A Decomposition-Based Approach for the Integration of Product Development and Manufacturing System Design

by

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ABSTRACT

Using a structured approach to understand the interaction between product design decisions and manufacturing system design is critical to reflect manufacturing system issues early in the product development process. Early consideration of manufacturing system issues prevents product design iterations due to manufacturing system constraints or unnecessary manufacturing system design modification to accommodate new product designs. However, in academia and industry, few frameworks are available to capture the interaction between manufacturing system design and product design decisions.

This thesis presents an approach to capture the interaction between manufacturing system design and product design decisions, which is called manufacturability evaluation process. The manufacturability evaluation process aims to guide product development teams to see the effects of their design decisions on manufacturing systems and thus, to make the right decision from the early stage of product development. The manufacturability evaluation process satisfies four objectives: 1) to describe the objectives of manufacturing systems clearly separated from the means of achievement, 2) to present the impact of various design decisions on the achievement of the objectives of manufacturing systems, 3) to provide a common platform to effectively communicate the impact across the organization, and 4) to provide a framework to put existing tools together to integrate manufacturing system design and product design. The manufacturability evaluation process is based on a recently developed Manufacturing System Design Decomposition (MSDD).

This thesis describes three groups of case studies to identify industry practices and provide application examples of the proposed manufacturability evaluation process. The manufacturability evaluation process has been successfully applied to the cases. In addition, the interaction between manufacturing system design and product design decisions are discussed with industry case study examples in the automotive industry. An evaluation tool is developed to evaluate the general practices of a company ensuring the manufacturability of product designs. Furthermore, this thesis provides a basis for future research to extend the scope of the MSDD into product development areas.

Thesis Supervisor: David S. Cochran, Associate Professor of Mechanical Engineering
Committee Member: Professor Deborah J. Nightingale
Committee Member: Dr. Hugh L. McManus

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ABS	Antilock Braking System
AMSDD	Aerospace Manufacturing System Design Decomposition
ASR	Acceleration Slip Regulation
AGV	Automated Guided Vehicle
APQP	Advanced Product Quality Planning
AS/RS	Automated Storage and Retrieval System
BR	Business Requirement
CA	Customer Attributes
CAD	Computer Aided Design
CE	Concurrent Engineering
CIM	Computer Integrated Manufacturing
CIMOSA	CIM Open System Architecture
CNC	Computer Numerical Control
CR	Customer Requirement
CT	Cycle Time
DD	Detailed Design
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
DFV	Design for Variety
DFX	Design for X
DM	Design Matrix
DP	Design Parameter
e.g.	Exempli Gratia (for example)
ERP	Enterprise Resource Planning
EWIP	Emergency Work In Process
FMS	Flexible Manufacturing System
FR	Functional Requirement
GIM	GRAI Integrated Method
GRAI	Graphe a Resultats et Activities Interlies
HOQ	House of Quality
i.e.	Id Est (that is)
ILVS	In Line Vehicle Sequence
IPPD	Integrated Product and Process Development
JIT	Just In Time
MI	Manufacturing Implementation
MR	Manufacturing Requirement
MRP	Material Requirements Planning
MP	Manufacturing Parameter
MS	Material Selection
MSD	Manufacturing System Design
MSDD	Manufacturing System Design Decomposition
P	Purchasing

PA	Product Architecture
PD	Product Design or Product Development
PDDD (PD^3)	Product Development Design Decomposition
PDSDD	Product Development System Design Decomposition
PM	Performance Measure or Preventive Maintenance
PS	Process Selection
PSD	Production System Design
PV	Process Variable or Product Variety
QFD	Quality Function Deployment
ROI	Return on Investment
SBCE	Set Based Concurrent Engineering
SCORE	Structured Company Operational Review & Evaluation
SE	Simultaneous Engineering
SMED	Single Minutes Exchange of Die
SPC	Statistical Process Control
SWIP	Standard Work In Process
TIPS (TRIZ)	Theory of Inventive Problem Solving
TPM	Total Productive Maintenance
TPS	Toyota Production System
TQM	Total Quality Management
TQD	Total Quality Development
VDC	Vehicle Dynamic Control
VDI	Verein Deutscher Ingenieure
VSM	Value Stream Mapping
WIP	Work In Process

1 INTRODUCTION

Product development is a series of organized activities to realize a product concept into a finished tangible product. Product development begins with the perception of a market opportunity and ends in the production, sale, and delivery of a product [Ulrich and Eppinger 2000]. Product design, process design, and manufacturing system design are core activities in product development. These three core activities significantly affect the success of a new product development project, which eventually shape the prosperity of a manufacturing company. Among the core activities, product design had been conceived as the activity that should be done first, followed by process design and lastly, manufacturing system design. In some sense, it is a natural sequence since process design or manufacturing system design exists to turn a given product design into a physical product. Therefore, it had been customary to finish product design first and deliver product design data to a production engineering group for process design, and then to manufacturing group for production.

However, in today's market where competition based on 'time-to-market' is strongly dominant, it is key for success to minimize the time between product concept and product realization [Ulrich and Eppinger 2000], [Utterback 1994], [Fine 1998]. The traditional sequential approach is not competitive in this market environment. One way to shorten the time between product concept to market is to minimize design iterations caused by downstream constraints and unnecessary downstream system changes resulting from inappropriate upstream decisions. Therefore, a new way of product development has been proposed that considers downstream issues in the earlier phase of product development to minimize potential problems later on (e.g., Andreasen [1987], Clausing [1994], Clark and Fujimoto [1991]). For example, manufacturing is supposed to produce given product designs. However, it can be very costly and time consuming to modify a manufacturing system [Heragu 1997] to support a new product design that does not fit to the existing manufacturing system. Therefore, if the existing manufacturing system is considered during product design and a new product is designed within the existing manufacturing constraints, the existing manufacturing system can more easily produce the new product and thus, total product development time and cost are minimized. This rationale is summarized in Figure 1-1.

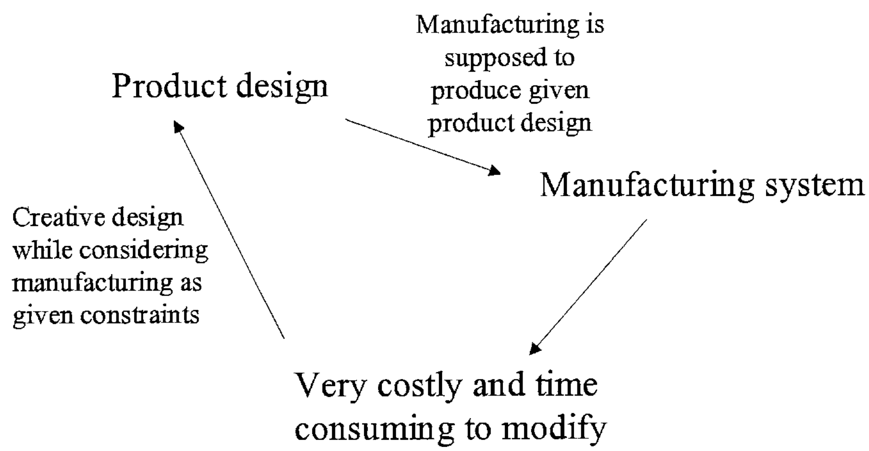

FIGURE 1-1. THE RELATIONSHIP BETWEEN MANUFACTURING AND PRODUCT DESIGN

To avoid design iterations and make correct decisions in the early product development phase, well-planned coordination of the core activities is essential, along with a lively exchange of information between functional groups responsible for each of the core activities. A number of structured methodologies have been developed to find the most efficient way to coordinate these three activities at various abstraction levels. Some of the examples are: Concurrent Engineering (CE), Robust Design, Simultaneous Engineering (SE), Design for Manufacturing and Assembly (DFMA), and Total Quality Development (TQD). Each of these methodologies provides useful tools to coordinate the core activities and ensure the information exchange between the functional departments typically responsible for each of the core activities. Typically, the product design (or engineering) group, production engineering group, and manufacturing (or production) group are responsible for each of the core activities.

These methodologies, however, often neglect or only partially consider the issues of manufacturing system design. For example, the traditional DFMA approach proposed by Boothroyd et al. [1994] focuses on process, material, and equipment issues without considering scheduling or changeover issues of manufacturing system design. Even in cases where manufacturing engineers participate in cross-functional product development teams, as suggested by the CE and SE approaches, tools are not readily available for review by manufacturing engineers as to adequateness of a product and process design from a manufacturing system viewpoint. The result is ad-hoc application of principles available in academia or rule-of-thumb guidelines based on engineers' personal experience. This approach often leads to endless design modifications or costly manufacturing system modifications, which lead to subsequent loss to the company. Therefore, a systematic approach to understand the interactions among product design, process design, and manufacturing system design is critical to reflect manufacturing system issues early in the product development processes and to avoid unnecessary manufacturing system design modifications to accommodate new product or process designs. Early consideration of manufacturing system design issues during product development is important, considering manufacturing systems often cannot be easily developed or modified [Heragu 1997].

This thesis presents an approach to capture the interactions between manufacturing system design and product development. This approach helps product development teams to see the effects of their design decisions on manufacturing systems and thus, to make a right decision in the early stage of product development. As a basis of the proposed approach, a recently developed manufacturing system design decomposition (MSDD) is applied. In addition to the proposed approach, interactions between manufacturing system design and product development will be discussed with an industry case study example. Without a clear understanding of the interactions between various aspects of manufacturing system design (e.g., material flow design, line balancing, etc.) and product development decisions (e.g., variety decision, product architecture decision, etc.), true concurrent engineering cannot be achieved. This understanding is important even to avoid having manufacturing engineers sitting in the corner of the meeting room and simply wasting their time during numerous product development meetings. If the manufacturing engineers clearly understand what part of their knowledge can contribute to avoiding product design decisions that negatively affect manufacturing systems, their productivity can be greatly improved.

1.1 Motivation

The introduction of a new product design to an existing manufacturing system affects the design and operation of the existing manufacturing system. Therefore, extensive consideration of the consequences of the new product design on the design and operation of manufacturing systems is necessary. Based on the extensive study of the effect of the new product design on the performance of manufacturing systems, it can be identified whether the product design decision affects manufacturing systems in a positive way or a negative way. Then, if there is any negative impact, it should be decided whether product designs would be modified or manufacturing systems would be modified in order to eliminate the identified negative impact. Even when a new manufacturing system or a production line is constructed for the new product design, the same rationale applies. A simultaneous consideration of both manufacturing system design and product design should be made. Except for the financial considerations associated with a development of a new manufacturing system, the only difference between modifying existing plants and constructing new ones will be a level of manufacturing constraints given to the product development team. When a new product is produced at an existing plant, the existing facility and the existing production of other products within the plant will behave as manufacturing constraints. However, this rationale is not extensively deployed in a typical product development process in the auto industry.

In the auto industry, it usually takes about three to four years to develop a new model of a car. This development is followed by four to five years of consequent commercial production of the model. During the commercial production, a new car design is developed and released for continuous sales. According to the cycles of model changes, manufacturing plants where the new product design is realized are modified, or sometimes newly constructed to accommodate the new product design. In fact, it is more typical to modify existing manufacturing plants, considering much longer lifecycle of a manufacturing plant than that of a product. The modification of existing manufacturing plants often involves large investment to change the tooling of the existing equipment or to implement a new production line. Sometimes, a manufacturing plant is re-equipped for its own sake (e.g., replacing old machinery, changing material flows for system improvement, etc.). Figure 1-2 illustrates a typical relationship between product development projects and manufacturing system design changes.

