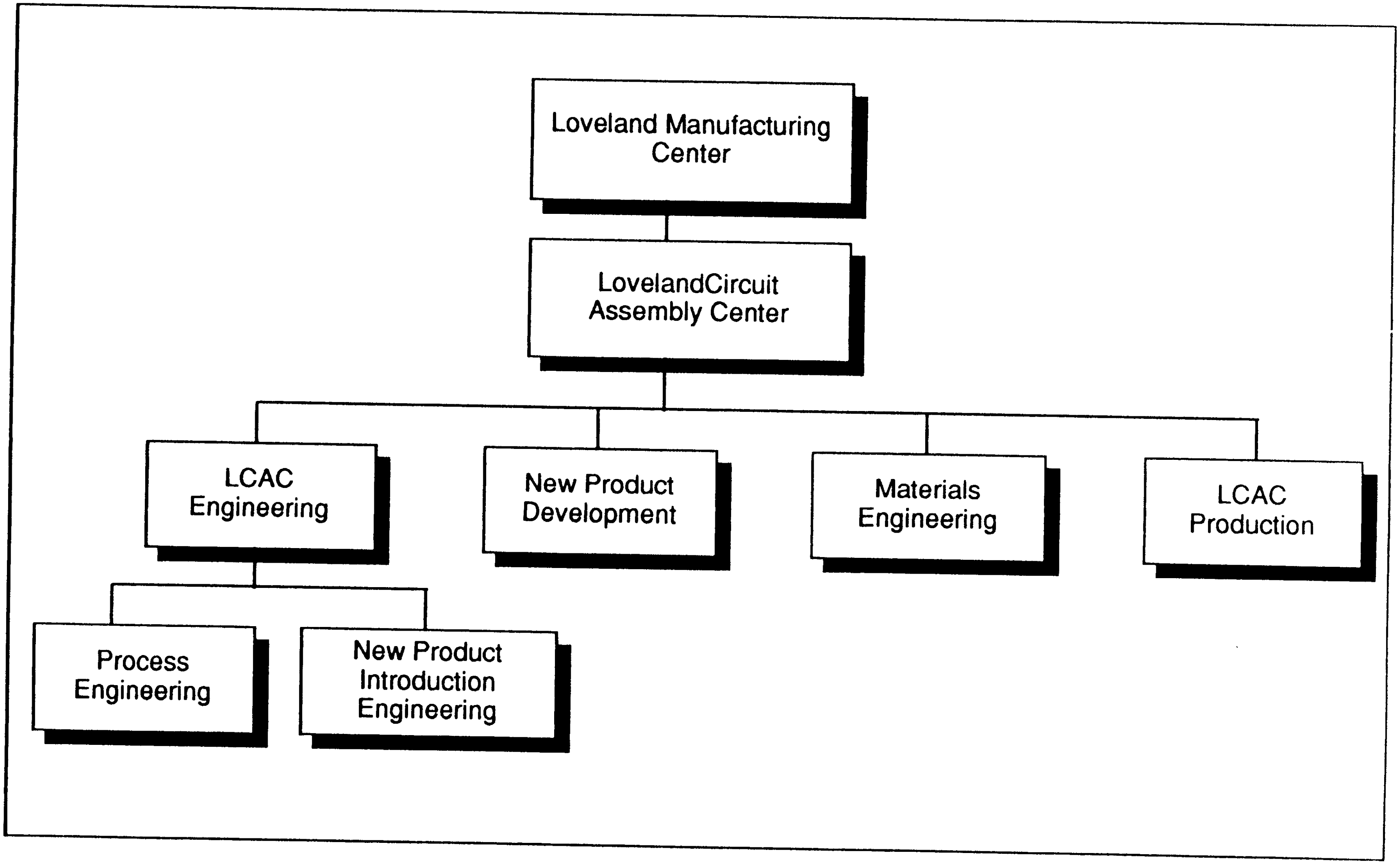

Figure 3.2: Loveland Manufacturing Center/LCAC Organization, 1994

the capabilities of the existing processes to the design engineers. The activities required by these two roles facilitates LCAC engineering effectiveness.

The largest group at LCAC is the production group that is responsible for assembling all of the production PCAs for the various business divisions. This group consists of all of the technicians, operators, engineers, and managers necessary to maintain and execute the requirements of production.

Materials Engineering is a strategic procurement group that evaluates alternatives for components and suppliers. Because a large percentage of the cost of a PCA is material and component costs[2], this group has an extremely important role to play in determining the competitiveness of LCAC.

Although the organizational entities within LCAC are presented separately, there is a great deal of interaction among these groups. They are all co-located within the same facility, and they rely on each other to perform their various tasks for the customers. The primary focus of this research is the NPD group and the NPI engineers. These two groups have primary responsibility at LCAC for ensuring customer satisfaction with the prototyping process.

3.2. Printed Circuit Assembly Prototyping Process Structure at LCAC

Currently, when the business divisions served by LCAC are developing products that incorporate PCAs, the prototype design is evaluated by acquiring prototype PCAs from LCAC. These PCAs are used to evaluate the electrical functionality of the board as well as the mechanical characteristics[3] important to the final product performance. Detailed below are the characteristics of the interactions that occur between the customers, or design centers, and LCAC during the development of a new PCA design. For clarity, a brief overview of the development process is provided first. Following the overview are details of LCAC's scope of involvement within this process. The potential for variation in this scope of involvement from project to project is discussed, and the reasons for this potential variation are described.

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[2]Component and material costs typically account for between 70 - 85% of the final cost of the PCA.

[3]Mechanical characteristics include size, shape, weight, and thermal properties of the PCA.

3.2.1. Overview of Printed Circuit Assembly Development Steps

Although LCAC's scope of involvement throughout the process can vary from project to project, many of the required steps to develop and deliver a prototype PCA are common regardless of the particular project. The design structure matrix format provides a useful illustration of the necessary process steps in the development and delivery of a PCA prototype. (Eppinger, Ulrich, 1994)

Figure 3.3 is a design structure matrix for the PCA prototyping process that includes brief descriptions of all of the elements that are enumerated within the matrix. For this analysis, many of the project steps have been combined, simplified, or ignored, but the central meaning of the matrix is not lost with this simplification. The tasks that are required for delivery of the prototype PCA are presented on the left side of the matrix in the order that they are typically performed. To the right of each of these task descriptions is a alphabetical identifier for that task. These identifiers are also presented along the top of the matrix to represent each of the tasks along the columns of the matrix. Each task has a row assigned to it (signified by the description of the task and the alphabetical identifier), and also each task has a column assigned to it (signified by the alphabetical identifier alone). In addition to the task requirements, this matrix also presents the group or organization responsible for each task on the far right side of the matrix. The flow of the process is then illustrated by filling in the inside of the matrix with appropriate marks corresponding to the task dependencies.

An X along a row within a certain column identifies a dependency for the task defined by that row on the task defined by the corresponding column. For a series of sequentially dependent tasks, the matrix would be lower triangular; no task impacts the decisions made previously in the process. If, however, Xs appear in the upper portion of the matrix, and no re-ordering of tasks is possible to change the dependency, the tasks are coupled. Coupled tasks require iteration to arrive at a satisfactory design solution. In this particular case, tasks B through H, from *Select components* to *Develop assembly documentation*, are coupled across organizations, and often across considerable geographies. Adding to the complexity and difficulty of the process is the parallel nature of tasks D through H, *Panelize image into PCB* through *Develop assembly documentation*. Three different

Task		A	B	C	D	E	F	G	H	I	J	K	L	Responsibility
Design Circuit	A	A												Design Center
Select Components	B	X	B	X				X		X				Design Center
Develop Image Layout	C	X	X	C		X				X				Design Center
Panelize image into PCB	D			X	D	X	X	X		X				Design Center
Develop PCB photo tools	E			X	X	E				X				PCB Fab
Develop assembly tools	F		X	X	X		F			X				LCAC
Develop assembly programs	G		X	X	X			G		X				LCAC
Develop assembly documentation	H		X	X	X		X	X	H	X				LCAC
Verify tool/prog. compatibility.	I		X	X	X	X	X	X	X	I				LCAC
Manufacture PCB	J					X				X	J			PCB Fab
Manufacture tooling	K						X			X		K		LCAC
Assemble PCA	L		X				X	X	X	X	X	X	L	LCAC

Coupled Tasks Potential Iteration

Three Organizations Involved

A. Design Circuit -- developing the circuit scheme that delivers the desired outputs based upon a given set of inputs.
B. Select Components -- replacing the generic devices of the schematic with appropriate, sourcable components.
C. Develop Image Layout -- converting the schematic and component information into a manufacturable circuit layout.
D. Panelize Image into PCB -- locating the images and the corresponding assembly fiducials into the PCB substrate blank.
E. Develop PCB photo tools -- converting the panelized image infrormation into photo tools for manufacturing the PCB.
F. Develop assembly tools -- converting the panalized image information into vacuum plates, stencils, and other tools for assembly.
G. Develop assembly programs -- converting the panelized image information into software tools for assembly machines.
H. Develop assembly documentation -- delivering all of the special instructions and details to the operators in a usable format.
I. Verify tool/program compatibility -- running software checks to ensure all functions are working with consistent data.
J. Manufacture PCB -- manufacturing the bare PCB.
K. Manufacture tooling -- manufacturing the vacuum plates, stencils, and other tools for assembly.
L. Assemble PCA -- Integrate all tools, components, PCB, and programs into the PCA utilizing the appropriate processes.

Figure 3.3: Design Structure Matrix for PCA Development

organizations are working in parallel on a set of coupled tasks. Changes that are made during one of these tasks affect the work that is being performed in the other tasks. Parallel processing on a series of coupled tasks requires a great deal of coordination and communication among the participating groups.

Currently, the communication between these groups occurs in two forms. The first form involves automated design rule checking and electronic messaging. When the design center transmits the design data for a prototype PCA to LCAC, an H-P 800 workstation server evaluates the data for design rule errors with regard to assembly programming requirements. This corresponds to task G, *Develop assembly programs*, in the design structure matrix. Based upon the results of this evaluation, a series of electronic messages are returned to the design center within 30 minutes of initial data transmission. These messages are interpreted by a coordinator[4] at the design center. The coordinator then relays the information to the layout person or designer as she deems necessary. There is no follow up mechanism to measure the design center response to the electronic messages regarding the design rule evaluation. No particular response is required to proceed with the prototype process.

The second form of communication occurs after a "pre-packet" of information regarding the design has been distributed to the functional experts responsible for tasks F through I, *Develop assembly tools\programs\documentation* through *Verify tool/program compatibility*. Each functional expert for these tasks performs a series of checks on the proposed design data, and each expert then communicates the results of these checks to a NPD coordinator at LCAC. No attempt is made to correct the data problems by LCAC personnel. Corrections would require speculative assumptions regarding the designer's intent. Also, LCAC is privy to only a copy of the data, not the actual design model of the design center. The actual design model resides at the design center with the project team. Changes to a copy of the information do not guarantee that the original design data will be modified prior to the production run or prior to the next revision of that design. In order for the appropriate changes to be made to the original data, the NPD coordinator at LCAC relays this information to another coordinator at the design center. The design center

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[4]The design center coordinator is a logistical and communication focal point for information flowing into the design center. This coordinator is analogous to the LCAC coordinator described in section 3.1.1, Hewlett-Packard Loveland Manufacturing Center Organization Structure.

coordinator interprets the information and distributes it to the persons most likely to be able to resolve the problems with the design.

The above illustrations of communication linkages that exist in the PCA prototyping process are representative of the minimum amount of exchange that always occurs. However, there is a wide variation in the modes of interaction and communication from one project to another. This variation depends primarily on the operating mode of the design lab project team. To a lesser extent, the variation is also a function of the operating priorities at LCAC.

3.2.2. Scope of LCAC Involvement in Printed Circuit Assembly Development Process

The PCA prototyping process begins with design team notification to LCAC that they intend to submit a new PCA design to LCAC for prototyping. This initial notification can occur at several different stages of the PCA development process. The stage at which the notification occurs is highly dependent upon the operating procedures of the business division as well as the operating procedures of a particular design lab or project team. Throughout H-P, the project groups are given a high amount of autonomy to accomplish their project objectives in a manner that the group or project manager deems to be most effective. Because of this cultural phenomenon, the variation in procedures for prototyping from division to division and project to project is extensive. Some design lab groups will notify LCAC personnel months in advance of any request for actual prototype hardware. They schedule extensive design reviews with the process engineers at LCAC, and the actual assembly of the prototype occurs only after much time has been spent identifying potential manufacturing problems and opportunities for improvement. At the other end of the involvement spectrum, some design labs will initiate the prototyping process by transmitting design data and a purchase order for assembly of some quantity of a particular new design. In this case, the actual prototyping assembly process serves as the only evaluation of the manufacturing characteristics of the design.

All of the variation in LCAC's scope of involvement in PCA prototyping cannot be attributed solely to the design center operating procedures. LCAC also contributes to this variation due to the nature of operating priorities within its organization. For example, if the process engineers at LCAC are heavily involved in major renovations of the process,[5] they are less likely to proactively approach their assigned business divisions regarding new designs that may be on the horizon. During periods of low assembly process change, however, the process engineers, who also carry the title of NPI engineer, often proactively insert themselves as an active member of a PCA development team. They become heavily involved in the design process for new PCAs being developed at their assigned business division. They will participate in component selection, process definition, and circuit layout optimization. These services the NPI engineers perform are billed to the design lab development budget at a rate consistent with the fully loaded cost of the engineer. Any request from the design team for LCAC participation in the design process is handled in a similar manner. LCAC provides a consulting service for manufacturing issues to any of the business divisions that it serves with assembly capacity. As mentioned previously, however, this service is provided only if the design lab project team approves funding for the NPI engineer's participation.

3.2.3. Printed Circuit Assembly Prototype Assembly Processes

Regardless of the timing of LCAC's initial involvement in the PCA development process, several final tasks must occur within LCAC for delivery of the PCA prototype hardware. As illustrated by the DSM of Figure 3.3, the final steps in the process involve the interpretation of the design information into the tools necessary to assemble the PCA prototype. Once these tools are developed, the actual assembly process occurs. Again, depending on the needs of the customer and the operating mode for the project, a few different processes can be utilized to assemble the prototype PCAs.

For example, if only a few boards are required for preliminary testing, LCAC and the customer might agree that the most economical and expedient method for assembly is a hand load method known at LCAC as "bread boarding." In bread boarding, a small group of highly skilled operators works from a material list and a board layout schematic to assemble the required prototype PCAs for the customer.