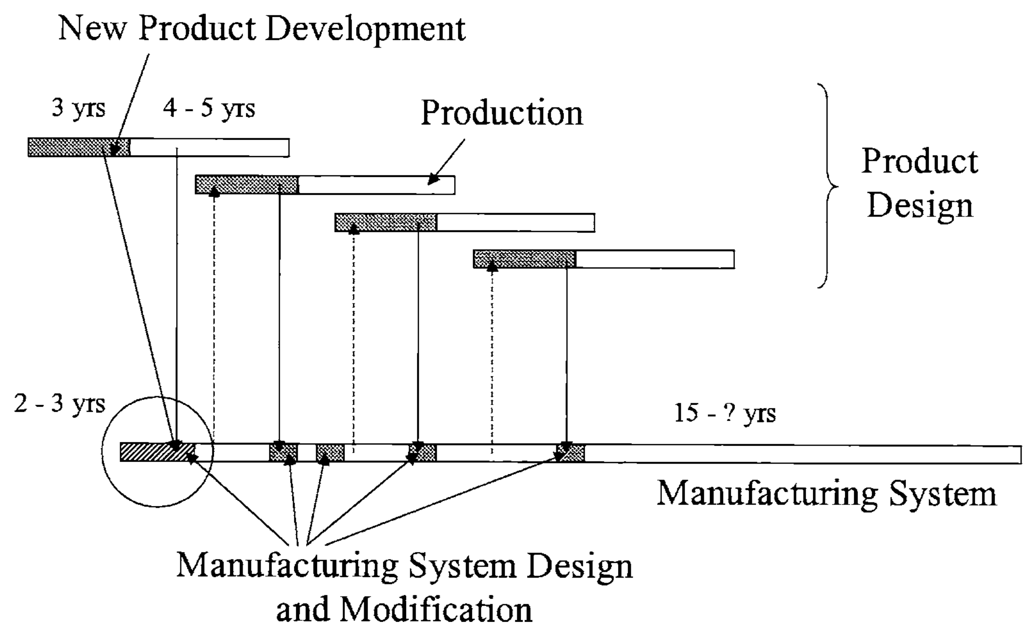

FIGURE 1-2. PRODUCT DEVELOPMENT AND MANUFACTURING SYSTEM DESIGN

In any case, the extensive communication and information sharing between manufacturing and product design is essential to develop a product that can be easily manufactured in current manufacturing systems and to modify manufacturing systems according to the new product design with minimum time and costs. Often, however, manufacturing systems are first designed without considering future product strategy and then, modified in an ad-hoc way to accommodate new product designs that do not reflect manufacturing systems constraints. Furthermore, it is not a well-established custom to manage knowledge gained from the previous manufacturing system design projects and to utilize it for a new project, which is partially due to the lack of a formal process to capture the knowledge [Grant 1996]. Figure 1-3 summarizes these problems.

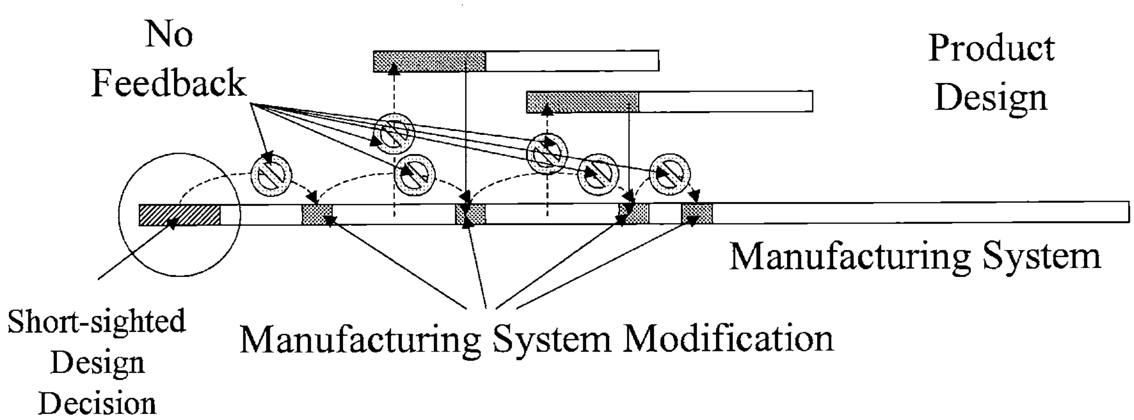

FIGURE 1-3. THROW-OVER-THE-WALL APPROACH

One of the root causes responsible for the lack of consideration of manufacturing system design during product design is that there is no systematic framework available to link manufacturing system design with product design. In fact, it is true that several existing methodologies address the issue of integrating manufacturing and product design. For example, the traditional DFMA approach helps product designers to avoid manufacturing problems, and estimate the cost of machining and assembly. Such methodologies as concurrent engineering and simultaneous engineering provide how to manage a product development project for better producible product design and more efficient product development process by presenting the needs for the integration of different corporate functions. However, there is no distinctive systematic approach to incorporate manufacturing systems issues (e.g., material flow design, mix-production scheduling, etc.) with product design decisions. The DFMA approaches are focusing on the impact of product design on an individual manufacturing process. Concurrent engineering centers on the organizational issues at a high level of abstraction. In some sense, the vast literature and industry practices on manufacturing system design is quite separated from the numerous articles and reports on product development.

Chapter 2 describes three types of typical problems in detail arising from the lack of a systematic method to see the impact of a product design decision on manufacturing systems. Please refer to the second chapter for more information on the problems identified in industry with regard to the consideration of manufacturing system designs during product design.

1.2 Problem Statement

To summarize, there is a need for product development teams to see the impact of their design decisions on manufacturing systems. This need may be transformed into the following two research problems.

(1) How do product development decisions interact with manufacturing system design?

(2) How can we systematically identify the interactions?

These main research problems are very general and thus, difficult to solve. Therefore, they need to be subdivided into the subproblems that can be easily handled and solved. The following four subproblems are identified.

1) How can we represent manufacturing system design?
2) How can we represent product development? What decisions in product development (especially related to product/process design) affect manufacturing system design?
3) How to identify the interactions between product/process design and manufacturing system design?
4) What are the examples of interactions and how the existing approach can be viewed with the new methodology?

The main research problems are solved by investigating solutions to the subproblems and developing tentative solutions for the sub-problems. For example, for the first sub-problem, the MSDD that is explained in Chapter 6 is considered as a tentative solution. The rationale behind the solutions to the subproblems is discussed throughout the thesis. Further discussion on the problem statements and the tentative solutions is available in Chapter 3.

Based on the solutions to the subproblems, a comprehensive framework that can guide product development teams to see the impact of their design decisions on manufacturing systems is proposed. This framework will satisfy the following requirements:

- Clearly describes the objectives of manufacturing systems separated from the design solutions to achieve the objectives
- Presents the impact of a design decision in various levels of abstraction on the achievement of the objectives of manufacturing systems
- Provides a common platform to effectively communicate the impact across the organization
- Integrates existing tools to integrate product design and manufacturing
- Provides an easily-applicable interface to product development team members to evaluate the manufacturability of their design decisions

1.3 Scope of Research

The goal of this research is to develop a methodology that will enable product development teams to see the impact of their design decisions on the achievement of the objectives of manufacturing systems. In order to achieve this goal, a framework to check the manufacturability of a design decision is proposed. The proposed manufacturability evaluation process is developed in four steps.

- Development of the manufacturing system design decomposition (MSDD)
- Identification of general design decision categories that affect manufacturing systems
- Development of the manufacturability evaluation process
- Validation of the manufacturability evaluation process

The MSDD shown in Appendix A is developed based on the axiomatic design methodology. The MSDD represents a logical decomposition of a high-level functional requirement and its corresponding solution (design parameter) of manufacturing systems into low-level requirements and their solutions. With this decomposition structure, the

MSDD can provide a systematic explanation of the relationships between many elements of a manufacturing system design. Consequently, the linkage of detailed design parameters to high-level system objectives can be identified with the use of the MSDD. The validity of the MSDD has been confirmed by many authors such as Cochran et al [2000d, 2001a, 2001b], Linck [2001], Duda [2001], and Arinez [2001] through its successful applications in the real industry problems. Therefore, the validation of the MSDD itself is not within the scope of this thesis. The MSDD is going to be accepted as useful to represent the objectives and corresponding solutions of manufacturing systems.

Six general design decision categories that affect manufacturing systems are identified based on extensive literature research. These categories are product variety, product architecture, purchasing, material selection, process selection, and detailed design. This categorization is made just to provide a guide when a specific design is evaluated in terms of its impact on manufacturing systems. In addition, the proposed categorization is general enough to significantly affect the proposed manufacturability evaluation process. Therefore, the effectiveness of the proposed categorization compared to other possible categorization is not considered or discussed in this thesis.

The proposed manufacturability evaluation framework uses the MSDD to systematically represent the requirements of manufacturing systems. The evaluation process shows what objectives of manufacturing systems are affected by a certain design decision. If some objectives are negatively affected by the design decision, the negative impact should be eliminated by modifying the design decision or the manufacturing system in consideration. However, this thesis does not attempt to provide general principles of eliminating the conflicts since the conflicts between the design decision and the manufacturing system design may result from various factors of product development such as marketing, corporate technology strategy, and financing. This thesis focuses on the interface between product design and manufacturing while the other corporate functions such as marketing and financing also affect a certain design decision. The interactions caused by the corporate functions other than product design and manufacturing are out of the scope of this thesis.

The validation of the proposed framework is done by providing the application examples of the proposed framework as well as analyzing the results of two questionnaires sent to industry. The triangulation strategy is adopted for the validation, which is frequently used in a qualitative research. Detailed discussion on the research methodology adopted in this thesis is provided in Chapter 3.

1.4 Organization of Thesis

This thesis consists of nine chapters. In the first chapter, the introduction of the research is given. The motivation of the research is presented along with a clear statement of research problems. The second chapter emphasizes the problem that this thesis addresses by showing three examples of problematic situations that can happen when the information exchange between manufacturing and product design is not clearly defined and extensively conducted. In the third chapter, the research methodology adopted by the thesis is explained. A brief review on the existing research methodologies is given, which is followed by a presentation of the methodologies adopted. The design of the research is provided in this chapter. The fourth chapter provides a literature review. Existing literature in the areas of product development and manufacturing system design is briefly reviewed while a detailed look at the literature related to the information exchange between manufacturing and product design is given. The fifth chapter reviews the industry practice related to the information exchange between manufacturing and product development. Many efforts in the automotive industry to facilitate the communication between manufacturing and product development are presented in this chapter. The sixth chapter describes the manufacturing system design decomposition (MSDD) in detail, which forms a basis for the proposed methodology that is presented in Chapter 7. Chapter 7 is a main chapter of this thesis. The framework to capture the interactions between product design and manufacturing is provided with the application examples. In addition, the rationale behind the proposed framework is discussed in detail. In the eighth chapter, an evaluation tool derived from the proposed methodology is provided as well as its industry applications. The relationship between the proposed evaluation tool and the validity of the proposed methodology is explained in this chapter. Chapter 9 summarizes the work presented in this thesis and suggests further research problems in the interface field between manufacturing and product design.

2 INDUSTRY PROBLEMS

In this chapter, three examples are provided to illustrate what can happen if there is no or weak communication between manufacturing and product design. Instead of providing traditional Design for Manufacturing (DFM) examples, this chapter presents the cases showing how manufacturing 'systems' are affected by certain product design decisions. The first example shows how a manufacturing plant has been evolved with the introduction of new product generation without a serious consideration of manufacturing system design. The second case presents how a detailed design decision can affect the overall manufacturing system design. The final example describes a possible problem within a product development team due to the lack of knowledge on how product design decisions affect manufacturing system design.

2.1 The Evolution of Plant M

This section describes a problem that a manufacturing plant has experienced because of the lack of communication between manufacturing and product development. A historical evolution of a plant is described and the role of new product designs on the modifications of the plant is discussed. Much of the content is adopted from the case study conducted by Linck [2001] and Cochran et al. [2001b].

2.1.1 Overview of the plant

Plant M produces plastic bumpers for the OEM companies in the automotive industry. In average, 7,500 bumpers are shipped to three final customers daily. Seven different styles of bumpers are produced along with additional service parts for old car models and they are painted in thirteen different colors. Plant M operates five days a week and three eight-hour shifts per day. Sometimes, if necessary, additional shifts are scheduled during the weekends to meet the demand. As is stated, plant M feeds three customers who operate five days a week and two nine-hour shifts per day. The customer plants also schedule some weekend shifts when necessary.

2.1.2 Historic Evolution of the Plant M and Problem Statement

Plant M was constructed in 1976 for the production of plastic bumpers, which replaced steel bumpers. OEM car manufacturers started to use plastic bumpers as a substitute of steel bumpers in the late 1970s. At that time, the bumpers were not designed as an integral part of the car body design. For example, it was not necessary to match the color of the bumper to the color of the body. UV protective coat was given to the bumper and some colors were painted, but those processes were for aesthetic reasons only. In addition, the size was smaller, the required level of quality was much lower, and the part complexity was lower than today. Today, in many cases, the bumper should provide integrated feeling with the car body to the customers. Therefore, the bumper is designed to fit in the curves of the car body and painted with exactly same colors of the car body.

Figure 2-1 illustrates today's plant layout. The manufacturing system consists of four main areas: injection molding, paint, assembly, and storage. The bumpers are stored in and retrieved from the AS/RS (Automated Storage and Retrieval System). AGVs (Automated Guided Vehicles) and electric overhead monorails transport bumpers between three main production areas and the AS/RS.

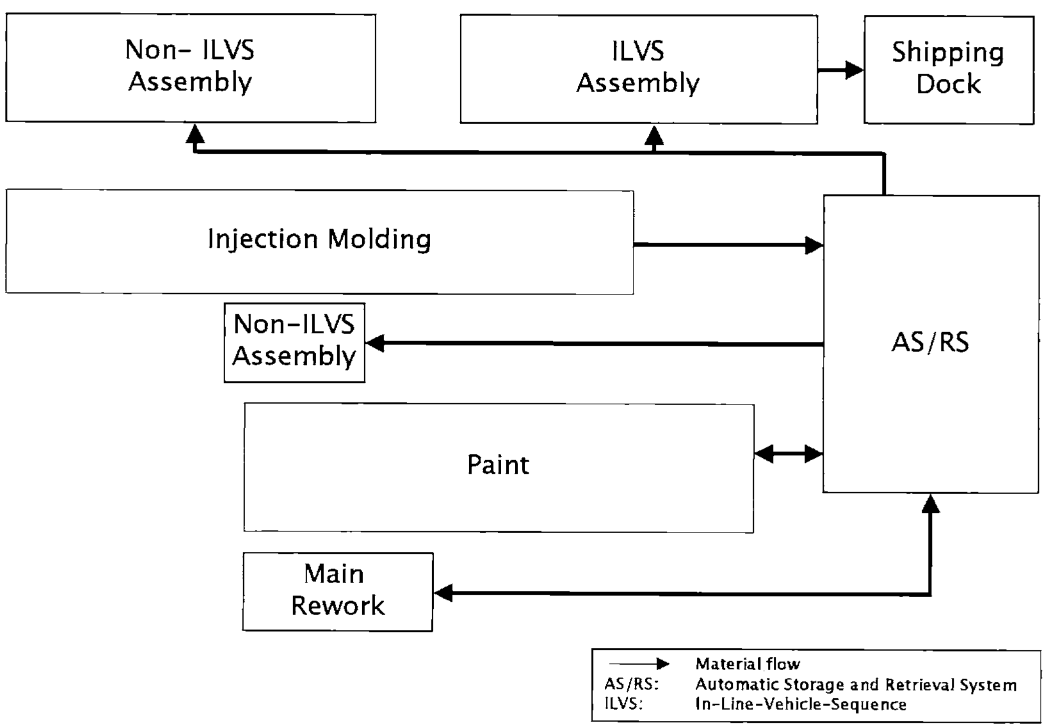

FIGURE 2-1. SCHEMATIC LAYOUT OF PLANT M (ADAPTED FROM [LINCK 2001])

The injection molding department runs seventeen injection molding machines with a clamping force of 4000 tons. As is previously stated, in the 1970s and 1980s, the bumper was smaller and less complex than today and thus, the molds were also smaller and less complex than today. Therefore, 2000 – 3000 tons of clamping force was enough to produce those bumpers. However, the molds used today are larger and more complex, which require higher clamping force up to 4000 tons. Therefore, the injection molding machines are running close to their capability limit in these days.

The paint system was installed in the late 1970s. The major system requirements were high volume capacity, low direct labor requirements, high reliability, and high repeatability. To satisfy these requirements, a highly automated paint system with a volume capacity of 14,000 bumpers per day was selected and implemented. As an additional effort to reduce direct labor requirements, automated loading and unloading system was sought originally but not realized due to the part handling problems. In addition to the main automated paint system, other smaller paint systems were implemented for prototypes or dual color painting. These paint systems were manual due to the lower volumes required, which are not used any more. The paint system has been upgraded several times to accommodate product design changes and to satisfy tightening quality requirements. In a series of upgrades, however, any upgrade was limited by financial resources and no building extensions were allowed. The present system operates at its limits with high downtimes (average uptime of the system is about 60%) and fallout rates (first time through rate can go anywhere between 95% to 25% but the average is 82%).

The original assembly line was a transfer line type and several assemblers worked on a flow line. However, the assembly content of current bumpers is much lower than the past and thus, one operator manually does all assembly works at one station. Currently two types of assembly are done. One is In-Line-Vehicle-Sequence (ILVS) assembly, which was installed in the summer of 1999. This assembly line assembles bumpers according to the sequence of cars assembled in the OEM customer plants. In other words, the ILVS assembly line is directly linked to the final vehicle assembly lines in the customer plants. Therefore, the delivery is critical. Since the stability of the manufacturing system is not good enough to run the ILVS assembly line with a small amount of buffers, the plant had to heavily invest in bumper buffers. The other is non-ILVS assembly that consists of five assembly cells. Some of the cells are dedicated to a certain type of bumper style and the rests are flexible.

The material handling system within the plant is highly automated. The system was installed between 1982 and 1986, and three major upgrades were made to be the present state of the material handling system. The material handling system consists of AGVs (Automated Guided Vehicles), electric overhead monorails, and an AS/RS (Automated Storage and Retrieval System). The original motivation for the highly automated material handling system was to manage the increasing product mix, reduce the floor space required for inventory storage, reduce forklift traffic in the aisles, and reduce direct labor costs. For further and detailed information on the plant M, please refer to [Linck 2001].

When viewed separately, each of the department seems to have made a series of rational decisions to adapt its system to the new environment. However, if all system design decisions were viewed from a holistic system point of view, it is evident that all decisions were locally optimized rather than optimized as a total system. In addition, it is note-worthy that one of the driving factors of the system changes is the introduction of new product design.

The original motivation for the plant was to produce plastic bumpers that would replace the old metal bumpers. Then, the first stimulus of the system modification was the introduction of new bumper design that has integrated feeling with the body of a car. The first problem occurred during this modification since the existing paint system was highly automated for high speed with a cycle time of 6 – 7 seconds. Due to the hard automation made for the original paint system, it was very difficult to modify the paint system. However, considering the large investment made for this paint system, management decided to modify the existing paint system instead of building a new one. Several tricks were made to keep the paint system and the rest of the manufacturing system was designed and modified around the given paint system. As time goes by, the requirement for variety of bumpers had been increased and a significant portion of manufacturing floor started to be consumed just for inventory storage to cover the variation of the process for variety of products. Increasing mix of product and the consequent increase in inventory required more frequent forklift transport of parts. To manage the complex logistics requirement, a highly automated material handling system was implemented. Another significant investment was made and thus, the rest of manufacturing system was required to be modified around the new AS/RS, AGVs, and electric overhead monorails. This brought ad-hoc add-in type of manufacturing system modification, which hurt the overall performance of the system. During the series of modifications, no critical feedback was given from the previous projects and the negative loop of manufacturing system design modification was reinforced by the performance measurement system that stresses the financial measures (e.g., cost per part, direct labor cost, etc.) only instead of operation measures (e.g., quality, lead time to customers, etc.). The evolution of the plant M is summarized in Figure 2-2.

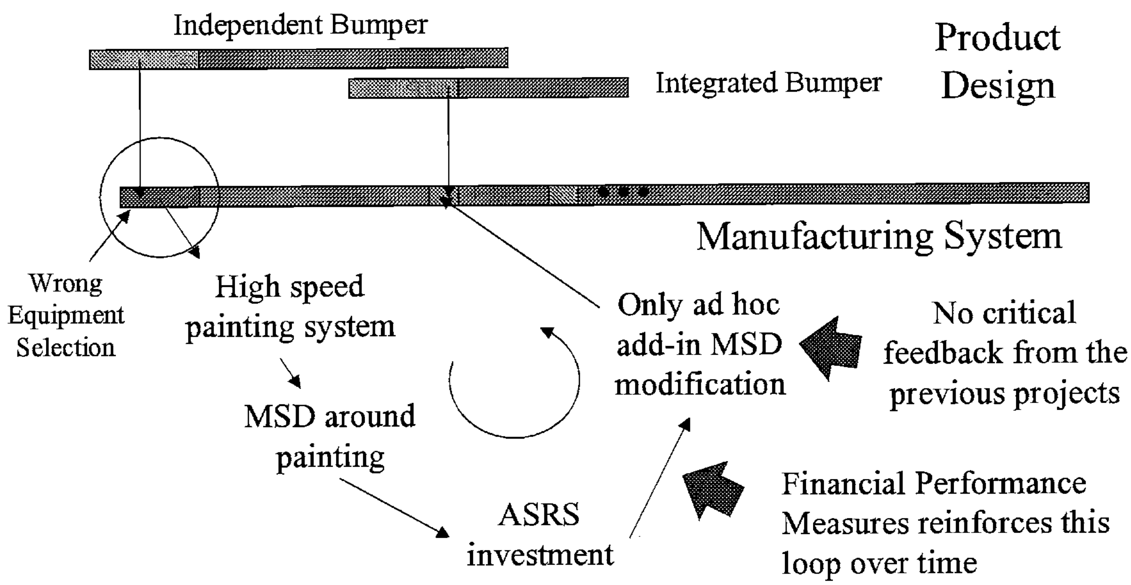

FIGURE 2-2. THE EVOLUTION OF THE PLANT M

2.1.3 Conclusion

In this section, a historical view on the evolution of the plant M is provided. This case represents a problem caused by a lack of communication between manufacturing and product design in a higher level of manufacturing system design. It describes how add-hoc responses of manufacturing system to product design changes that are made without considering manufacturing system design can drive the evolution of a manufacturing system in a wrong way. In this case, the erroneous evolution of the manufacturing system has been reinforced by the performance measurement system that values financial performance 'measures' only and disregards the system design aspect.

The evolution of the plant would have been very different if the product strategy emphasizing on product variety had been recognized by manufacturing group and necessary investment had been made accordingly. Otherwise the management should have made a product design decision after considering the existing manufacturing system design to avoid the flawed evolution of the manufacturing system. In this case, the problem grew slowly and thus, its seriousness was not recognized by the insiders.

2.2 Product and Equipment Design of Plant C

This section describes a problem that a machining department in an ABS (Anti-lock Braking System) manufacturing plant faced, which was caused by a couple of improperly angled fluid channels. The lack of communication between manufacturing and product design combined with traditional mass manufacturing system brought non-value adding fixture and machine implementation. Much of the content is adopted from the case study of [Kim 1999], [Weidemann 1998], and Cochran et al. [2001a].

2.2.1 Overview of the Plant and Its Product

Plant C produces anti-lock braking systems (ABS) for the OEM companies in the automotive industry. On the average, about 82,000 ABS units are produced per month and 4,100 units per day assuming 20 days of production per month. The ABS units produced in the plant C are supplied to seven final customers who are final vehicle assemblers. Shipping interval varies from daily to weekly depending on the customers.

There are three types of ABS products. One is ordinary ABS and ASR is an advanced version of the ABS with an additional function of traction control capability. ASR is an acronym of "Acceleration Slip Regulation" and sometimes called as traction control system (TCS). ASR prevents the slip of the wheels during the acceleration by endowing proper breaking force on the necessary wheels. The most advanced one is vehicle dynamics control system (VDC) that is ASR with vehicle dynamic control capability. VDC helps drivers to make a smooth curve by providing proper breaking force during the turn. There are numerous variations of these products, mostly driven by specific customer needs. The basic modular system, however, is same within a product family. The features that vary are: a selection of variable components that tune the modulator for the specific automobile, customer specific items for fit in the vehicle, customer specific visual criteria, customer specific integrated electronic functions, and the base system definition of either having only anti-lock breaking, ABS with traction control (ASR), or ABS/ASR with vehicle dynamic control (VDC). The variation in product types requires manufacturing flexibility and the increased cost due to the required flexibility is recognized as a problem. This case study focuses on the machining area that produces seventeen different housings for final products. The overall layout of the plant and the material flows are presented in Figure 2-3.