For larger quantities of prototype PCAs, or prototype PCAs that must be exactly representative of the final production product, a prototype run utilizing equipment that is identical to the production equipment is undertaken. Full production tooling and programs are developed and utilized for the assembly of the prototype PCAs. Section 3.3, Overview

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[5]Major renovations include installation of new process equipment or evaluation of new technologies or process parameters. These renovations can be very time intensive, and they are typically critical to the competitiveness of LCAC.

of SMT Production, provides additional detail on the processes associated with assembling PCAs.

Whether the prototype assembly involves manual operations or production processes, the business division is billed for the cost of the assembly based upon fully loaded cost rates for all operations required. These costs are applied against the development budget of the project team requesting the prototype assembly services.

3.2.4. Implications of Process Structure

The above descriptions of the various process scopes is evidence that there is more than one way to skin the proverbial cat with regard to prototyping of PCAs. This phenomenon results from the combination of high division autonomy with individual project variation. High autonomy is a characteristic of the H-P culture and business philosophy. The business divisions rely on this autonomy to facilitate creativity in design. The variation in project and organizational requirements results from the diversity of objectives among individual project teams and the organizations that must interact to complete the development tasks. A wide range of alternatives for LCAC participation in the development process results from the combination of these characteristics. There is a current precedence whereby some development teams do not use LCAC for assembly of prototype PCAs at all. These teams deem it more economical or expedient to utilize other providers of prototyping services for PCAs. If a particular process is to be utilized extensively, it will have to be sold to the development teams that pay for the services as the most economical, efficient, and expedient process.

3.3. Overview of SMT Production

Figure 3.4 below is a simplified flow diagram of the process steps involved in PCA SMT assembly. The goal of the process is to provide a particular electrical circuit functionality to an application user in a suitable form. For SMT technologies, that form is a series of components interconnected on a PCB substrate via individual solder joints on the surface of the substrate. The process begins with the application of a solder paste to the PCB substrate. The paste is applied utilizing a squeegee pulled across a selectively etched metal mask called a stencil. Application of solder is typically done utilizing an automated paste printing machine, but manual methods that utilize the stencil in combination with a manual squeegee process are also common. After application of the solder paste, the components are oriented and placed in their appropriate locations on the PCB substrate. As with application of solder, this process is usually highly automated with speedy pick and place equipment. However, the parts can be placed manually. The solder joints are then formed by reflowing the solder paste in a reflow oven. Inspection occurs next, followed by any final application of miscellaneous parts or connectors that are not compatible with the SMT procedures. The process is completed with tests to ensure the quality of the interconnects throughout the PCA.

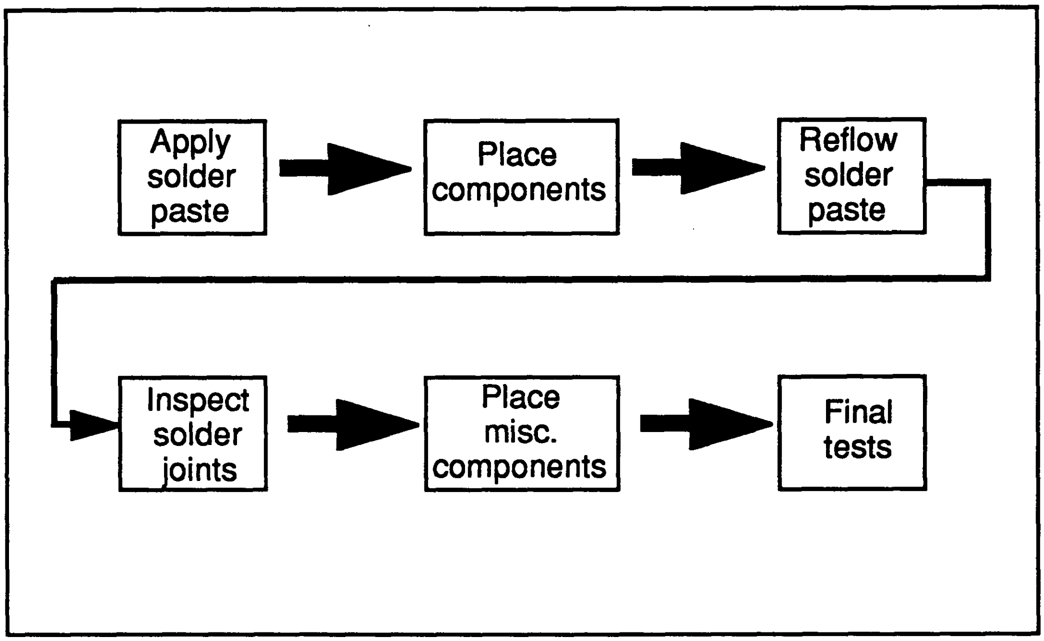

Figure 3.4: PCA Assembly Steps

This simplified description neglects the extraordinary challenges associated with SMT. The interactions among the various process steps are extremely complex, and it is very difficult to quantify them into an optimal set of operating procedures. Multiple books have been written on the physics and composition of solder paste alone. The variables that must be managed in the process include solder paste composition, paste volume, stencil aperture shape, squeegee type and pressure, squeegee angle, component application pressure, application speed, application sequence, component to component variation, oven temperature profile, oven atmosphere, and oven conveyor rate. These are just a small sampling of the variables that affect SMT process reliability, and the interactions among these results in an almost infinite set of possible solutions for optimization. Adding to the complexity is the rapid rate of proliferation of new components that must be incorporated into the process. The continuous pressure to go smaller and faster also presents a considerable challenge. The SMT process experts have an awesome responsibility in managing the process to deliver reliable and cost competitive PCAs.

3.4. Images of the Printed Circuit Assembly Prototyping Process

The information presented in the first several sections of this chapter describes the organizational structure and the process structure for PCA prototyping. This section provides insight into the stakeholders' perceptions of the process. During the stakeholder interview process (described in detail in section 4.1, Interview Questions and Demographics), the interviewees were asked to describe the images that came to mind when they contemplated the PCA prototyping process. From the descriptions given by the interviewees, an accurate visualization of the *operating environment* for PCA prototyping was developed in the form of a customer image KJ. (Shiba, et. al.,1993) The operating environment can be defined as the nature of the interactions among the various users and customers of the PCA prototyping process. The resulting KJ diagram is illustrated in Figure 3.5. This type of KJ diagram does not provide any causal analysis, it simply illustrates the environment in which prototype PCAs are developed. Understanding the various perceptions of the participants in the process provides additional insight regarding the strengths and weaknesses of the existing system.

The construction of the diagram follows a hierarchy. The lowest, most basic images are portrayed in black. These are typically direct transcriptions of customer images revealed during the interviews. Several black labels will often be grouped under a red label. The red label is a more general, or higher level descriptor for a group of common black labels. At the highest level, the blue labels describe very general observations or themes based upon the content of several common lower level labels. In constructing the diagram, an attempt was made to group the lower level images (black and red labels) according to the demographics of the respondents: design center engineers and managers, LCAC technical staff, LCAC production, and LCAC NPD group (see section 4.1, Interview Questions and Demographics for more details of interviewee demographics). The highest level images (blue labels) unite the several demographic responses under a common image descriptor. In this manner, the commonality among the several perceptions can be examined without losing the original images.

3.4.1. Customers Cannot Determine LCAC Capabilities

One example of a complete theme is represented by the collection of labels under the blue title label "Customers cannot determine LCAC capabilities." Three distinct perceptions of this high level image are illustrated by the lower level descriptions.

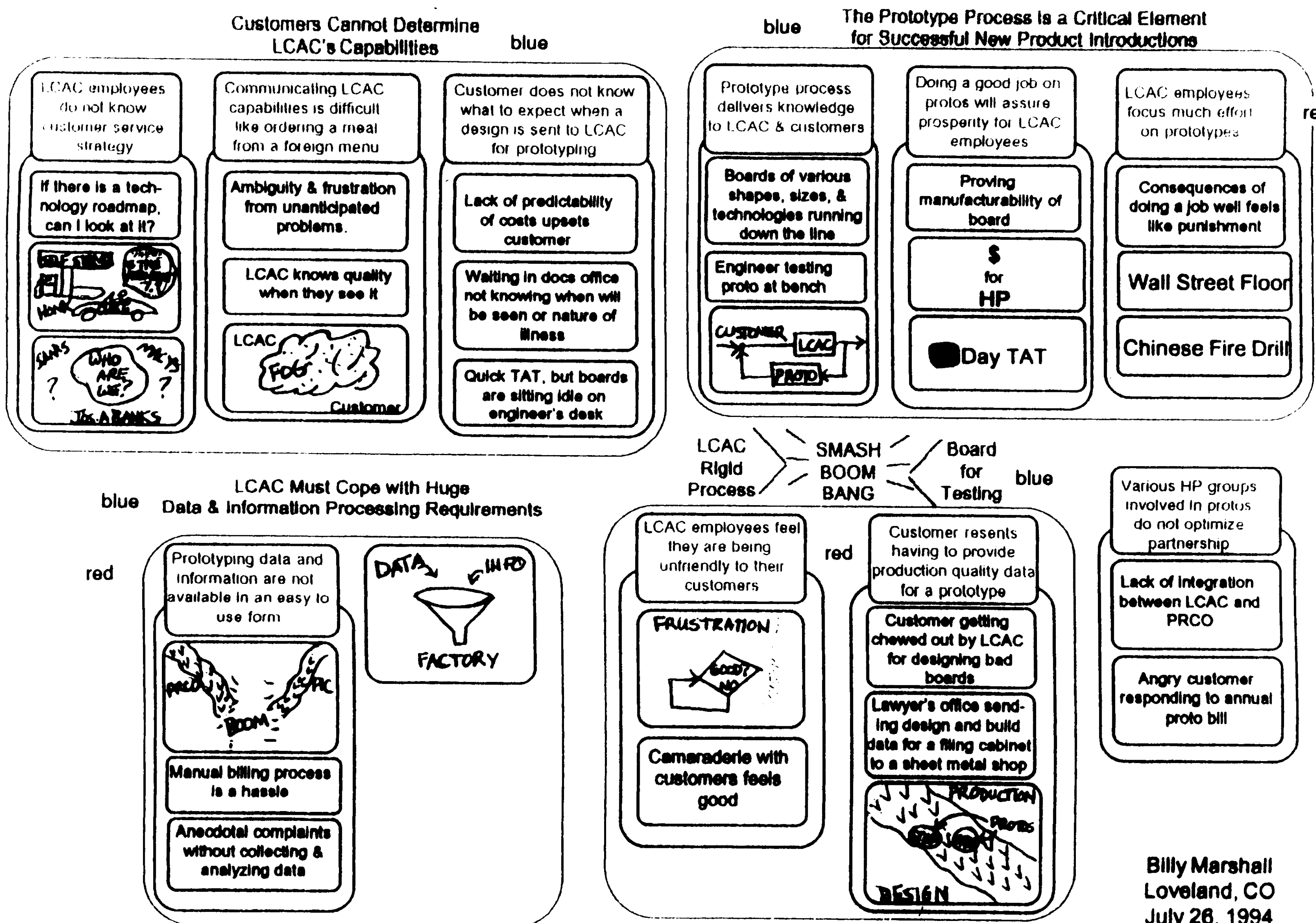

Figure 3.5: Images of PCA Prototyping KJ

The design center personnel describe an image of "waiting in a doctor's office not knowing when they will be seen or the nature of the illness." This description portrays a perceived lack of communication back to the design centers regarding a PCA prototype's status within the LCAC process. The LCAC NPD group's perception of the "Customers cannot determine LCAC capabilities" issue is illustrated by the red label "Communicating LCAC capabilities is difficult like ordering a meal from a foreign menu." This group knows the process, but describing it in language the customer can understand is like speaking in a foreign language. It is difficult to describe the problems of their operating environment to a customer base that has never been exposed to that environment.

Finally, the production operators at LCAC describe an image of the customer pulling up to the self service pump at the gas station, honking loudly, and yelling for an attendant to come out and fill up the tank with gasoline (this image is depicted visually, without words, in the image KJ). The operators perceive that the design center customers expect service beyond the prototype process definitions of LCAC. They feel that the design information provided during the prototype stage should be sufficient for the prototype PCA to flow smoothly through the production processes. All of these lower level images, though they are considerably different, reflect the higher level image descriptor regarding the difficulty of communicating prototyping expectations and capabilities.

3.4.2. Relationship Between Integration Effectiveness and Importance

The operating environment associated with PCA prototyping is recognized as critical to the success of new products, but responsibility is highly fragmented among the various participants in the process. The image KJ very clearly demonstrates the importance of communication linkages among the process participants, but it also demonstrates the frustration that occurs when the linkages do not function effectively. The relationship between integration effectiveness and importance is best illustrated by the two lowest level labels (black) listed beneath the red label "LCAC employees feel they are being unfriendly to their customers."

One label depicts an image of a feedback block diagram. This diagram is a description from a placement machine programmer of the frustration invoked by the negative, iterative feedback loop associated with resolution of programming errors in the design data. If the data received from the customer is incorrect, it is returned to the customer with a notation regarding the nature of the error. Even the most simple errors are not corrected by LCAC personnel because the error would occur again each time the customer transmitted the same design data. This operating procedure of finding the problem but not fixing it is frustrating for the programmers. They have an important task to accomplish, but the process of communicating and resolving problems identified at this stage of prototyping is complicated by the nature of the information relays. They do not communicate directly with persons who can resolve the problems, and data integrity requirements prevent them from solving the problems that they identify.

The other label that illustrates the relationship between integration effectiveness and importance is a direct quote from a LCAC NPD coordinator: "Camaraderie with my customers feels good." The coordinators have direct interaction, by phone or in person, with their counterparts at the design center. They can address the important subject of prototyping information exchange in a very effective manner. The combination of effective integration with a important process yields a high level of satisfaction for those involved. In this case, the coordinator "feels good" because he can discharge his duties quickly and effectively.

Figure 3.5, a two dimensional perceptual map, graphically documents the relationship that is described by these images of PCA prototyping. High effectiveness of the integration combined with high importance yields satisfaction from the participants. Low effectiveness of integration combined with high importance yields frustration from the participants.

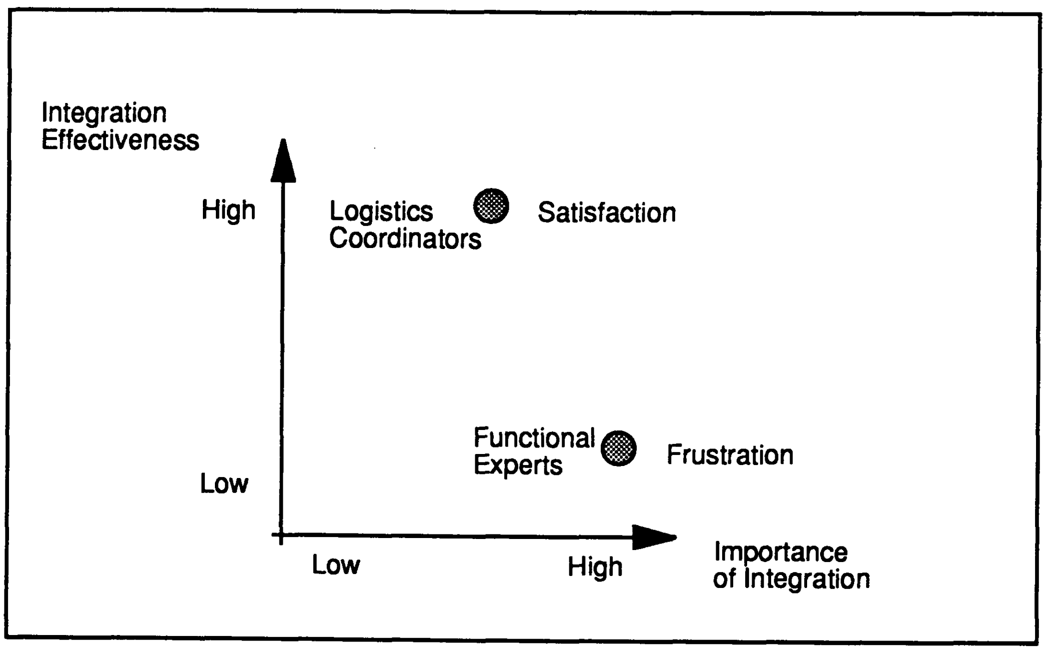

Figure 3.5: Perceptual Map of Integration Effectiveness and Importance

3.5 Summary of Key Items

The customers of the LCAC prototyping service are organizationally and geographically diverse. They, like LCAC, have operating norms and priorities that are highly influenced by the local management philosophies. This phenomenon can be attributed to the H-P culture that values autonomy as a vehicle for promoting creativity and innovation. Unfortunately, this situation presents considerable challenges to the integration of the functions during the development of new PCA designs. The structure of the process requires a considerable amount of interaction to occur among the various participants in the process, but these interactions are inhibited by the geographical and organizational boundaries. Further complicating this situation is the complexity of the technologies that are involved in designing and manufacturing PCAs for SMT assembly. The process participants acknowledge the importance of successful new PCA development efforts through their descriptions in Figure 3.5, *Images of PCA Prototyping KJ*. This importance coupled with the complexity of the process and the boundaries to successful integration results in frustration when problems are encountered during prototyping.

4. Establishing Understanding of Potential Areas of Improvement

This chapter describes the methodologies utilized to determine the customer requirements. Interview methods and questions, translation techniques for interview data, and survey development methods are detailed. Also presented within this chapter are the results of the customer analysis, detailed descriptions of the most important needs of the customers, and implications for action based upon these needs.

4.1. Interview Questions and Demographics

A series of interview questions was used to extract the voice of the customer[6] regarding the PCA prototyping process. Listed below are the questions asked during each interview:

1) Please describe your role in the PCA prototyping process.
This question establishes a context for the rest of the interview responses.

2) What images come to mind when you ponder the PCA prototyping process?
This question helps establish the nature of the operating environment by which prototype PCAs are delivered.

3) What are the weaknesses of the process as it exists today?
This question helps to identify areas for potential improvement. The interviewee is encouraged to give specific examples of when the process did not work optimally.

4) What are the strengths of the process as it exists today?
This question provides information regarding positive aspects of the process that should be maintained or enhanced with any proposed changes.

5) What process features will be necessary to address your future needs?
This question helps to establish direction for future process capabilities. It provides an opportunity for the interviewee to think beyond the confines of the process as it exists today. Through this question, latent requirements will be discovered that might have gone undetected with a simple discussion of current weaknesses and strengths.

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[6]Voice of the customer is a generic term for customer data as disclosed by the customer to the development group during interviews.

6) Any final images that might have surfaced during our discussion?

This question provides closure to the interview by allowing the interviewee to discuss any issue that may have been stimulated by the interview process but was not covered in the initial responses.

For each question, the interviewee was allowed to respond for any length of time she deemed necessary to complete her thoughts. Prompts and examples of other interviewee responses were given only if further explanation of the question was requested by the interviewee. No attempt was made to fit a current interviewee response into a framework provided by previous interviews. All of the interviews were recorded in their entirety with a portable tape recorder, and transcription of the interviews occurred within one day of the interview. The documentation of the interviews was not verbatim, but the important points from each interview were recorded. Table 4.1 provides a summary of the interviewee demographics, and Appendix 2 provides a sampling of interview transcripts.

Interview Group	Number of Interviews
LCAC Engineering	9
LCAC New Product Development	3
LCAC Production	3
LMC Finance	1
PCB Supplier	2
Design Center	6

Table 4.1: Interview Demographics

4.2. Interview Translation

The interview transcripts were reviewed to extract key images and customer voices. Each important item was transcribed onto a 3" x 5" label and posted on a working board area. These labels were then grouped based upon image similarity or content affinity. For each grouping, all labels within that group were reviewed again to establish a common image or customer need for the group. The images were used to develop the Images of Prototyping KJ (see Figure 3.5).

The customer needs were then translated into appropriate customer requirements. The development of the requirements was performed in a manner that provided a continuous variable for improvement (no binary or yes/no requirements) without implying a particular solution. (Clausing, 1993) (see section 2.3.3. Refining Customer Data for Surveys) For example, one customer voice claimed that the prototype production line has "too many part discrepancies, program problems, and machine breakdowns." Within the same grouping is a voice that claimed that "parallel rework loops are necessary." The requirement here was for prototype PCAs to be assembled quickly despite problems encountered in the prototype run. The continuous variable was prototype assembly time, but no solution (i.e. "parallel rework loops") was implied.

At this stage, it was necessary to narrow the requirements to a reasonable number for further examination and validation. Fifty-four requirements were generated by the interview process, but that number was too large to manage considering the scale of this project. Based upon the number of responses that corresponded to each requirement and a subjective "gut feel," the requirements for further examination were reduced to thirty. This set of thirty customer requirements for PCA prototyping was now suitable for incorporation into a survey form for determination of the nature of each of the requirements. Table 4.2 is a complete listing, in random order, of the thirty initial customer requirements.

4.3. Survey Development

After the requirements were extracted from the voice of the customer interviews, they were then incorporated into a survey format. Because the requirements had been formulated in terms of continuous variables for improvement, the phraseology of the requirements needed only slight modifications to be suitable for the survey. For each of these thirty requirements, four questions were asked within the survey. The questions were regarding importance of requirements, satisfaction level for the requirements, and Kano classification for the requirements (see section 2.3.4, Determining Priority of Needs through Surveys for more background on Kano's methodology).

Corrections to proto design data are easily incorporated in subsequent releases of that design and others.
Proto operators are involved in resolving problems identified in proto run.
Proto costs are easily understood from the billing statement.
Production quality design/build data is assured before beginning proto run.
Protos are assembled utilizing minimum production equipment time.
The design center has complete information on LMC changes to the design that made it more manufacturable.
Design center evaluation of protos is available to LMC employees.
Proto delivery date promised by LMC is accurate.
Data used to create stencils, tools, and Pic & Place programs is compatible with minimum manual data edits/changes.
Proto build documentation is easy for proto operators to use.
Proto board "turn on rate" due to assembly quality is easily determined before placing proto order quantity.
TAT to 1st boards delivered is long enough for design engineers to reflect and begin establishing testing routines.
The information to assemble the board as the designer wishes is readily available to proto operators.
Protos are processed quickly despite problems encountered during data evaluation.
Prototype status within the process is easily determined by design center personnel.

Table 4.2: Customer Requirements from Interview Process

Application/life cycle/market information is available for products that incorporate proto boards.
Thorough documentation of proto run problems is available to everyone.
Manufacturability of a design is easily determined by design centers prior to proto data release.
LMC continuously reduces the costs of prototyping.
LMC provides subpanel design services.
Proto solder joint quality is close to the quality of production solder joints.
Protos are assembled quickly despite problems encountered in proto run.
Proto operators know the machines, tools, & technologies beyond the requirements of normal operators.
Proto TAT is continuously reduced.
New part types are easily assimilated into the proto run.
Pic & Place capability for a design is completed prior to the proto run.
Communicating with the correct person to resolve a proto problem is easily accomplished.
LMC offers TAT/Cost/Process options for protos.
Documentation of proto run problems is available quickly.
The prototype process improves the design center's understanding of LMC SMT/assembly capabilities.

Table 4.2: Customer Requirements from Interview Process (cont.)

4.3.1. Importance Survey

The first group of questions asked for responses regarding the survey participant's perception of the importance of each specific PCA prototyping requirement. Accordingly, this portion of the survey is the "Self Stated Importance Rating." Determining the importance of each requirement was an essential step in establishing focus for LCAC improvement efforts. The questions and the possible responses took the following form:

Question -- How important is it, or would it be if: (requirement statement)

Responses:
1. Not at all important
2. Somewhat important
3. Important
4. Very important
5. Extremely important.

For example, the requirement for accuracy of the promised delivery date for the assembled prototype PCA took the following form in the importance survey:

How important is it, or would it be if:
Prototype delivery date promised by LMC is accurate?

The survey participant then rated the importance of this requirement according to the above scale.

4.3.2. Satisfaction Survey

The second group of questions asked for responses regarding the survey participant's satisfaction level under the current process for each particular requirement. This section of the survey was entitled "Self Stated Satisfaction Rating." Determining the level of satisfaction with the current process for each requirement highlights strengths and weaknesses. This information helps establish priority for improvement efforts. The questions and the possible responses had the following form:

Question -- How well does the current prototyping process satisfy the requirement: (requirement statement).

Responses:
1. Not at all satisfied
2. Somewhat satisfied
3. Satisfied

4. Very satisfied
5. Extremely satisfied

For example, the requirement for accuracy of the promised delivery date for the assembled prototype PCA took the following form in the satisfaction survey:

> How well does the current prototyping process satisfy the requirement:
> Prototype delivery date promised by LMC is accurate?

The survey participant then rated the level of satisfaction for this requirement according to the above scale.

4.3.3. Kano Questionnaire

The final group of questions was a Kano Questionnaire. (Shiba, et. al., 1993) These Kano questions took the form of a positive and a negative phraseology of the requirement:

Positive Kano Question: If (requirement satisfied), how do you feel?

Responses:
1. I enjoy it that way
2. It is a basic necessity, or I expect it that way
3. I am neutral
4. I dislike it, but I can live with it that way
5. I dislike it, and I cannot accept it

Negative Kano Question: If (requirement not satisfied), how do you feel?
Responses for the negative phraseology are identical to those for the positive.

The requirement for accuracy of the promised delivery date for the assembled prototype PCA took the following forms in the Kano Questionnaire:

> Positive Phraseology
> If the prototype delivery date promised by LCAC is accurate, how do you feel?
>
> Negative Phraseology
> If the prototype delivery date promised by LCAC is inaccurate, how do you feel?

The results of the Kano Questionnaire help establish focus and priority for process improvement efforts (see section 2.3.4, Determining Priority of Customer Needs Through Surveys for more details on Kano's methodology). "Must be" requirements should be high in priority and continually measured to determine performance levels. "One dimensional" requirements are similar, but the urgency is not quite so high. "Attractive" requirements should be targeted for future efforts, particularly if satisfying these requirements does not impose any hardship on the organization. "Attractive" requirements tend to evolve into "one dimensional" and "must be" classifications over time. Attention to these requirements early can provide potential advantage in the future.

While Shiba illustrates the positive and negative questions for a particular requirement being asked consecutively within the questionnaire (see Figure 2.1, reproduced below), this particular Kano questionnaire was implemented with a random sorting of the positives and negatives for each requirement. In this manner, respondents were prevented from generating a "logical" response to the negative phraseology based upon their response to the positive phraseology of the question just previous in the survey. Figure 2.1, reproduced below, illustrates the matrix analysis technique for determining requirement types from the responses (Shiba, 1993). While the ordering of the questions was randomized, the matrix analysis technique did not deviate from that of Figure 2.1. Figure 2.2, also reproduced below, is the corresponding graphical representation of requirement groupings as developed by Kano.

4.4. Survey Results

The survey was distributed to 93 persons. The majority of these 93 surveys went to design engineers at the various customer sites. LCAC engineering personnel, LCAC new product development personnel, and LCAC production personnel were also included in the distribution. 47 surveys were returned completed. The respondent demographics are presented in Table 4.3.

If the water drains quickly out of the stripping basket, how do you feel?	1. I like it that way. 2. It must be that way. 3. I am neutral. 4. I can live with it that way. 5. I dislike it that way.
If the water drains slowly out of the stripping basket, how do you feel?	1. I like it that way. 2. It must be that way. 3. I am neutral. 4. I can live with it that way. 5. I dislike it that way.