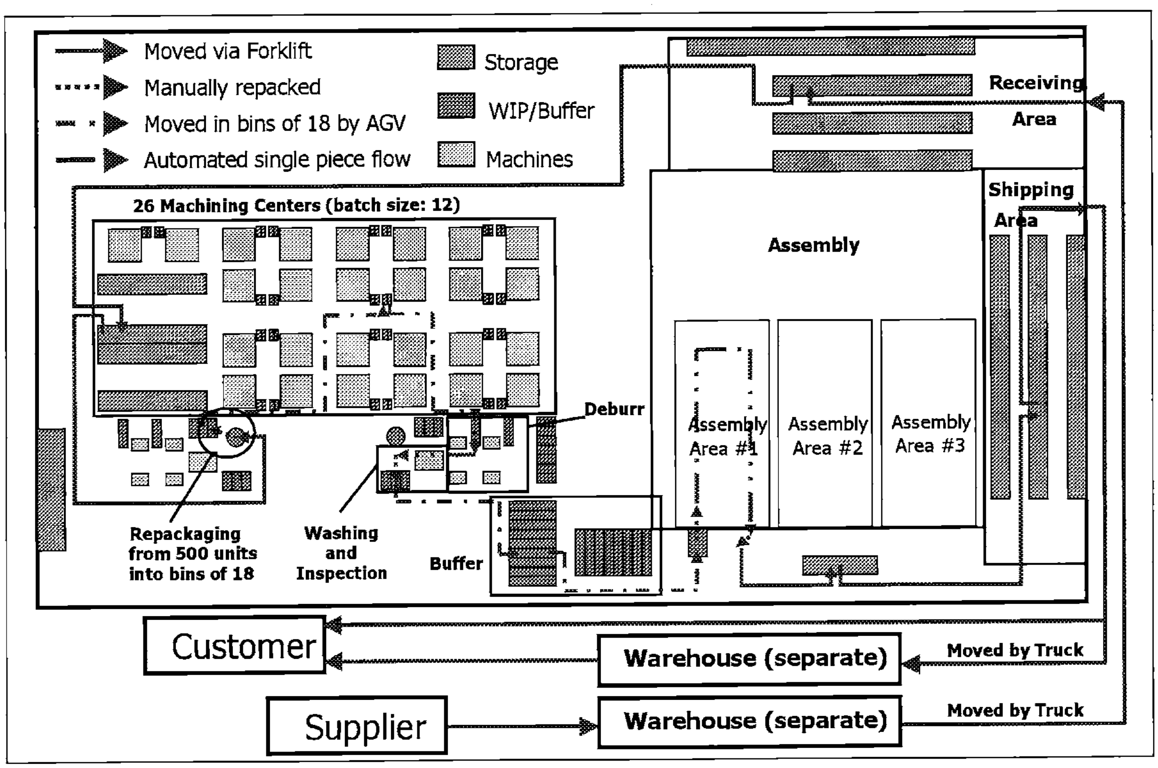

FIGURE 2-3. THE LAYOUT AND MATERIAL FLOWS OF PLANT C [COCHRAN ET AL 2001A]

The machining area produces housings with aluminum forged blocks supplied from outside vendors. There are fourteen different models of ABS housings and three for ASR/VDC units. ABS housings are different from ASR/VDC housings in terms of its external sizes, diameters of fluid channels, and the number of fluid channels. Within ABS housings or ASR/VDC housings, however, the only difference is the number of fluid channels, which can be easily handled by adjusting drilling operations. Machining area operates five days a week and three eight-hour shifts per day. Sometimes, if necessary, additional shift is scheduled during the weekends to follow up the customer demand.

The current manufacturing system design can be characterized by its departmental layout to maximize the machine utilization rate. The machining area is not balanced to the assembly lines while the assembly lines are not balanced with the customers. However, in the machining area, there have been several attempts to adopt some techniques of lean manufacturing in order to take advantage of its benefits in terms of throughput time and reduced inventory level. For example, automated guided vehicles (AGVs) are operated to reduce the time between operations. AGVs are continuously moving between machines in order to transport parts to downstream operations as soon as their processing is finished. There are three major departments within the machining area. The first is machining center group that is equipped with 26 high-precision machining centers. One operator operates four machining centers and conducts inspection on the finished parts while the machine is running. The second group is the deburring group of which eight water-jet deburring machines eliminate burrs produced during machining. Finally, two huge washing machines are implemented and final inspection is done right after the washing operation.

2.2.2 Machining Centers, Product Designs, and Problem Statement

The machining centers used in the machining center group are five-axis CNC machines equipped with three spindles, which can process three parts in parallel (See Figure 2-4).

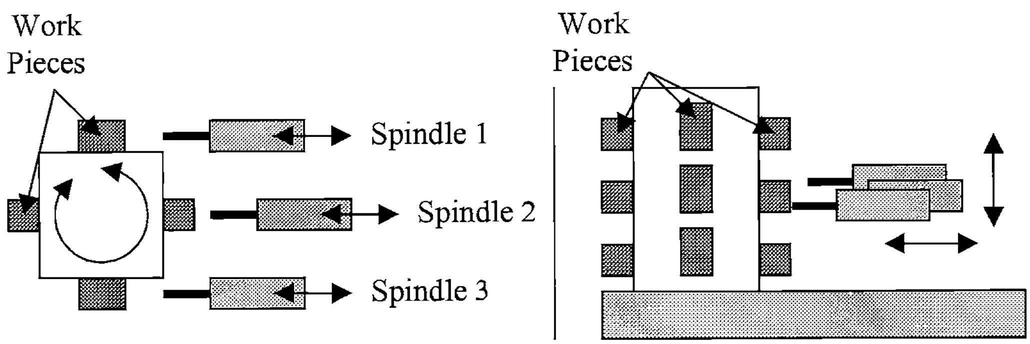

FIGURE 2-4. A SCHEMATIC VIEW ON THE INSIDE OF A MACHIING CENTER (TOP VIEW: LEFT, SIDE VIEW: RIGHT)

These machining centers have been purchased to perform as many operations as possible in one load to save manual loading/unloading time and minimize the unit cost. They are high-precision and high-speed machining centers equipped with over 100 tools to achieve this purpose. However, finishing a part cannot be done in one load because all faces must be processed. Due to this requirement, ABS housings, for example, have to be manually unloaded from one position (clamping A in Figure 2-5: left) in a fixture and then loaded to another position (clamping C in Figure 2-5: left), so that a total of 4 motions to load and unload are required to finish a part. Tombstone fixtures are applied as a part of the large investment in the machine to minimize the unit cost by producing as many parts as possible in one load. Each fixture holds 12 parts at a time. The fixtures used here are shown in Figure 2-5.

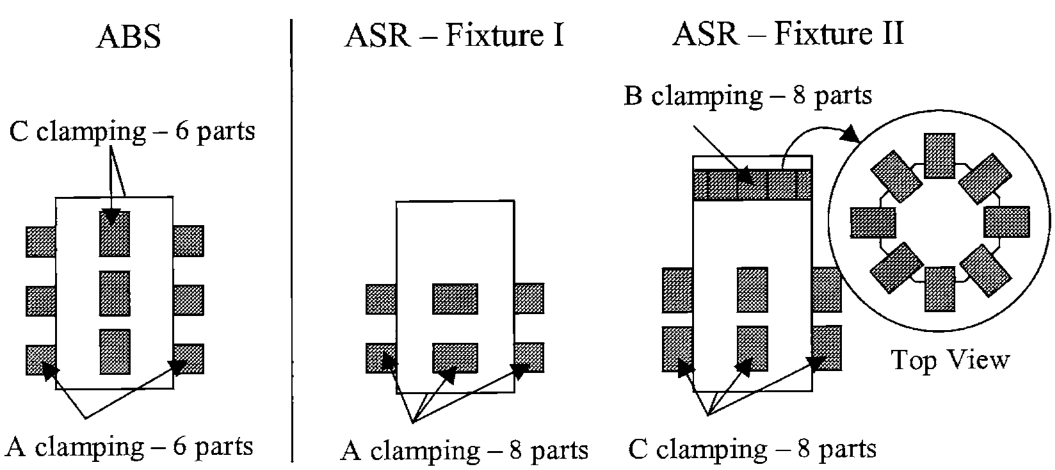

FIGURE 2-5. A SCHEMATIC VIEW OF FIXTURES FOR ABS (LEFT) AND ASR/VDC (RIGHT)

At the beginning of each cycle for ABS housings, 12 blocks of housings are set to the fixture, half of which are new blocks to position A and another half are the blocks moved from position A to C. Machining itself is relatively simple. It is necessary to face-cut all six faces of an aluminum-extruded block and drill about 50 to 100 holes with different diameters in the block, which consist of the circuits for the brake fluid. In spite of relatively simple machining processes, some holes with large diameters require large horsepower and high precision. Therefore, high precision and horsepower machining centers are currently used.

In the case of ASR/VDC housings, the machining process becomes trickier than that of ABS housings. ASR/VDC housings have four angled fluid channels that cannot be handled with the existing fixture for ABS housings. Therefore, new fixtures are designed as shown in the right side of Figure 2-5. In a new fixturing system, two different fixtures are used and each fixture is located on a machine. Therefore, two machines are grouped together to produce ASR/VDC housings. The fixture I type shown in Figure 2-5 has A type clamping and holds eight fresh housing blocks. The fixture II type has newly designed B type clamping on top of it as well as C type clamping. Each clamping position can hold eight parts and thus, fixture II type can hold sixteen parts in one cycle. Parts are moved from the position A to B and then moved again from the position B to C. The fixture I type holds only eight parts even though it can hold up to twelve parts because clamping B can only hold up to eight parts due to the space limitation. Parts are moved without buffers between clamping positions (A, B, and C) and thus, the number of parts held by each clamping position should be same.

Several problems can be identified with the production of ASR/VDC housings. First, two machining centers are required to be dedicated to process ASR/VDC housings since two fixtures are required for the production of ASR/VDC housings. In addition, it takes about a day to change the fixtures for ASR/VDC housings to the fixture for ABS housing due to the high precision required. This deteriorates the mix flexibility of the plant to the demand fluctuation. Furthermore, both fixture types of I and II should have the capability of rotating in one degree scale while the rotational capability in 90 degrees is enough for the fixtures for ABS housings. Another problem is quality. If defective parts were found after the machining operations and they were made during the processing in the clamping

B position, a total of eighteen parts are likely to be scrapped. Six finished parts along with twelve parts in the fixture type II in the run are likely to be defective.

All these troubles are a result of lack of communication between manufacturing and product design, combined with equipment design driven by unit cost minimization philosophy that strives to incorporate as many operations as possible in one load of the machining center. If the holes with unique angles were eliminated through extensive communication between manufacturing and product design, there would be no need for new fixture design and consequent separate operation of machining centers dedicated to ASR/VDC housings. These problems are solved in the new generation of the product. All fluid channels are designed to be perpendicular to the faces of the housing in the new ASR/VDC housing design.

2.2.3 Conclusion

In this section, the troubles that manufacturing engineers had to overcome regarding the production of ASR/VDC housings are presented. It is noteworthy that all troubles are caused by two fluid channels in unique angles that cannot be handled by the existing fixture, combined with the manufacturing strategy of incorporating as many operations as possible in one load of the parts to the machining center. If there had been extensive information exchange between manufacturing and product design, two angled fluid channels could have been avoided, causing no trouble to manufacturing. Even though manufacturing was able to come up with a solution to deal with the given product design, all efforts to find the solution of two fixtures would have been unnecessary with a review of the design at the manufacturing site early in the product development process.

In the next generation of the ASR/VDC, all fluid channels are designed to be perpendicular to the faces of the housings in order to prevent the same problem from occurring again according to the interview with a manufacturing engineer at plant C. This is only one solution to the problem, however, and more options to solve this problem may be found. For example, manufacturing system design may be changed to accommodate the angled fluid channel design. In any case, the manufacturability of the design decision can be checked with the framework that is proposed in Chapter 7 of this thesis. The proposed framework will show what elements of manufacturing system design can be affected by each solution option and thus, provide the motivation for searching for new solution.