Customer requirements → ↓		Dysfunctional 1. like	2. must-be	3. neutral	4. live with	5. dislike
Functional	1. like	Q	A	A	A	O
	2. must-be	R	I	I	I	M
	3. neutral	R	I	I	I	M
	4. live with	R	I	I	I	M
	5. dislike	R	R	R	R	Q

Customer requirement is

A: Attractive   O: One-dimensional
M: Must-be   Q: Questionable result
R: Reverse   I: Indifferent

Figure 2.1 (duplicate): Matrix Analysis Technique for Kano Questionnaire (from Shiba, et. al., 1993)

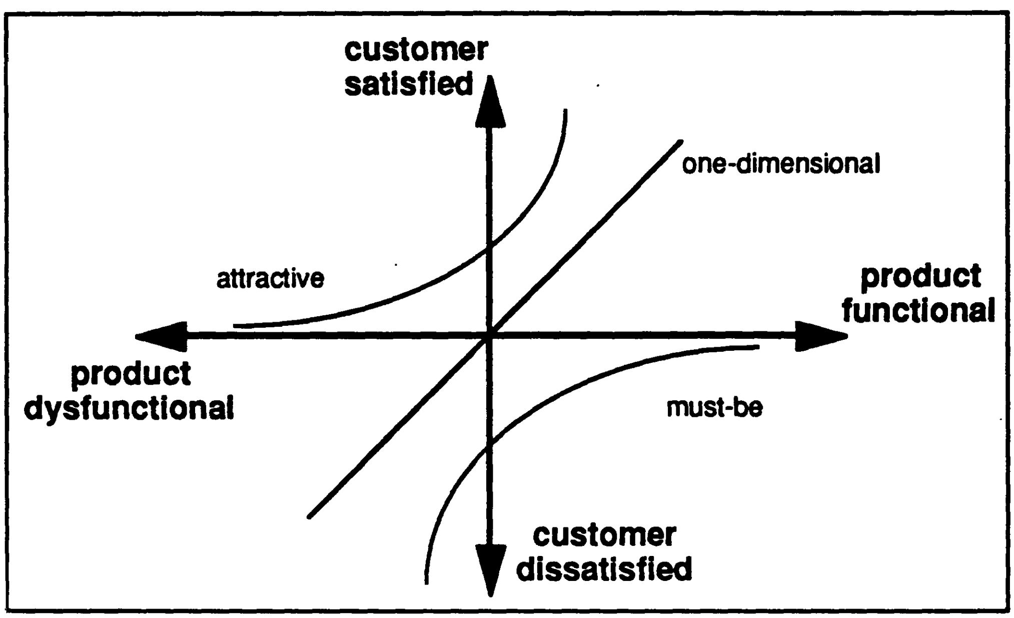

Figure 2.2 (duplicate): Graphical Representation of Kano's Hypothesis (from Shiba, et. al., 1993)

Survey Group	Responses	Percentage
LCAC Engineering	11	23%
LCAC New Product Development	4	9%
LCAC Production	8	17%
Design Center	24	51%

Table 4.3: Survey Demographics

An analysis of the responses to all 30 of the customer requirements would not be expedient for developing relevant improvement strategies for the PCA prototyping process. Another reduction in the number of requirements to carry forward to the next step of developing improvement initiatives was necessary. An initial review of the survey data indicated 13 requirements that should be utilized as guidelines for the development of improvement initiatives for the PCA prototyping process. These 13 were selected because they scored high on the importance scale and because they typically had Kano classifications of must be, attractive, or one dimensional.[7] The cut off number of 13 was somewhat arbitrary, but the requirements that were carried forward do provide a thorough framework for focusing improvement initiatives.

To utilize these 13 requirements most effectively for development of improvement initiatives, three types of information were reviewed:

- summary statistics from the survey results,
- detailed definitions of the meaning of each requirement,
- and high level implications for improvement initiatives based upon the survey results and requirement definitions

Review of these three pieces of information facilitated logical development of recommendations for improvement initiatives for the PCA prototyping process.

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[7]Indifferent ratings by the design centers on some important requirements probably reflects an attitude of resignation regarding the possibility of improvement.

4.4.1. Summary Statistics from Survey Results

Presented below in Tables 4.4, 4.5, and 4.6 are summary statistics for the 13 requirements. Statistics in the form of quartile ranges, high values, low values, means, and Kano classifications are presented at three levels: design center responses, LCAC responses, and the aggregate responses for these two groups combined. For consistency, the requirements are presented in each table in order of their mean importance score as indicated by the design center survey respondents. In this manner, inconsistencies between the design center customer responses and the LCAC personnel responses can be easily identified upon review of the LCAC mean importance data in Table 4.5.

4.4.2. Detailed Definitions of Meaning for Requirements

A detailed definition for each of the 13 requirements is presented below. These definitions draw heavily from the interviews that ultimately led to the requirement statements. In conjunction with the survey data presented above, these detailed descriptions will facilitate development of improvement strategies for the PCA prototyping process.

1. *Communicating with the correct person to resolve a prototype problem is easily accomplished.* Several interview comments addressed the weakness of the communication links between LCAC and the design centers when trying to resolve prototype problems that develop during design data evaluation or the actual PCA assembly process. Specific recommendations for changes are often misunderstood or misinterpreted by design center personnel. This results in unproductive iterations of design data transmission and evaluation. Contacting and communicating with the correct person for problem resolution, at LCAC or the design center, is not perceived as a straightforward process.

2. *Prototype delivery date promised by LCAC is accurate.* This requirement is easily understood. Upon receipt of a prototype PCA order from a customer, LCAC provides a promised delivery date. The design center customers want this date to be accurate so that they can effectively plan their testing schedules and engineering resources.

PCA Prototyping Requirement	Q3	Median	Q1	Hi	Lo	Mean	
Communicating with the correct person to resolve a prototype problem is easily accomplished	5	5	4	5	3	4.6	Importance
	3	2	1	4	1	2.1	Satisfaction
	Kano:	Must Be					
Prototype delivery date promised by LCAC is accurate	5	5	4	5	2	4.4	
	3	2	2	4	1	2.2	
	Kano:	Must Be					
The design center has complete information on LCAC changes to the design that made it more manufacturable	5	4.5	4	5	3	4.4	
	2.25	2	2	4	1	2.2	
	Kano:	Must Be					
Manufacturability of a design is easily determined by the design centers prior to ptototype data release	5	4	4	5	2	4.3	
	2	2	1.25	4	1	1.8	
	Kano:	Indifferent					
Thorough documentation of prototype assembly problems is available to everyone	5	4	4	5	2	4.2	
	3	2	2	4	1	2.4	
	Kano:	Must Be					
Prototype solder joint quality is close to the quality of production solder joints	5	4	3.75	5	3	4.2	
	4	3	2	5	1	2.9	
	Kano:	Must Be					
Prototypes are assembled quickly despite problems encountered during prototype assembly	5	5	3.25	5	2	4.2	
	2	2	2	4	1	2.2	
	Kano:	Attractive					

Table 4.4: Survey Summary Statistics -- Designer Responses

PCA Prototyping Requirement	Q3	Median	Q1	Hi	Lo	Mean	
New part types are easily assimilated into the prototype assembly process	5	4	4	5	3	4.2	Importance
	3	2	1.25	5	1	2.4	Satisfaction
	Kano: Indifferent						
Prototype turn around time is continuously reduced	5	4	4	5	1	4.1	
	3	2	2	4	1	2.4	
	Kano: Indifferent						
The information to assemble the board as the designer wishes is readiily available to prototype operators	4.25	4	4	5	3	4.1	
	2	2	1	3	1	1.8	
	Kano: Indifferent						
LCAC reduces the cost of prototyping	5	4	3.75	5	2	4.0	
	3	2	1	4	1	2.0	
	Kano: Indifferent						
Prototype status within the process is easily determined by design center personnel	4	4	4	5	2	4.0	
	2.25	2	1	3	1	1.9	
	Kano: Attractive						
LCAC offers cycle time/ cost / process options to design centers for prototyping	5	4	3	5	2	3.9	
	2	2	1	3	1	1.7	
	Kano: Attractive						

Table 4.4 (cont.): Survey Summary Statistics -- Designer Responses

PCA Prototyping Requirement	Q3	Median	Q1	Hi	Lo	Mean	
Communicating with the correct person to resolve a prototype problem is easily accomplished	5	4.5	4	5	3	4.5	Importance
	3	2	2	4	1	2.2	Satisfaction
	Kano: One Dimensional						
Prototype delivery date promised by LCAC is accurate	5	5	4	5	3	4.6	
	3	2	1	4	1	2.1	
	Kano: Must Be						
The design center has complete information on LCAC changes to the design that made it more manufacturable	5	5	4	5	3	4.6	
	3	2	1.5	5	1	2.2	
	Kano: Must Be						
Manufacturability of a design is easily determined by the design centers prior to ptototype data release	5	5	4	5	3	4.5	
	2	2	1	3	1	1.8	
	Kano: Attractive						
Thorough documentation of prototype assembly problems is available to everyone	5	4	4	5	2	4.1	
	3	2	2	5	1	2.4	
	Kano: One Dimensional						
Prototype solder joint quality is close to the quality of production solder joints	4.25	4	3	5	1	3.8	
	4	3	2.75	5	1	3.3	
	Kano: Must Be						
Prototypes are assembled quickly despite problems encountered during prototype assembly	5	4	3	5	1	4.0	
	3	2	2	4	1	2.5	
	Kano: Attractive						

Table 4.5: Survey Summary Statistics -- LCAC responses

PCA Prototyping Requirement	Q3	Median	Q1	Hi	Lo	Mean	
New part types are easily assimilated into the prototype assembly process	5	4	3	5	2	3.9	Importance
	3	2	1.25	4	1	2.3	Satisfaction
	Kano: Attractive						
Prototype turn around time is continuously reduced	5	5	4	5	3	4.4	
	3	2	2	4	2	2.5	
	Kano: Attractive						
The information to assemble the board as the designer wishes is readiily available to prototype operators	5	5	4	5	1	4.3	
	3	2	2	4	1	2.3	
	Kano: Attractive						
LCAC reduces the cost of prototyping	5	4	3	5	1	3.6	
	3	2	2	4	1	2.4	
	Kano: Attractive						
Prototype status within the process is easily determined by design center personnel	4	4	3	5	1	3.4	
	3	3	1.25	4	1	2.3	
	Kano: Attractive						
LCAC offers cycle time/ cost / process options to design centers for prototyping	4	3	2.25	5	2	3.3	
	2	2	1	4	1	1.8	
	Kano: Attractive						

Table 4.5 (cont.): Survey Summary Statistics -- LCAC Responses

PCA Prototyping Requirement	Q3	Median	Q1	Hi	Lo	Mean	
Communicating with the correct person to resolve a prototype problem is easily accomplished	5	5	4	5	3	4.5	**Importance**
	3	2	1	4	1	2.2	**Satisfaction**
	Kano:	Must Be					
Prototype delivery date promised by LCAC is accurate	5	5	4	5	2	4.5	
	3	2	2	4	1	2.2	
	Kano:	Must Be					
The design center has complete information on LCAC changes to the design that made it more manufacturable	5	5	4	5	3	4.6	
	3	2	2	5	1	2.2	
	Kano:	Must Be					
Manufacturability of a design is easily determined by the design centers prior to ptototype data release	5	5	4	5	2	4.4	
	2	2	1	4	1	1.8	
	Kano:	Attractive					
Thorough documentation of prototype assembly problems is available to everyone	5	4	4	5	2	4.2	
	3	2	2	5	1	2.2	
	Kano:	Must Be					
Prototype solder joint quality is close to the quality of production solder joints	5	4	3	5	1	3.0	
	4	3	2	5	1	3.1	
	Kano:	Must Be					
Prototypes are assembled quickly despite problems encountered during prototype assembly	5	4	3	5	1	4.1	
	3	2	2	4	1	2.4	
	Kano:	Attractive					

Table 4.6: Survey Summary Statistics -- Aggregate responses

PCA Prototyping Requirement	Q3	Median	Q1	Hi	Lo	Mean	
New part types are easily assimilated into the prototype assembly process	5	4	4	5	2	4.1	Importance
	3	2	1	5	1	2.3	Satisfaction
	Kano: Indifferent						
Prototype turn around time is continuously reduced	5	5	4	5	1	4.3	
	3	2	2	4	1	2.4	
	Kano: Attractive						
The information to assemble the board as the designer wishes is readiily available to prototype operators	5	4	4	5	1	4.2	
	2.75	2	2	4	1	2.2	
	Kano: Attractive						
LCAC reduces the cost of prototyping	5	4	3	5	1	3.9	
	3	2	2	4	1	2.2	
	Kano: Attractive						
Prototype status within the process is easily determined by design center personnel	4	4	3	5	1	3.7	
	3	2	1	4	1	2.2	
	Kano: Attractive						
LCAC offers cycle time/ cost / process options to design centers for prototyping	4	4	3	5	2	3.6	
	2	2	1	4	1	1.8	
	Kano: Indifferent						

Table 4.6 (cont.): Survey Summary Statistics -- Aggregate Responses

3. *The design center has complete information on LCAC changes to the design that made it more manufacturable.* This requirement relates to the exchange of information between LCAC and the design centers regarding the changes LCAC recommends or initiates to make the design more manufacturable. Although several groups within LCAC espouse a policy of not changing designs, there is a perception among design center personnel that changes do occur without a corresponding communication. On a more general level, this requirement highlights the need for LCAC to communicate manufacturability assessments regarding prototype designs in a timely, effective manner.

4. *Manufacturability of a design is easily determined by the design centers prior to proto data release.* Both LCAC and the design centers would like to avoid the iterative problem resolution process by eliminating all of the manufacturing problems prior to release of the design data for the prototype PCA. This would speed up the process and eliminate much of the frustration associated with problem resolution.

5. *Thorough documentation of proto run problems is available to everyone.* This requirement is another illustration of the perceived importance of communicating LCAC manufacturing knowledge back to the design centers. Currently, feedback occurs with a "post proto" report: a paper document that organizes the information from a meeting among production support personnel after the prototype PCA has been assembled. Interview comments from the design centers stressed the importance of this document and the information contained therein.

6. *Prototype solder joint quality is close to the quality of production solder joints.* The prototype PCA should incorporate a quality attachment process for components to the bare boards.

7. *Protos are assembled quickly despite problems encountered in the prototype run.* This requirement addresses the issue of recovery speed within the process when a problem is encountered. Several interviewees expressed frustration with the current process where information regarding problems travels through cumbersome communication channels with ambiguous responsibility for problem resolution.

8. *New part types are easily assimilated into the proto run.* New part types provide enhanced functionality to PCA designs. Smooth assimilation of these parts into the prototype assembly is important.

9. *Prototype Turn-Around -Time is continuously reduced.* As mentioned previously, time to market is considered an important competitive dimension. Decreasing the prototyping cycle time reduces time to market.

10. *The information to assemble the board as the designer wishes is readily available to proto operators.* Production operators described several situations where the documentation regarding the assembly of the PCA was incomplete or ambiguous. This issue becomes particularly acute when new part types or new procedures are incorporated into a prototype PCA.

11. *LCAC reduces the cost of prototyping.* This requirement is self explanatory.

12. *Prototype status within the LCAC process is easily determined by design center personnel.* Several comments during the interview process reflected the inability of design center personnel to ascertain the status of an impending prototype build once data has been released to LCAC. This requirement parallels the requirement for accurate delivery date promises from LCAC. If the status of a prototype is easily determined, design team resources can be more effectively utilized based upon accurate knowledge of delivery and problem situations.