2.3 Product Development in Xerox

This section describes a problem that a product development team in Xerox saw during the development of network printers, DocuPrint N4025 (see Figure 2-6). This case study is based on the author's term project [Kim et al. 2000].

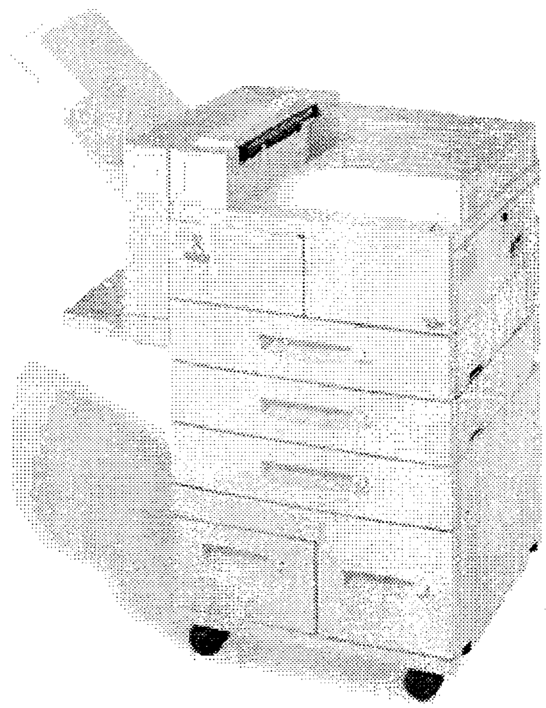

FIGURE 2-6. DOCUPRINT 4025 (ADAPTED FROM WWW.XEROX.COM)

2.3.1 Overview of the Company and Its Product

Xerox Corporation provides document solutions that enhance business productivity. Its activities encompass developing, manufacturing, marketing, servicing and financing a complete range of document processing products and solutions.

The product lines of Xerox include digital products, light-lens copying, supporting software and peripheral items for both digital and copying products.

The digital product line consists of five categories: black-and-white digital multifunction products (Document Centre products), black-and-white production publishing (DocuTech products), black-and-white production printing, color copying and printing, and black-and-white laser printers/other. The company also sells DigiPath Production Software, a major productivity tool that allows a printer's customers to use the World Wide Web to streamline print job submission and subsequent archiving, preparation, proofing, and reprinting. In addition to the digital product line, Xerox markets the broadest line of light-lens copiers and duplicators in the industry, ranging from a three copies-per-minute personal copier to a 135 copies-per-minute fully featured duplicator. Many of its state-of-the-art products retain enhanced fundamental characters of ease of use, reliability, copy quality, job recovery, and ergonomics as well as productivity-enhancing features, including zoom enlargement and reduction, highlight color, copying on both sides of the paper, and collating and stapling which allow the preparation of completed document sets. The company also sells cut-sheet paper to its customers for use in their document processing products. The company also offers a wide range of other document processing products including devices designed to reproduce large engineering and architectural drawings up to 3 feet by 4 feet in size, facsimile products, scanners, and personal computer and workstation software.

In February 2000, Xerox introduced the new DocuPrint N Series printers, a family of five network laser printers ranging from 20 to 40 pages per minute that offer faster speeds, better paper-handling and productivity, and more value than printers available from other vendors.

2.3.2 Network Printer Development and Problem Statement

Network printing is a very mature product segment, which has such established market leaders as Hewlett-Packard (HP) and Lexmark, as well as other fast moving competitors like Canon and Ricoh. In this market, Xerox is attempting incremental innovation of the products by improving the processes used in the value chain of product development through transforming the organization. This is a strategic direction taken at the corporate level. Management believes that the improved product development process will greatly contribute to the enhanced customer-recognized values and thus, profit generation in a shortened product development cycle. This is possible by adopting new technology curves and incrementally innovating the product attributes through improved product development processes. Product development by competitors has moved from years to months while complexity and newness of products has significantly increased at lower unit manufacturing costs. "Faster, better and cheaper" is the name of the game.

The product development process of Xerox is called as, "Time to Market (TTM)" process. Xerox's Time to Market process has been fairly well established. It includes formation of a Time to Market Team also known as Product Delivery Team, which brings in all stakeholders within the company together when the product concept has been approved. The team is chaired by the designate Product Manager and consists of representatives from various functional parties (see Figure 2-7). The team meets weekly through out the entire product development period from concept through launch. The formation of a Time to Market team contributes to two objectives. It allows for early involvement of all upstream and downstream parties and thus, decisions are made with consensus of all stakeholders. It also allows for concurrent processes to be initiated and not wait for sequential handoff between functions. The team's focus moves from one organization to another as the product development proceeds through logical steps.

The underlying idea is to keep everyone involved in the TTM team to prevent possible downstream problems caused by upstream decisions. The current structure is designed in a way that the functional groups know clearly when they are expected to add value to the process and also get ahead start to provide what is required, as opposed to the standard industrial practice of sequential handoff between different functions of the organizations. Xerox hopes that by keeping a large number of people in the TTM team, every functional organization is well informed and thus, the total product life cycle time cost as well as the product development time is minimized. As a result of this effort, DocuPrint N4025 family was developed in eight months, even though the Xerox company wide product development time in average is about 14 months to 18 months.

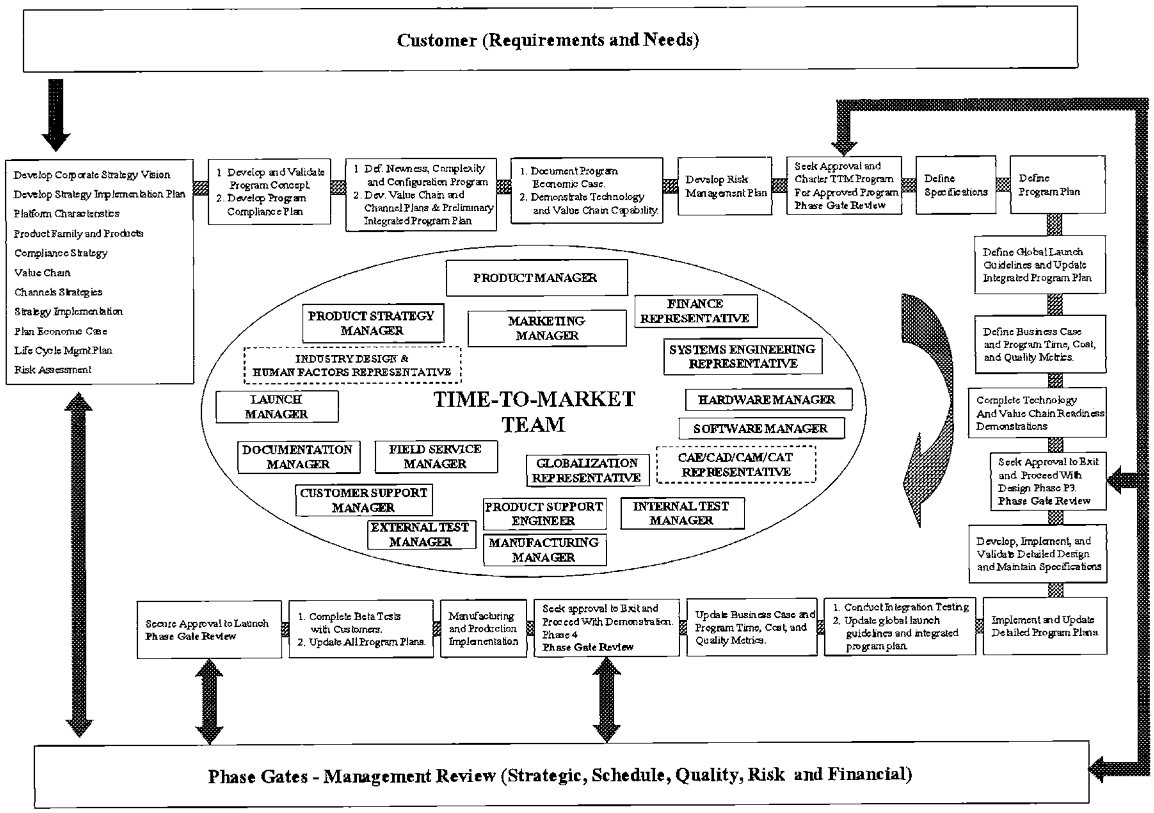

FIGURE 2-7. XEROX'S PRODUCT DEVELOPMENT PROCESS CENTERED ON THE TIME-TO-MARKET TEAM (ADAPTED FROM [KIM ET AL. 2000])

The fast development of DocuPrint N family, however, is partly a result of expediting and using more man-power than planned. According to [Kim et al. 2000], for example, 240% of planned man-hours were spent on specification design that takes 12% of the total planned product development man-hours. The TTM team spent 63% more man-hours than planned on design validation and 16% more on integration testing. This is due to several causes but one of the major root causes was the lack of clear identification of information flows between functional parties within the TTM team. Unclear information flows cause several sources of inefficiency. First, there are too many functional representatives in the TTM team. The TTM team has as many as 25 representatives from relevant functional parties or more during the product development. This number of people deteriorates the efficiency of the TTM meetings and this disadvantage may be more significant than the advantage that can be gained by making sure every design decision is made with the consensus of the entire team. Even though Clausing [1994] mentions about the 'flood of information' to make sure all information is available to product designers, Wheelwright and Clark [1992] stressed that development projects do not need deep, cross-functional integration when all the interfaces between functional parties are clearly defined.

In addition, it took 7 days to review the project at each phase gate review process during the DocuPrint N4025 development. There were 4 phase gate reviews and thus, almost about a month was spent solely on the formal reviewing process. This represents almost 1/9 of the total product development time while reviewing does not necessarily add any value to the product from the customer point of view. Considering more than 25 representatives were supposed to attend all phase gate review meetings, a great source of inefficiency is observed. A portion of this time may be minimized through the standardization of reviewing processes, which can be greatly enhanced by the proposed methodology in this thesis.

To eliminate the sources of the above-mentioned inefficiency, clear information flows between each functional party are required. This is possible only by a thorough understanding of the interactions between upstream decisions and downstream results. For example, the interactions between product design decisions and manufacturing system design should be known for the reference of manufacturing engineers in the TTM team in order to give faster review of the proposed design. Furthermore, if product designers have a tool to evaluate the impact of their design decisions on planned manufacturing systems, the first-time-right design decision can be made, which eliminates the need for continuous design reviews and iterations to solve the contradictions between manufacturing and product design. Knowing what information should be exchanged between functional parties along with a tool to support it will eventually lead to faster product development time and lower product development cost.

2.3.3 Conclusion

In this section, the sources of inefficiency of a large cross-functional product development team are presented. . This case represents a problem associated with the organization and management of the product development process, which can arise due to the lack of knowledge on the interactions between manufacturing and product design.

Even though Xerox's TTM team approach demonstrated its advantage over the traditional sequential methods in terms of product development time, there are still rooms for further improvement. One way for the improvement is to clearly define the information flows and their contents between functional parties within the product development team. This improvement is possible only by thorough understanding of the interactions between downstream and upstream.

In this sense, even though it may be secondary, the knowledge on the interactions between manufacturing systems and product/process design can greatly contribute to the reduction of total product development time and cost even with the enhanced concurrent engineering approach. The proposed methodology in this thesis enables product development teams to see the interactions between their design decisions with the manufacturing system design.

2.4 Chapter Summary

In this chapter, three examples are presented to illustrate what can go wrong with the lack of communication between product design and manufacturing. The first example is in a higher level of manufacturing system design. It describes the consequence of add-hoc responses of manufacturing to product design changes on the evolution of a manufacturing system. The second example is more in a lower level of manufacturing system design. The troubles caused by just two fluid channels in unique angles on equipment design and operation, are discussed along with the consequent impact on the overall manufacturing system performance. The third example is about the organization and management of product development processes. The sources of inefficiency associated with large product development teams are identified and it is presented how well-defined interactions between manufacturing system and product/process design may contribute to more efficient product development teams.