13. *LCAC offers cycle time/cost/process options to design labs for prototyping.* A recurring theme in the interviews was the need for choice in prototyping process options. "I should be able to buy time with money" is a quote from an interview that reflects this requirement. Prototypes can serve several functions for the design labs (functional electrical tests, customer evaluation, etc.), and the prototype process should address the various needs with options for cycle time, cost, and manufacturing methods.

These thirteen requirements or customer needs adequately describe a set of important process parameters for PCA prototyping at LCAC. While no list could ever represent a complete set of all customer's requirements, the above "important few"[8] will provide a focus for substantial improvements in customer satisfaction and process effectiveness.

4.5. Implications for Printed Circuit Assembly Prototyping Improvements

To provide a platform of shared understanding that will facilitate development of PCA prototyping improvements, some analysis of the implications of this requirement set is useful. As indicated by the review of Fine and Hax in section 2.1, Performance Criteria in the Manufacturing Organization, cost, quality, delivery, and flexibility are all candidates for dimensions along which to improve any manufacturing endeavor. (Fine, Hax, 1985) Cost and delivery dimensions present themselves in the form of requirement numbers 11 and 9 respectively. Requirements 2 and 7 also reflect delivery concerns. Requirement 2 addresses the predictability of prototype delivery, and requirement 7 addresses the speed of prototype problem resolution to achieve more rapid delivery. The dimension of quality is represented by requirement 6. Solder joint quality is important for prototyping success.

A characterization of the remaining requirements cannot be succinctly accomplished within the framework of cost, delivery, quality, and flexibility. An argument could be made that all of the remaining requirements that have not been addressed as cost, delivery, or quality could be identified as items related to flexibility. However, this characterization is not obvious or intuitive. Success in prototyping of potential new products is not adequately measured if utilizing only typical manufacturing metrics. Analyzing the remaining requirements within the context of the goals of the PCA prototyping process reveals the importance of effective information exchange.

4.5.1. Information Availability and Utilization During Printed Circuit Assembly Prototyping

A key dimension along which prototyping success should be measured is information availability and utilization. The review of Eppinger and Ulrich in section 2.2.2, Purposes of Prototyping, indicates that learning, communication, integration, and milestone achievement are all purposes served by prototyping. (Eppinger, Ulrich, 1994) With regard to learning and communication, some of the information regarding the viability of a design will manifest itself in the form of the prototype PCA hardware. For example, if LCAC were to return a prototype PCA to a design center in the form of a partially assembled board

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[8]Shiba stresses a focus on the "important few" requirements to avoid over analysis that slows progress. (Shiba, et. al., 1993)

and an attached packet of unassembled parts, it would become clear to the designer that the design was not compatible with the manufacturing process. Information in this form, however, is not easily utilized to determine solutions for improving the design. The communication is ineffective and the learning does not occur.

The design centers need detailed information regarding the manufacturing issues associated with each particular design. If the learning and communication is effective, the design centers will utilize LCAC information to improve the manufacturability of the design. This facilitates delivery of the lowest cost, most reliable products when production is initiated. Finally, milestones are of little use if they do not propel the development process forward. A prototyping milestone is not an end to itself. Achieving the prototyping milestone effectively is a means for timely accomplishment of the learning, communication, and integration that is essential for successful new product introductions. For these things to be accomplished, the information that is provided through the prototyping process must be readily *available* and easy to *utilize* by the development team.

Further examination of the requirements that do not address cost, delivery, quality, or flexibility shows that seven of the thirteen requirements document the importance of information availability and utilization. Requirement number 1 emphasizes the need for clear channels of communication between persons at LCAC and the design centers who are most capable of resolving problems with the prototype design. Requirement number 3 details the need for LCAC to communicate recommendations for changes to the design data that would make the design more manufacturable. Requirements 4, 5, 8, 10, and 12 further document the need for a seamless exchange of knowledge between LCAC and the design centers when this knowledge relates to the successful implementation of a new PCA.

The challenge presented by these needs is for LCAC is to develop potential improvement initiatives for PCA prototyping that address more than the typical manufacturing metrics of cost, quality, delivery, and flexibility. The need for rapid and effective exchanges of information and knowledge between LCAC and the design centers must be considered in developing LCAC's prototyping strategy.

Given the details of the organization and process structure presented in section 3.1, Hewlett-Packard Corporate Organization Structure, and section 3.2.1, Overview of Printed Circuit Assembly Development Steps, it is not surprising that the process requirement survey yielded data that establishes communication and information sharing as a crucial area for process improvement. Most current literature on product development emphasizes the need for representatives of all product stakeholder groups (marketing, design, manufacturing, etc.) to be in close communication from concept development through product launch. (Eppinger, Ulrich 1994) Within each of the business divisions served by LCAC, product development teams do exist with functional representation across disciplines. Manufacturing representation within these groups is typically accomplished by personnel that previously managed manufacturing functions when each business division had through hole[9] assembly capacity. The current manufacturing process owners for SMT, however, are all responsible to the LCAC organization. They are not co-located with the development teams at the business divisions. To improve the PCA prototyping process while preserving the advantages of consolidation of manufacturing capacity, an evaluation of mechanisms and techniques for improving information flow across geographical and organization boundaries is necessary. Information utilization and availability should be included with cost, quality, delivery, and flexibility as important improvement dimensions for the PCA prototyping process at LCAC.

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[9]Prior to SMT, PCAs were assembled by inserting the leads of the components through connection holes in the PCB substrate, and then soldering the connection utilizing wave solder processes. This process is much more robust to variation than SMT. It is considerably different than SMT.

5. Recommendations for Printed Circuit Assembly Prototyping Improvements

This chapter provides details regarding design review techniques to improve the PCA prototyping process. These techniques address the key improvement dimensions of information availability and utilization identified in the previous chapter. Design reviews will enhance the availability and utilization of LCAC process knowledge. Specifically, a tactical design review (TDR) process and a strategic design review (SDR) process are recommended.

The TDR addresses the tactical issues associated with corrections or changes that are necessary to assemble the PCA prototype after design data has been transmitted to LCAC. This information is tactical because only simple changes affecting the assembly of the PCA can be incorporated into the design at this stage. The SDR addresses the strategic manufacturing concerns for designs early in the design process. This information is strategic because it affects the long term competitiveness of LCAC and H-P in delivering production PCAs to their customers. Both the TDR and the SDR facilitate sharing and learning across organization and geographical boundaries.

Key elements and implementation guidelines are provided for both the TDR and the SDR. These elements and guidelines are based upon the insights that were developed through the above examination of the purposes of prototyping, the nature of the organizational and process structures, and the customer requirements for PCA prototyping.

5.1. Tactical Design Review

LCAC should develop a tactical design review process to communicate problems and opportunities to the design team during the "build phase" of the PCA prototyping process. The "build phase" here refers to all of the activities that occur after design data has been transmitted to LCAC for a PCA prototyping order. These activities include development of software tools (programs), hardware tools (stencils, vacuum plates), part kitting, fabrication of the bare PC board, and assembly of the PCA.[10] Because the design has already been uploaded into a CAD format at this stage, opportunities for improvement are

[10]More detail on each of these activities is presented in Figure 3.3, *Design Structure Matrix for PCA Development*. These activities correspond to tasks E through L , *Develop PCB photo tools* through *Assemble PCA,* in the matrix.

mostly tactical. These opportunities deal with the issues of assembling the PCA prototype for the design center customers.

5.1.1 Impact on Customer Requirements

A tactical design review has potential to improve the satisfaction level for seven of the customer needs presented in section 4.4.2, Detailed Definitions of Meaning for Requirements. These seven needs are duplicated below. They are enumerated in order of customer importance according to the data presented in Table 4.4, *Survey Summary Statistics--Designer Responses*. For each of these, details are presented regarding how a tactical design review would improve customer satisfaction.

1. *Communicating with the correct person to resolve a prototype problem is easily accomplished.* All problems would be presented in the tactical design review. The persons who are capable of resolving the issues would be present and involved in the review.

2. *Prototype delivery date promised by LCAC is accurate.* The inaccuracy of the current process is due largely to the uncertainty associated with communicating and resolving problems. A tactical design review would improve the promised delivery date by establishing a deterministic path for delivery based upon the resolution of issues presented in the review. The uncertainty of the problem resolution process is greatly decreased by utilization of a tactical design review.

3. *The design center has complete information on LCAC changes to the design that made it more manufacturable.* A tactical design review would present all of the information regarding LCAC tactical improvements during a single, interactive forum. The information would be complete and highly usable due to the interactivity of the review.

5. *Thorough documentation of proto run problems is available to everyone.* High participation in a tactical design review by those involved in the PCA prototyping process would improve the wide availability of information regarding proto run problems.

7. *Protos are assembled quickly despite problems encountered in the prototype run.* A tactical design review would improve LCAC personnel's understanding of potential

problems that might occur during assembly. This understanding, and the closer relationship with each designer due to the tactical design review, would improve the problem resolution process during the prototype run.

8. *New part types are easily assimilated into the proto run.* A tactical design review would facilitate discussion regarding questions that arise because of new part types. This discussion would improve assimilation of new part types into the proto run.

10. *The information to assemble the board as the designer wishes is readily available to proto operators.* The communication from the designer to the proto operators would be improved by having the designer interact with LCAC personnel during a tactical design review. Even without the operator present in the review, information regarding the designer's wishes can be easily disseminated within LCAC if several persons at LCAC are familiar with the issues.

5.1.2 Key Elements for Tactical Review Effectiveness

The key elements for success in a tactical review process are:

- timely communication of issues
- direct communication between manufacturers and designers
- synchronization of corrective actions

Each of these three elements must be included in the tactical design review methodology. A potential solution set is provided below as a framework for beginning the development of the tactical design review for PCA prototyping at LCAC.

5.1.2.1. Timely Communication of Issues

To facilitate rapid delivery of the PCA prototypes, problems that slow or stop the build process must be communicated quickly. Currently, LCAC has quick communication mechanisms in place. These mechanisms take the form of the automated design rule checkers that generate and relay electronic messages back to the design centers regarding the compatibility of the design data with the manufacturing process. This checking and messaging process occurs within 30 minutes of the initial design data transfer. However, no response is required for the prototyping process to proceed. The communication loses its timeliness if several iterations of communication have to occur before the problem is resolved. Therefore, timeliness of communication is not sufficient for effective problem resolution. Timeliness must be considered in concert with satisfaction of the other two elements of an effective tactical design review: direct communication and a solution oriented approach.

5.1.2.2. Direct Communication Between Manufacturers and Designers

The communication of the problem or opportunity for improvement during the build phase of the PCA prototyping process must directly involve the functional expert that can explain the problem and the design center personnel who can determine and implement a proper solution for the problem. As detailed in section 3.2.1, Overview of Printed Circuit Assembly Development Steps, several hand offs and translations of problem information occur prior to delivery of the information to persons that can resolve the problem. These hand offs and translations result in miscommunication and confusion regarding the true nature of the problem. The most effective problem information exchange involves no hand offs or translations. The person who can solve the problem is contacted by the person who identified the problem. Unfortunately, most problems and the corresponding solution sets impact more than a single function or parameter of the design. Therefore, direct communication, as with timely communication, is not effective without considering the necessity for synchronization of corrective actions by involving all stakeholders simultaneously.

5.1.2.3. Synchronization of Corrective Actions

The most important aspect of the tactical design review is the synchronization of corrective actions. The coupled nature of the steps involved in delivering the PCA prototype is represented by Figure 3.3, *Design Structure Matrix for PCA Development*. This characteristic of the process dictates that all stakeholders in the problem resolution process must act in concert if the problem is to be resolved quickly and with little iteration. Synchronization of corrective actions during the TDR ensures a usable solution that is acceptable to all parties. Without this synchronization, no real improvements can be made to the design without several hand offs and translations occurring. As mentioned previously, hand offs and translations are not optimum for rapid problem resolution.

Figure 5.1 below illustrates the current problem resolution process without the synchronization of a TDR, and Figure 5.2 illustrates the improved problem resolution process with the TDR. The arrows in the figures represent the exchanges of information and their directions. From the diagrams, it is easy to understand how the TDR, through

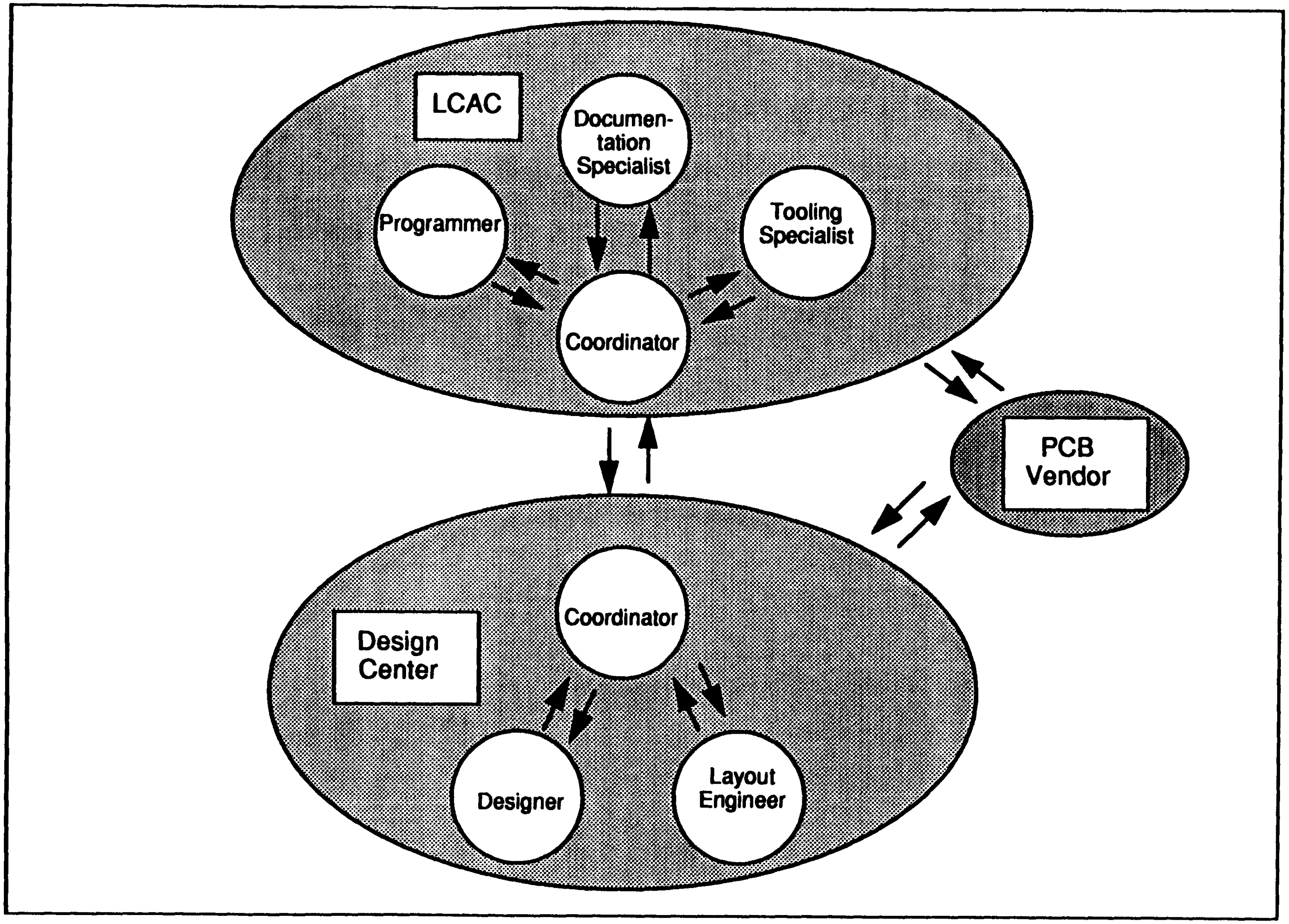

Figure 5.1: Problem Resolution without TDR

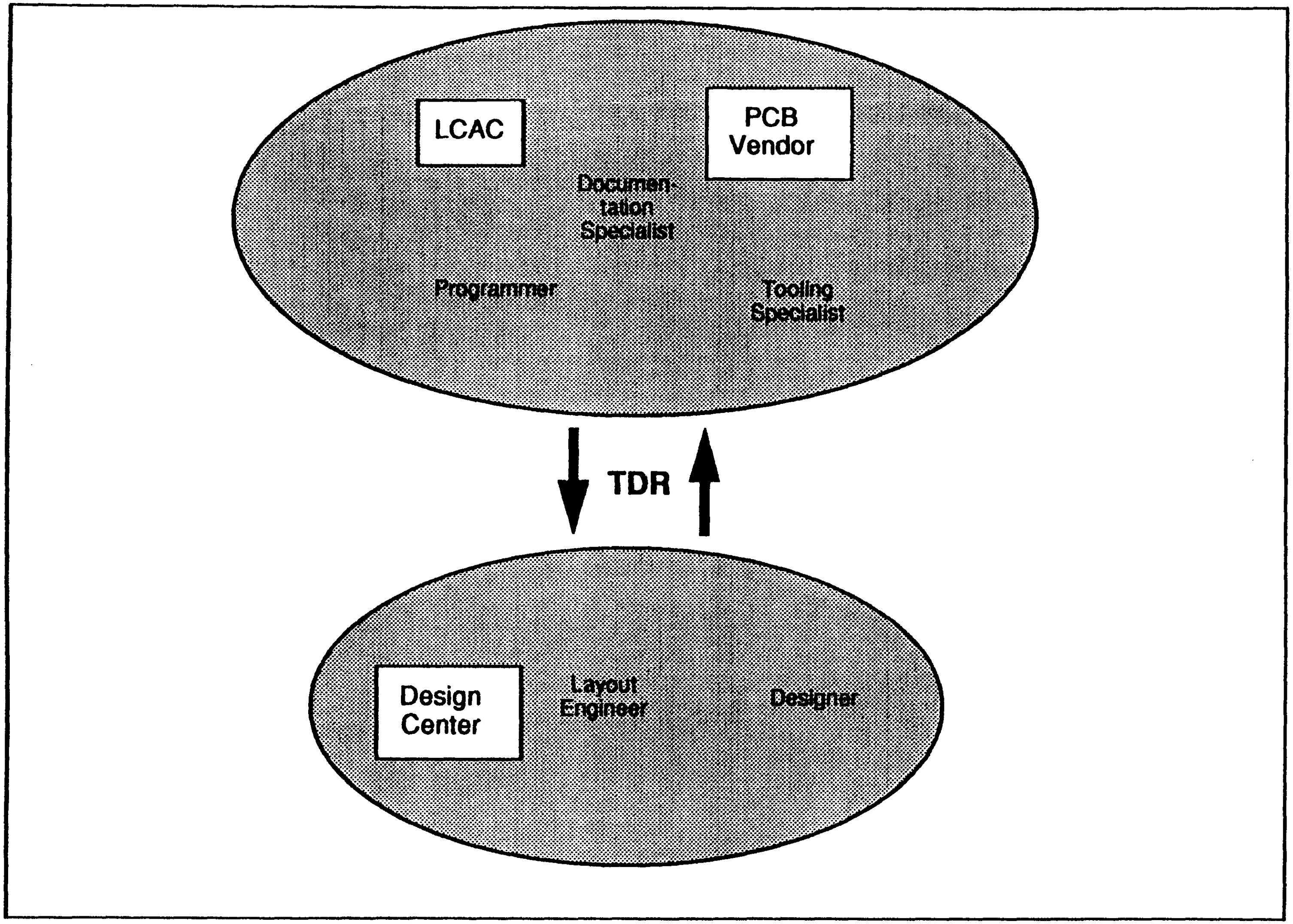

Figure 5.2: Problem Resolution with TDR

synchronization of problem resolution actions, simplifies the process. The logistics of synchronization of corrective actions are not trivial, and substantial planning and discipline are required for the process to be effective.

5.1.3. Implementation Guidelines

The following steps are recommended for obtaining optimum results from a tactical review process.

Establish a schedule for tactical design review processes to occur.

Part of the critical path for the PCA prototyping process should be a milestone entitled "Tactical Design Review." This milestone should be scheduled at a deterministic point in the process when all of the functional experts have had an opportunity to review the design information and develop recommendations. The design center personnel should be aware of this scheduled milestone and should be prepared to participate in the review for timely resolution of potential problems. One evolutionary way to approach this schedule requirement is to have the coordinators, who currently serve as communication relays, instead begin to serve as communication coordinators. Upon receipt of design data, they coordinate all of the necessary parties into a meeting that has a pre-specified time window within the schedule. There should be some slack in this window to allow for successful coordination of schedules among the stakeholders.

Develop mechanisms for multi-party participation in the review.

The communication must occur with all stakeholders participating in the problem resolution process in real time. Therefore, real time communication mechanisms must be utilized as the information medium. Figure 2.3, *Graphical Representation of PCA Tactical Design Review System* and is reproduced below. This schematic provides a good example of the capability that is necessary for the review to be effective. Phone conferencing with shared video display files or full video conferencing are attractive alternatives if all of the stakeholders are not located at the Loveland site. If all stakeholders are located at the Loveland site, it is highly recommended that everyone conference together during the tactical design review.

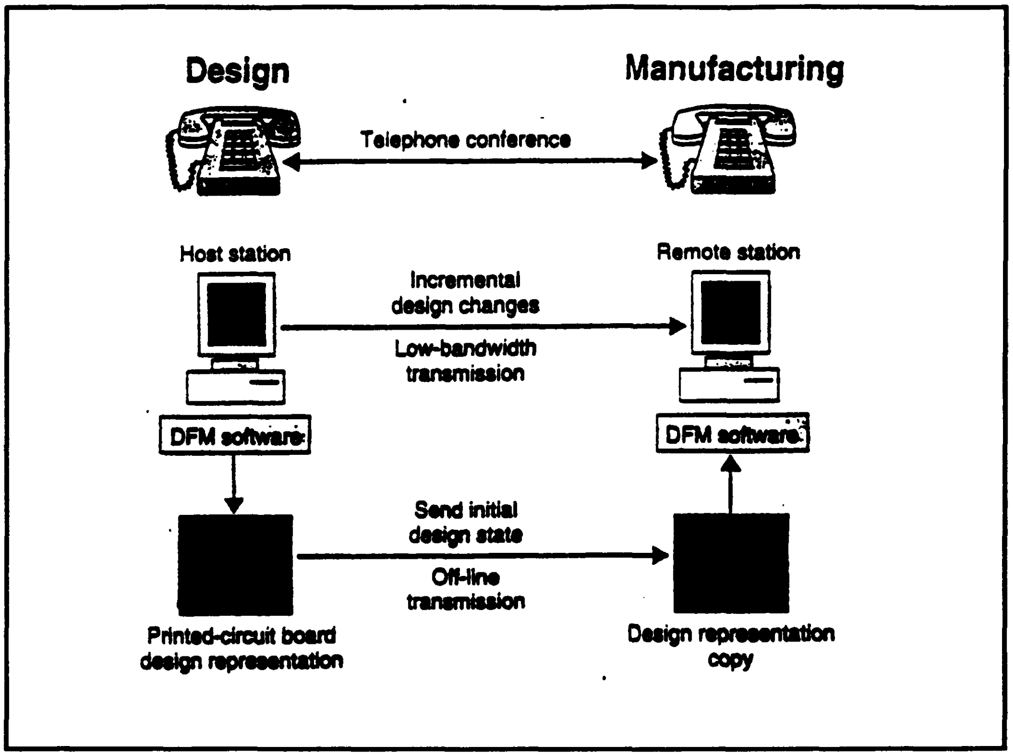

Figure 2.3 (duplicate): Graphical Representation of PCA Tactical Design Review

Prepare to iterate to a successful solution during the tactical design review.
This feature stresses the integrative approach that must be utilized if the tactical design review is to be successful. If possible, all of the tools that determine the producibility of the design should be utilized during the review to confirm that an acceptable solution has indeed been determined. This means that design files should be accessible during the meetings. These files should be modified based upon the review proceedings, and the modifications should be verified as acceptable for delivering the prototype PCA by LCAC verification tools as well as by the PC board vendor's tools . At the very least, the potential solution set should be evaluated off line from the review process in an expedient manner, and then all stakeholders should return to the review quickly to evaluate the potential improvement. If the problems prove too large to be resolved in this manner, another review should be scheduled prior to the end of the first review. At this second review, specific action items that were identified during the first review should be completed. The same stakeholders then begin the process again with the aim of resolving all problems prior to the end of the second tactical design review.

Figure 5.3 is a modified version of Figure 3.3, *Design Structure Matrix for PCA Development.* A task has been inserted into the matrix that represents the TDR. Figure 3.3

is reproduced below for comparison. If the issues associated with preparing the design for assembly are all resolved during the TDR, no iteration occurs in the process after the TDR. The matrix is completely lower triangular after task E. By contrast, Figure 3.3 shows the upper triangularity of the current process of funneling information back to the designers without engaging them in a problem solving forum. In H-P LCAC terminology, the TDR provides a rapid process to go from "bits" to "good bits."[11] After the TDR, the design data is completely compatible with the production processes; it is "good design data."

Provide incentives for participation.

The tactical design review has to have a high participation rate for it to be effective. Upper level LCAC management should provide incentives for full LCAC participation in the review. The design center customers should be incentivised by the more rapid resolution of problems and quicker delivery of prototypes. The total system cost of establishing and maintaining this process should be lower than the current cost of miscommunication and iteration. Therefore, the procedure should be offered as a free service that is a standard part of the PCA prototyping procedure.

5.1.4. Summary of Tactical Design Review Impact

If the above guidelines are followed in developing a tactical design review process, the problem resolution stage of the prototype build process should be greatly enhanced. The TDR provides schedule discipline for real time, interactive resolution of problems. This discipline should provide enhanced customer satisfaction. The injection of the TDR into the build stage will not always provide enhanced delivery performance in terms of absolute cycle times. Designs that are received by LCAC that are perfect will experience no improvement in this area. However, most designs are not perfect.

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[11]The process of resolving all of the manufacturing issues associated with the design data is called going from "bits" to "good bits" at LCAC. "Bits" refers to the design data that is received with a PCA prototyping request. "Good bits" is design data that is ready to go to the production process.

Task		A	B	C	D	E	F	G	H	I	J	K	L	Responsibility
Design Circuit	A	A												Design Center
Select Components	B	X	B	X										Design Center
Develop Image Layout	C	X	X	C		X								Design Center
Panelize image into PCB	D			X	D	X								Design Center
Tactical Design Review	E		X	X	X	E								PCB Fab
Develop PCB photo tools	F		X	X	X	X	F							LCAC
Develop assembly tools	G		X	X	X	X		G						LCAC
Develop assembly programs	H		X	X	X	X			H					LCAC
Develop assembly documentation	I		X	X	X	X	X	X	X	I				LCAC
Manufacture PCB	J					X	X			X	J			PCB Fab
Manufacture tooling	K							X		X		K		LCAC
Assemble PCA	L		X				X	X	X	X	X	X	L	LCAC

Iteration during TDR

Figure 5.3: Design Structure Matrix for PCA Development with TDR Included

Task		A	B	C	D	E	F	G	H	I	J	K	L	Responsibility
Design Circuit	A	A												Design Center
Select Components	B	X	B	X				X		X				Design Center
Develop Image Layout	C	X	X	C		X				X				Design Center
Panelize image into PCB	D			X	D	X	X	X		X				Design Center
Develop PCB photo tools	E			X	X	E				X				PCB Fab
Develop assembly tools	F		X	X	X		F			X				LCAC
Develop assembly programs	G		X	X	X			G		X				LCAC
Develop assembly documentation	H		X	X	X		X	X	H	X				LCAC
Verify tool/prog. compatibility.	I		X	X	X	X	X	X	X	I				LCAC
Manufacture PCB	J					X				X	J			PCB Fab
Manufacture tooling	K						X			X		K		LCAC
Assemble PCA	L		X				X	X	X	X	X	X	L	LCAC

Coupled Tasks Potential Iteration

Three Organizations Involved

A. Design Circuit -- developing the circuit scheme that delivers the desired outputs based upon a given set of inputs.
B. Select Components -- replacing the generic devices of the schematic with appropriate, sourcable components.
C. Develop Image Layout -- converting the schematic and component information into a manufacturable circuit layout.
D. Panelize Image into PCB -- locating the images and the corresponding assembly fiducials into the PCB substrate blank.
E. Develop PCB photo tools -- converting the panelized image infrormation into photo tools for manufacturing the PCB.
F. Develop assembly tools -- converting the panalized image information into vacuum plates, stencils, and other tools for assembly.
G. Develop assembly programs -- converting the panelized image information into software tools for assembly machines.
H. Develop assembly documentation -- delivering all of the special instructions and details to the operators in a usable format.
I. Verify tool/program compatibility -- running software checks to ensure all functions are working with consistent data.
J. Manufacture PCB -- manufacturing the bare PCB.
K. Manufacture tooling -- manufacturing the vacuum plates, stencils, and other tools for assembly.
L. Assemble PCA -- Integrate all tools, components, PCB, and programs into the PCA utilizing the appropriate processes.