These examples are only a few of the problems that the author has observed. Motivated by the observation of the problems like the provided examples, a literature study was made (Chapter 4) and industry questionnaire was developed (Chapter 5), which eventually lead to the development of the proposed framework to capture the interactions between manufacturing and product design (Chapter 7).

3 RESEARCH DESIGN

In this chapter, the research design applied in this thesis is presented. Due to the breadth of the field of product development and manufacturing system design, there lacks a unified research design that has been applied to the research in the interface area between product development and manufacturing system design. This chapter is devoted to the identification of the available research methods that fit to the characteristics of the field and the objective of the thesis, and the selection of appropriate ones. Overall, this study is to ensure the thesis is following and adopting scientific approaches to find the answers to the research questions posed in Chapter 1.

3.1 Introduction

Research design is the complete strategy of attack on the central research problem. It provides the overall structure for the procedures to be followed, the data to be collected, and the data analysis to be conducted [Leedy 2001]. It can be said that research design is the planning of research or the design of a research framework[1].

The importance of research design has been addressed by many researchers in the evaluation study. For example, Robson [1993] addresses the problem of typical researchers who tend to use their favorite approach without considering any alternative research approaches. Miles and Huberman [1984] claim that pre-structured research design can help selective collection of data and facilitate multiple site research. Manstead and Semin [1988] assert that the strategies and tactics in carrying out a research depend much on the type of research question that is being answered. These researchers point out that research design is important to decrease the efforts for collecting and analyzing data, and to use appropriate research methods that fit to the type of questions to be answered and the type of data to be collected.

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[1] According to the Oxford dictionary, a framework is a structure composed of parts framed together, especially one designed for inclosing or supporting anything. Linck [2001] views a research framework as a set of ideas, conditions, or assumptions that determine how something will be approached, perceived, or understood.

There have been debates on research methods in terms of what scientific research is. These debates have been more serious in social science since it deals with very different research questions and collects very different types of data from the natural science. Patton [1978] points out that evaluation research is dominated by the unquestioned, natural science paradigm of hypothetico-deductive methodology. He claims that this dominant paradigm assumes quantitative measurement, experimental design, and multivariate, parametric statistical analysis to be the essence of "good" science. However, this traditional approach shows shortcomings when dealing with complex problems [Parlett and Hamilton 1976] in a real world situation under messy and poorly controlled settings [Robson 1993]. Patton [1978] describes the alternative paradigm of qualitative approach, which counts on open-ended interviewing, observation, and holistic analysis. Therefore, Reichardt and Cook [1979] propose to use a flexible approach that employs different research methods depending on the individual research situation. Many other researchers such as Patton [1980, 1990], Robson [1997], Yin [1994], and Leedy [2001], have the same view, which is widely accepted in recent days.

The research presented in this thesis follows the flexible approach. Both quantitative and qualitative methods are used in a mixed way whenever appropriate in order to achieve the two primary objectives of the thesis: 1) to determine how product development decisions interact with manufacturing systems and 2) how to systematically capture the interactions. Considering the characteristics of the research area, however, qualitative research methods are more frequently applied than quantitative methods. Detailed explanation of the research methods adopted in this thesis as well as the characteristics of the field that this research attempts to study is presented in the following sub-chapters.

Before going into the detailed explanation of the adopted research methods, the terms in the evaluation research used in this chapter need to be described in order to avoid a confusion of terms. Manstead and Semin [1988] adopt a river-crossing analogy for this purpose. According to them, the general research focus corresponds to the task of crossing the river. Specific research questions are similar to asking how many people want to cross the river, the frequency with which they want to cross, the current of the river, and so on. The choice of research strategy is analogous to a choice between swimming, walking, flying, or sailing across. The research tactics or methods (sometimes called methodologies) of investigation concern the particular type of boat, bridge, aircraft, etc.

3.2 Review of Research Procedures

As previously discussed, there are several different research approaches that focus on different types of problems. Leedy [2001], however, claims that a normal research process follows the basic format regardless of the research approaches that are adopted. The basic format of the research process is shown in Figure 3-1.

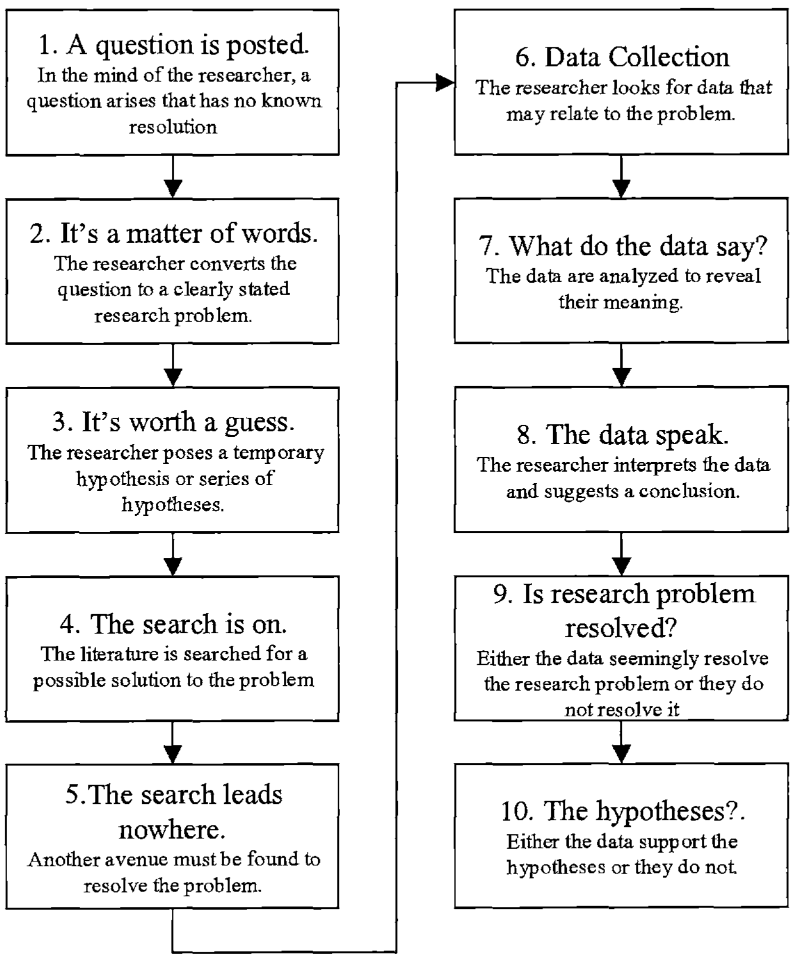

FIGURE 3-1. THE BASIC FORMAT OF THE RESEARCH PROCESS [LEEDY 2001]

The research process presented in Figure 3-1 does not end up by the completion of the proposed ten steps. Leedy [2001] stresses that research is, by its nature, cyclical or more exactly, helical. The resolution of the research problem or validation of the research hypotheses leads to the completion of a cycle but research is rarely conclusive. In exploring the research problems, additional problems show up and research bursts into more research.

The research process shown in Figure 3-1 does not mean that every research follows the exactly same sequence of the presented process. It only shows the general flow of the research. For example, problem statement or hypothesis generation can be done iteratively or simultaneously with literature research. Robson [1993] points out this aspect by stating, "*the model with its orderliness and separation into a clear linear sequence is more of a reconstruction enshrined in methods textbooks and conventional journal formats than an account of the scientific research process in practice. (...) Real life science does not escape the messiness of other aspects of real life.*" He claims that the approach like interpretive approach tends to generate theories and concepts after data collection and analysis. In addition, in the interpretive approach, data collection and analysis are not clearly separated. In other words, initial data collection and analysis may lead to decide the type of data to be collected and analyzed next time.

In the next section, various approaches to the hypotheses generation, data collection, and data analysis are reviewed.

3.3 Review of Research Methods

As is presented in section 3.2, research design is the overall planning of the research and the general approach to planning a research is similar across disciplines. However, the specific methods to collect and analyze data can be specific according to the research objectives, the characteristics of data to be collected, or the particular academic discipline.

Leedy [2001] distinguishes two types of research strategies: quantitative and qualitative. In general, quantitative or experimental strategy is used to answer questions about relationships among measured variables with the purpose of explaining, predicting, and controlling phenomena. In contrast, qualitative research strategy is typically used to answer questions about the complex nature of phenomena, often with the purpose of describing and understanding the phenomena from the participants' point of view.

Quantitative methods usually start with a specific hypothesis to be tested [Leedy 2001]. Then, the variables to be studied are isolated whereas extraneous variables are controlled. A standardized procedure is normally used to collect some form of numerical data and statistical methods are applied to draw conclusions from the collected data. Quantitative methods usually end with confirming whether the hypotheses that were tested are supported by the data or not.

On the other hand, qualitative methods often begin with general research questions instead of specific hypotheses [Leedy 2001]. An extensive amount of verbal data are usually collected from a small number of participants and organized into some form that gives them coherence. Then the situation studied is portrayed by verbal descriptions. A qualitative study is likely to end with tentative answers or hypotheses about what was observed. Table 3-1 highlights the characteristics of two approaches.

TABLE 3-1. CHARACTERISTICS OF QUANTITATIVE AND QUALITATIVE RESEARCH METHODS (ADAPTED FROM [LEEDY, 2001]).

Question	Quantitative	Qualitative
What is the purpose of the research?	To explain and predict	To describe and explain
	To confirm and validate	To explore and interpret
	To test theory	To build theory
	Outcome-oriented	Process-oriented
What is the nature of the research process?	Focused	Holistic
	Known variables	Unknown variables
	Established guidelines	Flexible guidelines
	Static design	Emergent design
	Context-free	Context-bound
	Detached view	Personal view
What are the methods of data collection?	Representative, large sample	Informative, small sample
	Standardized instruments	Observations, interviews
What is the form of reasoning used in analysis?	Deductive analysis	Inductive analysis
How are the findings communicated?	Numbers	Words
	Statistics, aggregated data	Narratives, individual quotes
	Formal voice, scientific style	Personal voice, literary style

The categorization of research methods into qualitative and quantitative strategies, however, is not absolute. In other words, two strategies cannot be clearly separated. Reichardt and Cook [1979] argue that a researcher can take both strategies in his/her research since some research methods contain the characteristics of both strategies and there is overlap between two strategies.

As will be explained in detail in the next sections, the field of this study seems to call for qualitative strategy more than quantitative strategy, even though both methods are employed in the study. Leedy [2001] differentiates five categories of qualitative research methods: case study, ethnography, phenomenological study, grounded theory study, and content analysis. The characteristics of each method are presented in Table 3-2. Again, these five categories are not absolutely separable. There are overlaps between different methods.

Qualitative research studies typically serve one or more of the following purposes (Peshkin, 1993):

- Description – they can reveal the nature of certain situations, settings, processes, relationships, systems, or people.
- Interpretation – they enable a researcher to (a) gain insights about the nature of a particular phenomenon, (b) develop new concepts or theoretical perspectives about the phenomenon, and/or (c) discover the problems that exists within the phenomenon.
- Verification – they allow a researcher to test the validity of certain assumptions, claims, theories, or generalizations within real-world contexts.
- Evaluation – they provide a means through which a researcher can judge the effectiveness of particular policies, practices, or innovations.

In section 3.4, the selection of research strategies and methods for this thesis is discussed.

TABLE 3-2. DISTINGUISHING CHARACTERISTICS OF DIFFERENT QUALITATIVE DESIGNS (ADAPTED FROM [LEEDY 2001])

Design	Purpose	Focus	Methods of Data Collection	Methods of Data Analysis
Case Study	To understand one person or situation (or perhaps a very small number) in great depth	One case or a few cases within its/their natural setting	• Observations • Interviews • Appropriate written documents and/or audiovisual material	• Synthesis into an overall portrait of the case(s) • Categorization and interpretation of data in terms of common themes
Ethnography	To understand how behaviors reflect the culture of a group	A specific field site in which a group of people share a common culture	• Participant observation • Structured or unstructured interviews with informants • Artifact/document collection	• Focus on significant events
Phenomeno-logical study	To understand an experience from the participants' point of view	A particular phenomenon as it is typically lived and perceived by human beings	• In depth • Purposeful sampling of 5-25 individuals	• Search for "meaning units" that reflect various aspects of the experience • Integration of the meaning units into a "typical" experience
Grounded theory study	To derive a theory from data collected in a natural setting	Human actions and interactions, and how they result from and influence one another	• Interviews • Any other relevant data sources	• Prescribed and systematic method of coding the data into categories and identifying interrelationships • Continual interweaving of data collection and data analysis • Construction of a theory from the categories and interrelationships
Content analysis	To identify the specific characteristics of a body of material	Any verbal, visual, or behavioral form of communication	• Identification and possible sampling of the specific material to be analyzed • Coding of the material in terms of predetermined and precisely defined characteristics	• Tabulation of the frequency of each characteristic • Descriptive or inferential statistical analyses as needed to answer the research question

3.4 Applied Research Procedures and Methods

The interface field of product development and manufacturing system design can be characterized by a lack of understanding of the variables involved and a very complex nature of the relationship between the relevant variables. As a consequence, there are few established research frameworks in the interface area of product development and manufacturing system design. Therefore, it is necessary to define a new research design tailored to the specific needs of the research.

The objectives of this research are to understand (1) how product development decisions interact with manufacturing systems, (2) how to systematically capture the knowledge on the interactions, and (3) see the effectiveness of the proposed methodology. Considering the characteristics of the field, for the objective (1) and (2), the traditional hypothetico-deductive 'scientific' approach that is based on established theories and hypotheses, does not seem to be appropriate. It is simply because there is no established theory available that shows the relationships between manufacturing system design and product development, from which a hypothesis can be derived. To develop a methodology to capture the interaction knowledge is in fact, one of the research objectives. Therefore, qualitative research methods are adopted to 'generate' the methodology to capture the relationship between product development and manufacturing system design.

Another factor that is considered in the selection of research methods is the type data to be collected. The data and methodology are inextricably interdependent [Leedy 2001]. For this reason, the methodology to be used for a particular research problem must always take into account the nature of the data to be collected in order to resolve the problem. The characteristics of the data to be collected in this research is primarily verbal information of the practices in the industry and the methodologies proposed by the academia. Therefore, qualitative strategy is more appropriate than quantitative strategy in general.

After the methodology is available, a hypothesis can be generated on the effectiveness of the methodology. To support the hypothesis, both qualitative and quantitative methods are applied. Table 3-3 illustrates the characteristics of the adopted research methods. The shaded boxes in Table 3-3 indicate the characteristics of the research methods used.

Even though various research methods are adopted in this research, the general procedure of the research is followed as is presented in Figure 3-1.

In section 3.4.1 to 3.4.4, details of research steps and adopted research methods are explained.

TABLE 3-3. CHARACTERISTICS OF THE RESEARCH METHODS ADOPTED FOR THE RESEARCH PRESENTED IN THIS THESIS

Question	Quantitative	Qualitative
What is the purpose of the research?	To explain and predict	To describe and explain
	To confirm and validate	To explore and interpret
	To test theory	To build theory
	Outcome-oriented	Process-oriented
What is the nature of the research process?	Focused	Holistic
	Known variables	Unknown variables
	Established guidelines	Flexible guidelines
	Static design	Emergent design
	Context-free	Context-bound
	Detached view	Personal view
What are the methods of data collection?	Representative, large sample	Informative, small sample
	Standardized instruments	Observations, interviews
What is the form of reasoning used in analysis?	Deductive analysis	Inductive analysis
How are the findings communicated?	Numbers	Words
	Statistics, aggregated data	Narratives, individual quotes
	Formal voice, scientific style	Personal voice, literary style

3.4.1 Research Steps

This thesis consists of four major steps as is shown in Figure 3-2. The first step is to identify problems and clearly state the research problem and divide it into manageable sub-problems. The result of the first step is clearly stated research problem and its sub-problems. The second step is to investigate existing solutions in the academic literature and industry practices. The outcome is the confirmation of the lack of methodologies to solve the raised research questions. The third step is to develop the new methodology to systematically capture the interaction between product development and manufacturing systems. The fourth and final step is to find out evidences that support the effectiveness of the proposed methodology. In this step, some discussions on the new findings in the interactions between product development and manufacturing systems are made. The steps are summarized in Figure 3-2.

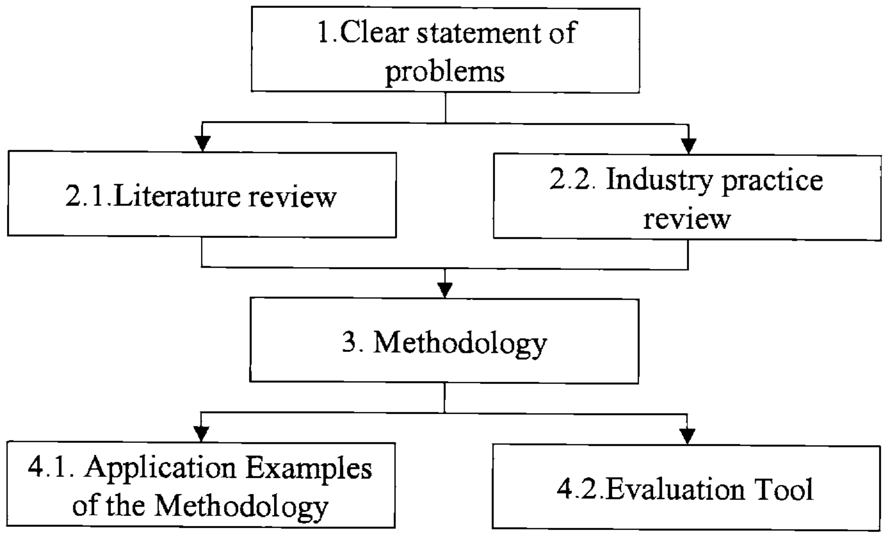

FIGURE 3-2. OVERALL RESEARCH STEPS OF THE THESIS.

3.4.2 Problem Definition

As is addressed in the introduction chapter, the main research problems of this research are two-fold:

(1) How do product development decisions interact with manufacturing system design?

(2) How can we systematically identify the interactions?

Since these two problems are too general to be solved, the following sub problems are derived from the two main problems.

1) How can we represent manufacturing system design?
2) How can we represent product development?
3) What decisions in product development (especially related to product/process design) affect manufacturing system design?

4) How to see the interactions between product/process design and manufacturing system design?

5) What are the examples of interactions and how can the existing approach be viewed with the new methodology?

Then tentative solutions for each sub-problem are developed. For example, for the first sub-problem, the MSDD (explained in Chapter 6) is adopted to represent the objectives and corresponding solutions of manufacturing systems. For the second and third sub-problems, the design decisions affecting manufacturing systems are identified and grouped into six categories. Identifying design decisions affecting manufacturing systems is considered more important than modeling the entire product development process within the context of the research. This research aims to find how product design decisions affect manufacturing systems. For the fourth sub-problem, it is studied how a specific product design decision affects the achievement of FRs of the MSDD. Using the MSDD, it can be understood how a product design decision affects the achievement of the general objectives (FRs) of manufacturing systems. A relationship matrix between the design decisions and the FRs and DPs of the MSDD is developed as the result. These tentative solutions are modified and elaborated as the literature review and industry practice review are conducted.

3.4.3 Literature and Industry Practice Review

To investigate the existing solutions to the research problems, the methodologies proposed in literature and the practices used in industry are explored and studied. The methodologies and industry practices studied are used to consider the interactions between product development decisions and manufacturing in the early phase of product development. These methods are believed to reduce the design iterations made in the later phases of product development due to the mistakes made in the earlier phases.

As is presented in Chapter 4, several existing approaches to the research problems are reviewed, including the classical Design for Manufacturing (DFM) approach. As for the practices made in industry, cases presented in literature are consulted and a questionnaire is sent to several companies asking their practices. The questionnaire is designed to capture the current practices of industry to facilitate the early consideration of manufacturing issues in product development. This questionnaire is sent to six different companies in the automotive industry and the results are presented in Chapter 5. In addition to the questionnaire, several on-site interviews as well as personal observations are used to collect additional information.

3.4.4 New Methodology and Validation of the Methodology

Among the five qualitative research methods presented in Table 3-2, the case study method and grounded theory method seem to be appropriate for the research in this thesis, considering the purpose of the research methods. Grounded theory is different from case study in terms of the timing of theory development. With the grounded theory method, building a theory prior to data collection is avoided in order to form a theory based on collected data. Case study[2], however, starts with the development of a theoretical framework prior to data collection [Leedy 2001]. Yin [1994] claims that a successful case study requires a theoretical framework.

The research presented in this thesis can be grouped into two parts. The first part aims to develop a methodology to systematically identify the interactions between product development decisions and manufacturing system design. The second part is to validate the proposed methodology by collecting supportive evidences for the effectiveness of the proposed methodology. In this sense, grounded theory method is applied in the first part of the research and the case study method is used in the second part. Strictly speaking, however, these two methods are used in a mixed way. The data collected from the interviews with engineers, personal observations, and the open-ended questionnaire survey are categorized and used to develop the methodology while the same data are also applied to modify and refine the methodology in the later part of the research. Robson

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[2] The difference between survey and case study is subtly defined. Robson [1993] explains that generally a relatively small amount of information is collected from any one individual by a survey, contrasting with a case study, where a great deal of information might be obtained from a key informant. Survey is also different from experiment since normally it does not attempt to manipulate variables or control conditions.

[1993] points out the same phenomenon in the research of real world investigation – it is difficult to clearly separate the research methods applied in the real world investigation.

In the first part of the research, a methodology to systematically identify the interactions between product development decisions and manufacturing system design is developed, which later serves as the theoretical framework of the case study method. This newly developed methodology is based on the tentative solutions on the sub-problems of the research. For instance, the MSDD is developed for the effective representation of manufacturing system design and some high level product development decisions that affect manufacturing system design are identified.

Then this methodology is modified and refined based on the multiple-case study method proposed by Yin [1994]. The multiple-case study framework is shown in Figure 3-3.

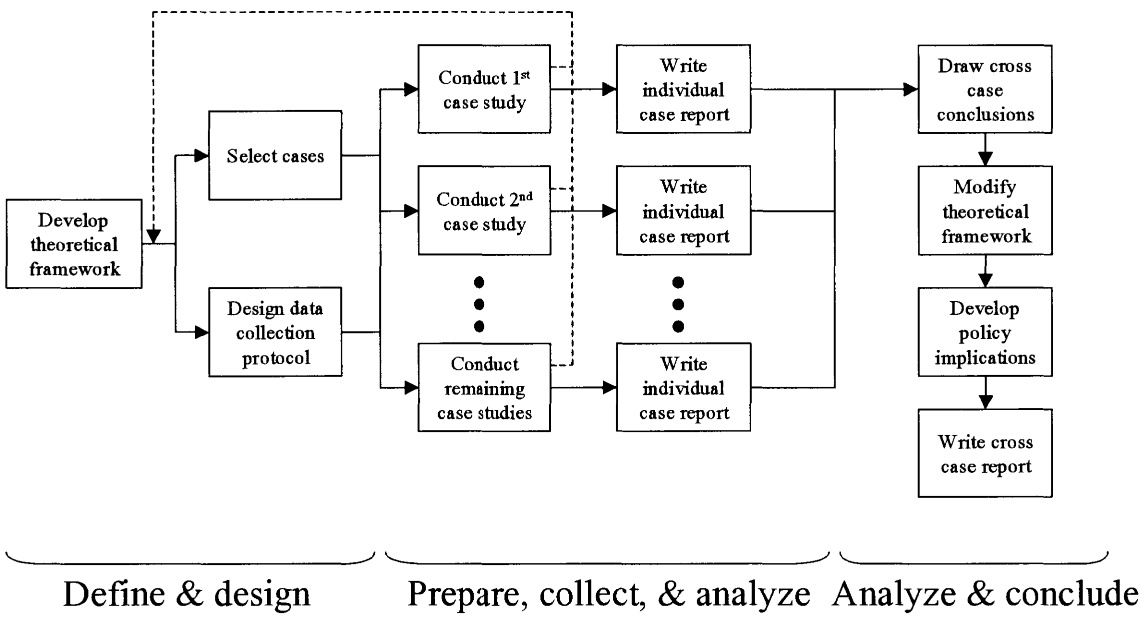


FIGURE 3-3. FRAMEWORK FOR MULTIPLE-CASE STUDY RESEARCH (ADAPTED FROM [YIN 1994])

Strictly speaking, two rounds of case studies are made. The first round case studies are to identify the problems and the existing solutions in industry, regarding the communication between manufacturing system design and product design. In this stage, the theoretical framework was relatively rough and included the MSDD. The data collection protocols used include: interviews with engineers and managers, personal observations, and the first round questionnaire. The first round questionnaire was sent to six different companies in the automotive industry and complementary face-to-face interviews along with personal observation were followed. According to the case study results, the methodology was modified and refined to reflect the results. The overall structure of the first round case studies are presented in Figure 3-4.