Figure 3.3 (duplicate): Design Structure Matrix for PCA Development

The TDR allows for a great deal more determinism in the delivery of the assembled PCA prototype for these imperfect designs by removing the variability associated with problem resolution iterations. This determinism enhances the design team's ability to do scheduling and resource planning. Also, the process will facilitate learning by forcing greater levels of interaction among all of the various functions. The availability and utility of information is enhanced without sacrificing, and indeed improving, the classical manufacturing measurements of cost, quality, delivery, and flexibility.

5.2. Strategic Design Review

LCAC should develop a strategic design review (SDR) process to improve communication of problems and opportunities to the design team during the design stage of the PCA prototyping process. The "design stage" here refers to all of the activities that occur before design data has been transmitted to LCAC for a PCA prototyping order. These activities include design of the circuit logic, selection of components, and development of image layout.[12] Because the design has not been uploaded into a CAD format at this stage, opportunities for improvement are strategic in nature. These opportunities deal with the issue of determining the optimal production process for delivering the functional PCA required by the designer for the final customer's application.

5.2.1 Impact on Customer Requirements

A SDR has potential to improve the satisfaction level for five of the customer needs presented in section 4.4.2, Detailed Definitions of Meaning for Customer Requirements. These five needs are duplicated below. They are enumerated in order of customer importance according to the data presented in Table 4.4, *Survey Summary Statistics--Designer Responses*. For each of these, details are presented regarding how a SDR would improve customer satisfaction.

1. *Communicating with the correct person to resolve a prototype problem is easily accomplished.* In instances where the designers are confused regarding a series of manufacturing tradeoffs, the SDR would be a proper forum for asking questions and receiving clear answers. The correct person for resolving these issues, in most cases the NPI engineer, would be an active participant in the process.

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[12]More detail on each of these activities is presented in the design structure matrix of Figure 3.3, Design Structure Matrix for PCA Development. These activities correspond to tasks A through C, *Design Circuit* through *Develop Image Layout*, in the matrix.

3. *The design center has complete information on LCAC changes to the design that made it more manufacturable.* A SDR would present all of the information regarding LCAC design recommendations during a single, interactive forum. The information would be complete and highly usable due to the interactivity of the review.

4. *Manufacturability of a design is easily determined by the design centers prior to proto data release.* By incorporating a manufacturability index into the SDR methodology, it would be very easy to correlate the manufacturability of the design to the characteristics of the design. Various trade offs and scenarios would be suggested and evaluated interactively during the review.

8. *New part types are easily assimilated into the proto run.* A SDR would facilitate discussion regarding the introduction of new part types. This discussion would improve assimilation of new part types into the proto run.

10. *The information to assemble the board as the designer wishes is readily available to proto operators.* The communication from the designer to the proto operators would be improved by having the designer interact with LCAC personnel during a SDR. Even without the operator present in the review, information regarding the designer's wishes can be easily disseminated within LCAC if the NPI engineers at LCAC are familiar with the issues.

5.2.2. Other Impacts of a Strategic Design Review

Aside from the direct impact on the customer requirements listed above, a SDR should improve other general competitive dimensions for H-P and LCAC. A SDR would increase sharing of knowledge across the organization, raise the productivity of the manufacturing effort at LCAC, and improve the viability of LCAC as the supplier of choice for their design center customers.

5.2.2.1. Effective Sharing of Knowledge

Sharing of knowledge across the organization is important because not all knowledge can be easily communicated in the form of standards and guidelines. For example, the standards document for PCA design for manufacturability is document 926: *SMT Device, Design, and Documentation.* The designers refer to it as "926 du jour" because it seems to change constantly. It is also very hard to use in their opinion. The document has grown so cumbersome that most designers pay little attention to it now.

A SDR would improve the sharing of knowledge and the communication of issues by establishing a forum for sharing experiences and stories. This sharing would facilitate learning. It would also address only the issues that are relevant to delivering the design that is currently in development. In this manner, the scope of the interaction is much more focused and detailed as compared to an all encompassing document like document 926. The design and manufacturing organizations would establish a closer relationship with each other, and appreciation for the needs of each functional area would be heightened. The SDR would help establish effective relationships for the future.

5.2.2.2. Improving Manufacturing Productivity

The manufacturing productivity of LCAC would improve as a result of the implementation of the SDR. The SDR would enhance the manufacturability of the PCA designs that LCAC must support with production capacity. The cost, quality, and delivery performance of LCAC would improve due to the increased manufacturability of the PCA designs entering production.

Figure 5.4 presents two simple causal loop diagrams that illustrate the production situation with and without the SDR. These diagrams are based upon the assumption that there is a finite amount of NPI engineering expert resources that must be divided among two tasks: improving the production process and improving the manufacturability of designs. These two tasks are represented in the diagram as *Attention to Production Processes* and *Attention to Design* respectively. Focusing a disproportionate amount of the scarce resource of NPI engineering on improving the processes without improving the designs increases the depth of knowledge within LCAC. However, this process knowledge is not shared effectively because there is no time for sharing due to the proliferation of "dog designs" that must be supported in production. This phenomenon is illustrated in Diagram 1 of Figure 5.4.

Diagram 2 of Figure 5.4 illustrates the effect of increasing the amount of time devoted to sharing knowledge across the functional boundaries of design and manufacturing. This sharing creates a positive reinforcement of behaviors that improve competitiveness. The designers become more knowledgeable of manufacturing issues and how to improve the

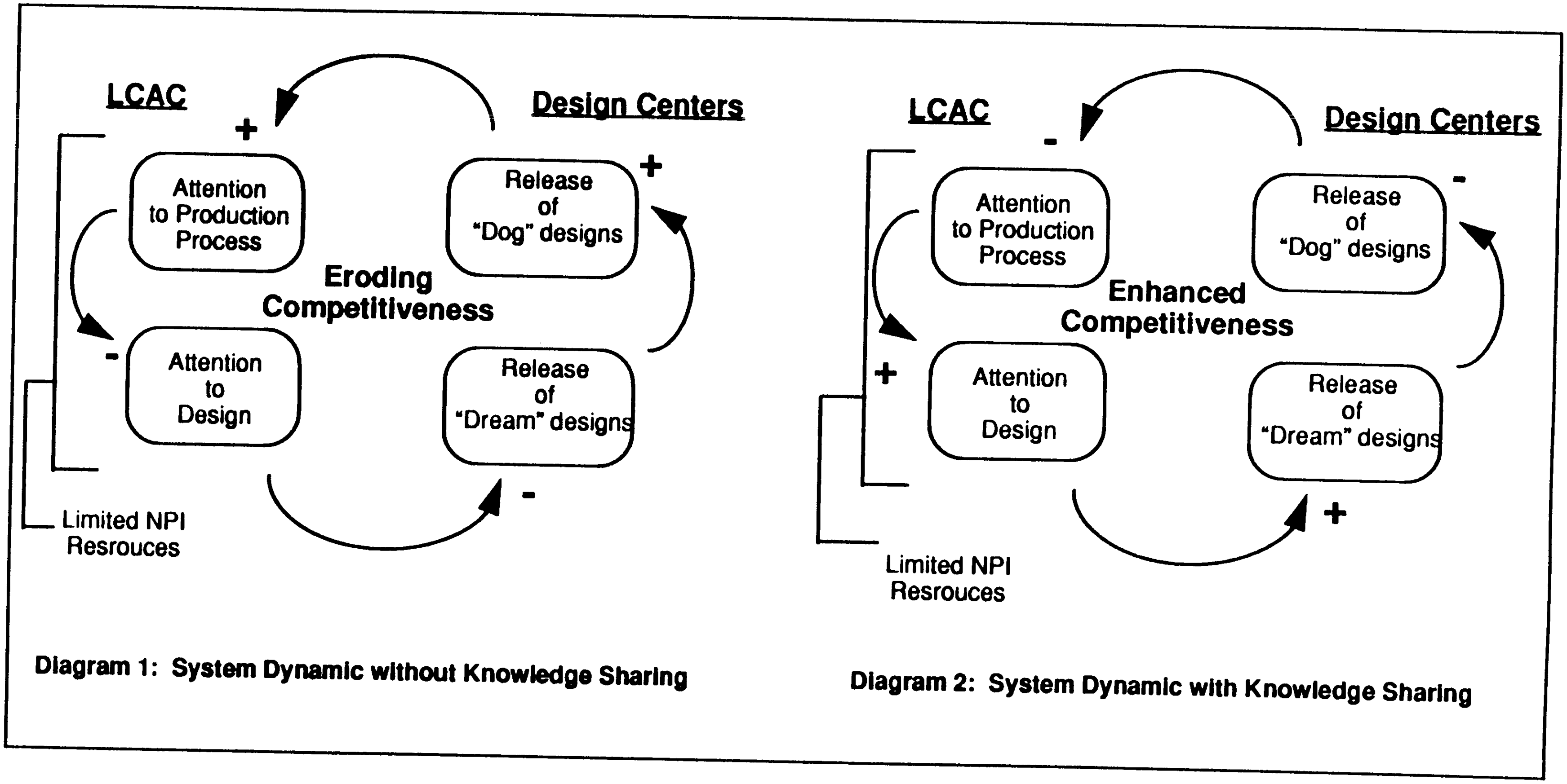

Figure 5.4: Causal Loop Diagrams for System Dynamic of Sharing Knowledge

quality, cost, and delivery for their designs. The NPI engineers become more knowledgeable of the requirements that the designers will have for future process improvements. In this manner, their efforts to improve the process become much more focused on the customer's needs. The LCAC technology roadmap for future process development becomes more aligned with the direction of its customer's design needs. The NPI engineers will spend less time improving the process, but their improvements will have a greater impact.

The opportunity of an SDR to improve the productivity of the manufacturing process is reinforced by the Pareto principal. The majority of improvement efforts should address the largest potential area for improvement. The limited resources of the NPI engineers should be focused on the tasks that have the largest potential for enhancing competitiveness. For PCAs, the vast portion of the manufacturing costs are determined prior to the release of the drawings and specifications. When only 35% of the design budget for a PCA has been expended, 60% of the manufacturing costs for that PCA design have already been determined. (Holden, Kenyon, 1994) The SDR addresses this phenomenon by beginning the improvement efforts earlier in the development process when the opportunity for improvements has not been diminished by irreversible decisions.

5.2.2.3. Improving LCAC Viability

Implementation of an effective SDR procedure would improve the viability of LCAC as a long term supplier of manufacturing capacity within H-P. The systems benefits provided by the SDR would raise the switching costs for the design labs to select alternative suppliers for prototyping or manufacturing their PCAs. The cost of switching to another supplier becomes a barrier because other suppliers will have difficulty providing the benefits of a SDR on a short time schedule. Without the SDR, only the transactional costs associated with quality, cost, and delivery are considered regarding the purchase of PCA prototyping and manufacturing services. By implementing the SDR, LCAC can begin marketing their services based upon the relationship benefits instead of marketing them based solely upon the transaction costs. (Bund, 1989) By measuring and communicating the successes associated with the SDR, an effective relationship marketing plan would establish LCAC as the supplier of choice for a longer time horizon.

5.2.3. Implementation Guidelines

For the SDR to be implemented as an effective process, four issues need to be considered:

- customer's needs regarding the SDR
- data to incorporate into the tools that will be utilized in the SDR
- format of the tools that will be utilized in the SDR
- participation of relevant persons in the SDR

Each of these four issues must be addressed in development of a SDR methodology. A potential solution set is provided below as a framework for beginning the development of the SDR at LCAC.

5.2.3.1. Determining Customer Needs Regarding the Strategic Design Review

The needs of the design center customers should be quantified regarding early stage communication and consultation. The team that is assigned to develop the SDR process should interview customers utilizing the same type open format described in section 4.1, Interview Questions and Demographics. All members of the team should participate in this exercise to develop a detailed, common understanding of the customer's needs regarding a potential SDR. The interview questions should focus on the weaknesses of the current mode of communication. The types of communication that would address future needs of the customer should also be explored during the interview process. As the customer begins to relate details of weaknesses and future needs, more specific questions can be raised to probe for additional insights. For example, the team should consider asking the customers how a design review would have to be structured to ensure participation on the part of the designers and project managers. This question is analogous to asking customers of a product how they will make their purchase decision.

After a sufficient number of customers have been interviewed (20 interviews spread across several customers should be enough), the team should distill the customer voices into images and requirements. At this stage, the team should use its discretion in determining how to establish the importance of each of the requirements. A full survey methodology is probably not necessary. Team voting and discussion would probably be sufficient, and this method is considerably less time consuming than surveys. The resulting requirements should guide the team in developing the concept for the SDR. A simple matrix process can be utilized for evaluating potential concepts and iterating to the most desirable implementation scenario. (Eppinger, Ulrich, 1994).

5.2.3.2. Using Data to Develop Strategic Design Review Tools

In order for the recommendations presented by NPI engineers to be credible, they must be based upon data related to the manufacturability of PCAs. This data takes the form of failure, rework, and cost statistics for processes, components, and configurations. For example, any configuration that involves a great deal of manual handling or manual assembly will be subject to higher failures due to craftsmanship errors. These failures are documented within the quality systems at LCAC. Similarly, field failure statistics for components should be considered in the development of the SDR tools. Garrison, Hume, and Komm provide an excellent example of the type of information that should be considered for a SDR in "Design Report Card: A Method for Measuring Design for Manufacturability."

The NPI engineers have access to a wealth of information regarding the weaknesses associated with particular processes, components, and configurations. The real issue is prioritizing this data and presenting it in a usable format. It is recommended that the tacit knowledge of the NPI engineering group be used to prioritize the data. All potential sources of data should initially be considered. Then, through a team voting and discussion approach, the sources of data for the SDR should be narrowed to a reasonable scope and prioritized for importance. Once a reasonable scope has been established, more sophisticated tools, such as regression analysis, can be utilized for further prioritization of the issues.

The team should include manufacturing issues that are troublesome without being well understood. In many cases, definitive data is not available for particular configurations that are very difficult to support through the production process. These difficulties should be considered when developing the basis for the SDR tools. When future process improvements remove these difficulties, the SDR tools can be modified to reflect the new robustness of the manufacturing process to what was once a difficult configuration. The intelligence that is incorporated into the SDR tools should be dynamic. As the process changes or improves, these improvements should be reflected in the SDR tools and communicated to the designers.

5.2.3.3. Format for Strategic Design Review Tools

The three main concerns regarding the format of the SDR tools are:

- simplicity,
- user ownership and maintenance,
- and solution orientation

Simplicity

Simplicity is important for a number of reasons. A difficult algorithm or a complicated implementation of a simple algorithm will be hard to explain to the designers during the SDR. If it is hard to explain, the designers will be suspicious of its validity. A simple algorithm with a simple implementation will facilitate credible discussion about the real issues. Correspondingly, this simplicity will minimize bickering regarding the validity of the underlying intelligence that supports the tools. Simplicity also ensures ease of user maintenance and improvement.

User Ownership and Maintenance

User ownership and maintenance are important to ensure the tools remain current. If the users have to rely on some other group to update or improve the tools, it is unlikely that the tools will get updated or improved. The NPI engineering users must be able to react quickly to designer improvement suggestions to maximize the impact and utilization of the tools. Also, as the manufacturing processes are updated and refined, these changes should be quickly incorporated into the SDR tool algorithm.

Solution Orientation

Finally, the SDR tools should be used in a solution oriented manner. This type of utilization implies that the NPI engineers must do their homework before engaging the design centers in a SDR. The tools should be able to display several potential scenarios and their resulting strengths and weaknesses. In this manner, the SDR will progress quickly towards an acceptable solution through discussion of the rationale for particular strengths and weaknesses. This discussion will facilitate understanding and learning.

5.2.3.4. Incentives for Participation of Relevant Persons

In order for the SDR to be effective, the correct persons must participate in the process. At a minimum, these should include the design engineer, the layout engineer, the NPI engineer, the PCB board vendor, and the material specialist. Other relevant participants might include the project manager, a production technician, and an engineering manager from LCAC. Due to the autonomous nature of the H-P culture, participation of the relevant persons from the design centers can only be achieved by affecting the measurements that impact the design project team. The most obvious choices for measurements to impact are the project budget and the project schedule.

Pricing and scheduling policies can be developed by LCAC to achieve the desired impact on project schedule and budget. Initially, it will appear that participation in a design review will add time to the schedule by requiring the designers to take time out of their already busy schedule. However, if those designs that have had a SDR are given assembly priority within LCAC, convincing the project managers of the expediency of the review will be easily accomplished. In a similar manner, if a rebate is offered for prototyping charges based upon the participation level of the project team in the SDR process, high levels of participation will probably be achieved.

Another clever way to incentivise the design project team to participate in an SDR is to appeal to their achievement oriented and competitive nature. One manifestation of the SDR is the previously mentioned non-dimensional score for manufacturability. Rather than using this number as a stick for punishment, it should be used as a carrot for reward. The measurement should be utilized such that the designers receive accolades for achieving high scores. Compare the scores to previous scores for similar designs and scores for competitor's designs. The accolades for a high or record setting score can come in the form of price rebates or congratulatory letters from the GM of manufacturing to the project manager on behalf of the designer. This type of response could have a very positive impact on the enthusiasm for participation in the SDR.

One final note on participation is appropriate. The initial customer for the SDR should be one that is willing to experiment and offer constructive criticism for improvement of the early process. Preferably, it will be a local customer that has been easy to work with in the past. This customer should be offered additional preferential treatment for being the guinea pig of the SDR.

5.2.4. Summary of Strategic Design Review Impacts

An SDR would address the customer needs that relate to information availability and utilization. It would serve the prototyping purposes of learning and communication by providing a specific forum for discussion of issues particular to new PCA designs. The current consulting services offered by LCAC are effective when the design center customers engage LCAC early in the process and are receptive to the suggestions presented by the NPI group. An SDR has the potential to improve the current integration of the organizations if the following issues are addressed:

- develop a simple algorithm for scoring manufacturability of designs
- communicate basis for algorithm
- maintain algorithm flexibility for future changes and improvements
- incentivise participation by impacting design budget and schedule favorably

In this manner, effective relationships for future competitiveness are established. The design center customers will participate in the reviews to improve their budget and schedule measurements, and the hard work and thoughtfulness that LCAC put into the process will be evidenced by the tools and discussion formats utilized. LCAC can begin a process of marketing its services based upon the value of its communication efforts. The knowledge of the organization will be more available and easier to utilize to improve designs and processes. Potential competitors to LCAC will have a difficult time imitating these relationship type services. The long term viability of LCAC as a manufacturing center should be enhanced through improved customer satisfaction and through more efficient production performance due to greater manufacturability of PCA designs.

6. Conclusion

LCAC has a difficult challenge in supplying fourteen H-P divisions with PCA production capacity and prototyping services. LCAC management faces the task of determining how to utilize the resources at LCAC to satisfy customer's needs and deliver competitive advantage to H-P. For production requirements, the metrics of cost, quality, delivery, and flexibility provide a thorough framework for evaluating performance. (Fine, Hax, 1985) For PCA prototyping efforts, however, the effectiveness of the process cannot be measured solely with manufacturing metrics.

Information availability and utilization are important dimensions for improvement of LCAC's prototyping service. Data gathered through 24 interviews and 47 surveys indicates that the greatest opportunity to improve the PCA prototyping process is through initiatives that enhance the availability and utility of information generated during prototyping. Seven of the top thirteen requirements for improvement are directly related to how information is made available and how it is subsequently utilized. These findings are consistent with the challenges to information sharing presented by:

- the organizational diversity of H-P,
- the geographical boundaries separating LCAC from its customers,
- and the iteration inherent in the current PCA prototyping process.

These are considerable challenges that must be overcome to integrate the knowledge of LCAC with the knowledge of its customer base during PCA prototyping.

6.1 Recommendations Highlights

Improvements in information availability and utilization can be realized through the implementation of design reviews during particular phases of the PCA development effort. A strategic design review methodology and a tactical design review methodology are recommended to address the particular issues of LCAC and its customer base.

6.1.1. Strategic Design Review

The important features of the strategic design review are:

- Early involvement when opportunities for improvement are greatest
- Simple algorithms for discussion based upon NPI engineering knowledge
- Solution orientation that capitalizes on opportunities identified during process

Effective implementation of the strategic design review will require LCAC to solicit their customers regarding the weaknesses inherent in the current consulting services offered by the NPI engineers. Based upon the responses, a process that provides the correct incentives for involvement should be developed. The value that is provided through the strategic design review must be easy to recognize if it is to be used extensively by LCAC's customers.

If the strategic design review is widely utilized, the information that is made available through the discussion will enhance the competitiveness of H-P. By focusing on the issues of a particular design using simple, solution oriented tools, knowledge regarding the specific needs of LCAC and the design customers will be transferred across the organizational boundaries. Future designs will become more manufacturable; the manufacturing process improvement efforts of LCAC will be focused on the needs of the customers. The relationships that are established through this strategic review process will position LCAC as the most valuable supplier of PCAs for many of its customers.

6.1.2. Tactical Design Review

The important features of the tactical design review are:

- Timely communication of issues
- Direct communication between manufacturers and designers to avoid misunderstanding
- Synchronization of data correction efforts to avoid iteration

As with the strategic design review, LCAC should solicit input from customers regarding the weaknesses of the current solution resolution process. If the tactical design review is developed with understanding of these weaknesses, the value for customer participation should be easy for LCAC to communicate and easy for the customers to recognize.

All of the key items address the potential to reduce the turn around time for PCA prototypes. For flawed or misinterpreted design data, the current PCA prototyping process is susceptible to a great deal of variation in turn around time due to the process structure. The interdependency of the tasks that must be performed by several different persons to resolve discrepancies results in iteration. By addressing the issues is a timely manner, with direct communication, and synchronized corrections, the time required for correcting data flaws becomes much less variable. PCA prototype turn around time should improve with this reduction in variability.

6.2 Summary Comments

By focusing on the needs of the customers and by scrutinizing existing processes in light of these needs, LCAC can establish improvement initiatives which increase the satisfaction of the customers of the process. The basis for improvement initiatives should be the detailed understanding of the customer that is obtained by interactions with the customer at all levels by several of LCAC's personnel. The TDR and the SDR presented in this thesis are foundation concepts to begin the process of increasing the value of PCA prototyping based upon customer needs. These results and the corresponding methodologies are a starting point for a continuous process of evaluating customer requirements and changing the process to enhance the competitiveness of the enterprise.

Appendix 1: References

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Appendix 2: Sample Interview Transcripts

R&D Project Manager
July 20, 1994

High performance data acquisition products. Analog intensive and high density.

Must design in diagnostics and self test for manufacturing.

Images:
People standing around a cubicle waiting for the first board to come back. The anticipation of the first time. What will it do, is it ready to go.

You can be very confident of a paper design, but our accuracy is so high that getting the stuff of the board has a large affect on the performance of the circuits. Getting the product back is the proof of your efforts.

Frustration of sitting there waiting like waiting in the doctors office not knowing if you are going to be called next.

Current basis of selection:
We work at high density. High R is a requirement. TAT is a requirement.

TAT is a key driver, and quality is important in the testing phase, but you are willing to sacrafice a little quality during the prototype if that means quicker TAT.

The thing that drives my cost is headcount dollar driven. 90% of my cost is time. Reasonable turn around is important.

Other tradeoffs: do I turn the board again or do I work with the board I have in hand and not risk the time to turn another board.

Try to do the right things the first time.

Really want to prototype where you are going to build it for a manufacturing reality check. The manufacturability feedback is critical.

The earlier you get the information the cheaper it is too make it right.

Adequate technology is required. Not bleeding edge.

Weaknesses:
Needs and user needs point of view. We design into a known process. Work with a partner to be able to understand what the process is and be proactive in developing the physical product.

Good working relationship with the process engineers. But the guidelines change rapidly.

People are trying to determine if no clean is really going to work.

I view a proto shop as someone who can take my data and make it work and tell us what to fix next time.

Serial rework loops are not satisfactory. We want parallel rework loops. We have to fix too many problems while the proto is on hold.

The time to physically build a board is too long.

days is the window from data to boards that we want.

We use the breadboard process for initial turn on. The second run is a larger run for software developers, beta site evaluation, manufacturing build data.

They are protos, not prodution.

Sometimes I am changing my parts or layout, but I want a run of the last revision. The system does not handle that very well because they believe that there can be only one set of data.

Protos are not production, protos are not production, protos are not production.

Protoing within a production process has its limitations.

The solder quality is survivable for prototyping, but it is not good enough for production.

Non value added screening for defects is a weakness probably due to no clean.

Strengths:
The technology gives me a density advantage.

Geographical proximity to the NPI engineers and process engineers is extremely helpful. They have a really good user needs focus in that group.

The coordinators and people on the line are really trying to meet the customer needs. It causes some conflict and stress when they are trying to satisfy the customer and they are not towing the team or party line of the organization.

The people doing the work are really trying.

You want to work with partners. You do not want to send them crap. You want to give a best faith effort and then listen to the advice they give you for the next time.

good people down in the trenches.

Future capabilities:
We need to have a good flexible way to communicate with our design tools.

If there are process specific requirements, such as when the organization changes the process, that we have to change things, those changes should be owned by the process not by the design group. They should do it themselves. Test fixtures should be born by the process. The process is not capable, then they should pay for that lack of capability. If they do not have to pay for the screening mechnanisms, then there is no incentive to make it better to get rid of them.

Flexibility and TAT in prototyping. TAT is not reasonable. day TAT is adequate, rarely do you need it shorter. If I do want it shorter I would be willing to pay for it. If I am going to do a large run on the prototype line, I would expect to pay more for that than the same quantity in a production setting.

Customs or personalizations would be nice to build on a prototype line. We will never see that design again, and there is no reason to make it super producible.

Reasonable quality. It is not production. the process should be flexible by having things available, making things work and getting design for manufacturability back in a hurry.

TAT is from data sent to boards on desk.

Determinism is critical. I need to be able to plan within a reasonable window. Just let me know when it is going to happen. Give me a good, accurate delivery date.

It takes a pretty good need to require a day TAT. I don't think I would use that a lot. Sometimes to get a line going again, but not for protos.

Currently I am seeing about .

Final images:
I like the flexibility of breadboard. If protos were to days, I would never use breadboarding. it is nice to get one or two things turned on.

I would like to throw the switch from proto to production without it taking to weeks. A quick and smooth migration would be useful. If there are data issues, make it work and get us the data fixes back as soon as possible.

Adequately stay up on technology. The entity that owns technology should be mapping the processes that will be necessary.

Design Engineer
July 18, 1994

Responsible for electrical design of signal conditioning modules. Take idea from conception to a schematic that will do the job, have it laid out, protoed, and then turn it on and test it out.

Nothing really flashes to mind in terms of images. Maybe a process that really isn't mainstream with a lot of hand operations. The word prototyping itself implies somethin not normal. Have to be very versatile to do it. Therein lies some of the problems because there is a wide variety of things that do not have to be handled yet in production.

The period of prototyping is kind of a lull. We reflect and take another look. Often we find errors. Hopefully we can still do something about it at that stage.

We also begin developing our testing routines for the boards at that time.

Weaknesses
Problems loading the board. Bad solder joints or cold solder or a crack or polarity. Those cost us big time. Rare parts that we cannot afford to lose.

It becomes a real struggle for us. We have to do characterizations as well as trouble shooting board problems. They usually come back pretty good for the most part.

The human aspect is a weakness of the system. But that also gives us the quick turnaround time.

Strengths:
The fact that we got the boards. Mostly the parts are put down properly. One out of 100s isn't necessarily that bad.

I like the fact that we have a prototype facility with the quick turnaround time. My time at $/hr is expensive waiting for a board to come back to test.

The speed of the breadboard, flexible process is a strength, but it is also the biggest opportunity for error.

The fact that we are physically located in the same site is excellent. The feedback path is shorter, but I do not know how well we really utilize that.

Future:
Density issues in general. We cannot even afford the space for a label. Buried vias and blind vias are on the way.

Spacing between components is going to get tighter.

Always the schedule issue. Really out of my area, so I don't think about it much. I have to live with whatever it is, I can't worry about it.

We are doing more and more simulations on computers. It only goes so far however. A strength is the opportunity to turn a couple of boards on before we order 30 or 50 of them. Then we can change material lists, etc. before we get all of the production run. Two answered a lot of questions. Had we not built these two, we would have had a lot of work to do reworking them.

Unique parts costs. Something needs to be done to address this some way. Leverage the corporation or something.

Final Images:
The working relationship with is good. Their ability to come over and talk things out is a strength. We should try to capitalize on that a little more. Make the interface a little smoother.