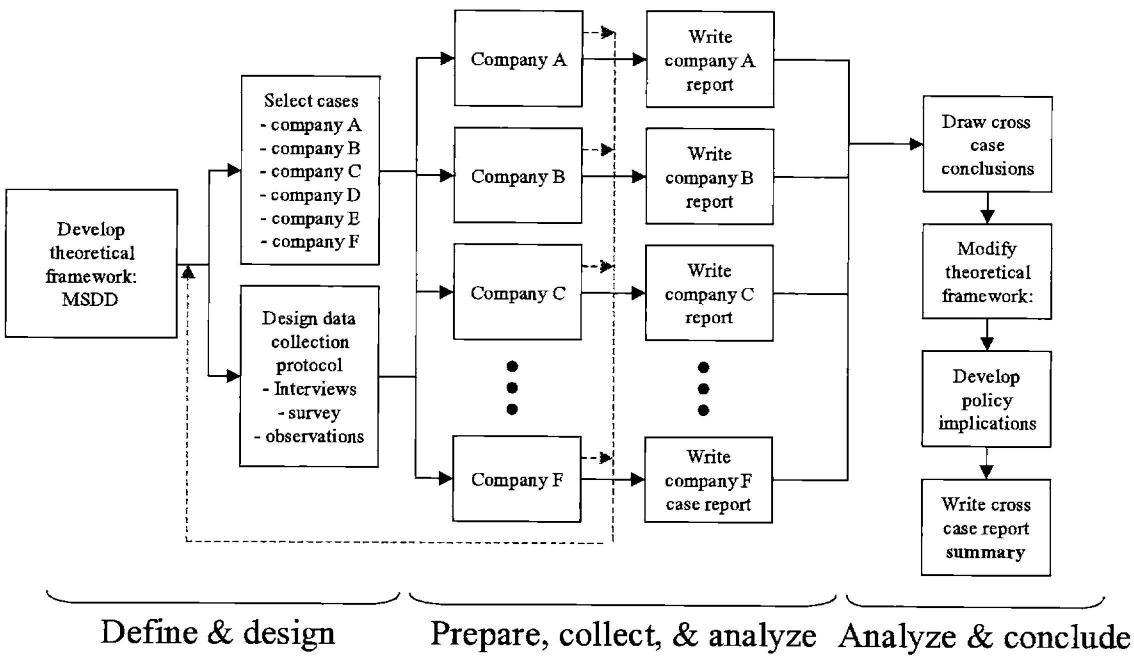


FIGURE 3-4. THE MULTIPLE-CASE STUDY FRAMEWORK APPLIED IN THE FIRST ROUND CASE STUDIES TO COMPANIES A, B, C, D, E, AND F, AND LITERATURE.

In the second round, two case studies on the application of the proposed methodology were conducted. In this stage, a complete theoretical framework was ready to be applied and the same data collection protocols were used as the first round. Such data collection protocols as interviews with engineers and managers, personal observations, and the second round questionnaire were used. The second round questionnaire was sent to three OEM companies in automotive industry in order to evaluate their practices to ensure the manufacturability of product designs. According to the case study results, the proposed methodology has been fine-tuned. The overall structure of the second round multiple case studies is shown in Figure 3-5.

The application of the case study method in the second round case studies can be seen as a validation process. Validation in social science is a confirmation process for gathering evidence to test hypotheses [Krathwohl, 1998]. The validation of the proposed methodology is to show that the proposed methodology provides a useful framework for better consideration of manufacturing system issues in early product development phases. In this research, one hypothesis may be that the proposed methodology shows the strengths and weaknesses of the existing approaches in use, which are linked to the overall performance of the product development system of a company. The usefulness of the proposed methodology is to be established with the help of a multiple-case study approach.

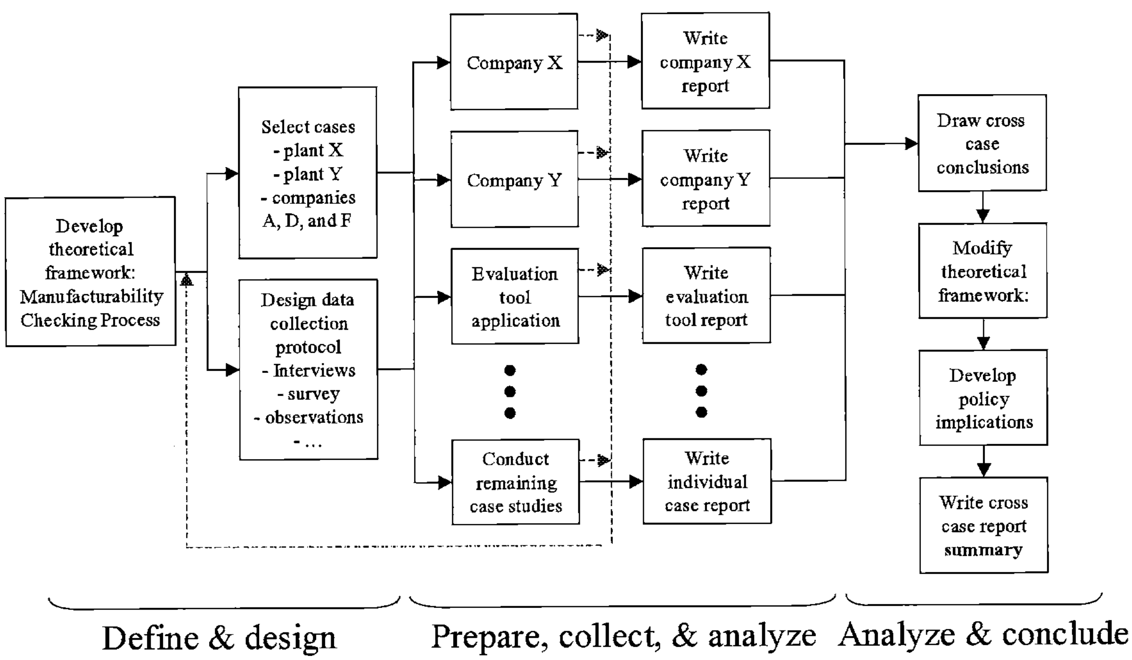


FIGURE 3-5. THE MULTIPLE-CASE STUDY FRAMEWORK APPLIED IN THE SECOND ROUND CASE STUDIES TO COMPANIES X, Y, A, D, AND F.

3.5 Validity of Applied Research Methods

The validity of the research methods indicates the accuracy, meaningfulness, and credibility of the research project as a whole [Leedy 2001]. It is very important to think about the validity of the applied research methods since the research results are meaningful and defensible only to the extent that its validity allows. Leedy [2001] distinguishes two types of validity: internal validity and external validity. The internal validity of a research study is the extent to which its design and the data that it collects allow the researcher to draw accurate conclusions about the cause-and-effect and other relationships within the data. There are several ways to ensure the internal validity of the research study. The following strategies are used to increase the probability that the explanations of the researchers are the most likely ones for the observations they have made [Leedy 2001]:

- Controlled laboratory study – conducting an experiment in a laboratory setting in order to carefully regulate the environmental conditions.
- Double-blind experiment – both the participants and the method-deliverers are blind with regard to whether they are in a group hypothesized to be more or less effective than another group.
- Unobtrusive measures – participants are observed in such a way that they do not recognize if their behaviors are recorded.
- Triangulation – multiple sources of data are collected with the hope that they all converge to support a particular hypothesis or theory.

As triangulation strategy is frequently used in qualitative research, it is used in the study presented in this thesis. By conducting multiple case studies with various data collection methods including direct observations, surveys, and in-depth interviews, the internal validity of the research is assured. In addition, the explanation building strategy proposed by Yin [1994] for ensuring internal validity is adopted.

The external validity of a research study is the extent to which its results apply to situations beyond the study itself [Leedy 2001]. In other words, it indicates the extent to which the conclusions drawn can be generalized to other contexts. For this reason, sometimes, external validity is called as generalizability. Leedy [2001] presents three commonly used strategies to enhance the external validity of a research study. They are:

- Real-life setting – research that is conducted in the outside world, although it may not have the tight controls of a laboratory study, may be more valid in the sense that it yields results with broader applicability to other real-world context.
- Representative sample – when a sample is studied to draw conclusions about a category as a whole, which the sample belongs, a representative sample of the category is studied.
- Replication in a different context – if two research studies conducted in very different contexts reach the same conclusion, it may be an evidence to show that the conclusion has validity and applicability across diverse contexts and situations.

The multiple case studies conducted in this thesis show the cases of representative companies of both OEM companies and first-tier suppliers in the automotive industry in its real life setting. Therefore, the validity of the research methods is assured in the automotive industry. In addition, as is described in Chapter 6 and 7, the proposed methodology is based on a model that can be generally applied to repetitive, discrete part manufacturing industry. Consequently, the external validity may be extended into repetitive, discrete part manufacturing industry.

In fact, the concepts of internal and external validity come from experimental research [Leedy 2001]. In qualitative approaches, the meaning of the term validity may be understood somewhat differently. Researchers like Lincoln and Guba [1985] and Creswell [1998] suggest using such words as credibility, dependability, confirmability, verification, and transferability instead of the term validity, which shows the meaning of the validity within the qualitative research context. In qualitative research like the study provided in this thesis, several other strategies can be sought to assure the validity. Leedy [2001] enumerates:

- Extensive time in the field – the researcher may spend a long time on studying a particular phenomenon.

- Negative case analysis – the cases that contradict existing hypotheses are looked for in order to continually revise the explanation or theory until all cases have been accounted for.
- Thick description – sufficiently rich description of a situation enables readers to draw their own conclusions from the presented data.
- Feedback from others – the opinion of colleagues in the field is sought.
- Respondent validation – the research conclusion is taken back to the participants in the study and the participants are asked if they agree with the conclusion.

For the research presented in this thesis, all above-listed strategies are adopted to ensure the validity of the study. For instance, the author has been studying the relationship between manufacturing system design and product development for nearly five years. Different case studies are conducted to continually revise the proposed methodology as presented in Figure 3-4 and 3-5. Thick descriptions are given for each case study and the opinions of engineers in industry and faculty members at universities around the world (including MIT (USA), Meijo University (Japan), Portland State University (USA), Tampere University of Technology (Finland), and The Royal Institute of Technology (Sweden)) are reflected in the development of the proposed methodology.

3.6 Chapter Summary

As is presented in section 3.3, there are two general strategies for research design: quantitative and qualitative. In general, quantitative strategy represents the traditional hypothetico-deductive approach based on theory and hypothesis, which favors experimental methods with a focus on outcomes. Qualitative strategy, on the other hand, favors qualitative methods listed in Table 3-2, with a focus on processes. Often qualitative methods are used for exploratory research in the field where no established theory is available.

In this thesis, qualitative methods are primarily applied due to the characteristics of the interface area between manufacturing and product development. The interface area between manufacturing and product development is characterized by the following factors.

- Lack of the understanding of the variables (e.g., people, information, etc.) involved
- Complex relationships between the relevant variables
- Real world situations under messy and poorly controlled settings

Multiple case study research framework proposed by Yin [1994] is adopted as an overall research framework and several case studies are conducted to support the proposed theoretical framework. By thoroughly considering the research methodology to be used in the thesis, it is possible to confirm the internal and external validity of the proposed methodology to capture the interactions between product development and manufacturing system design.

4 LITERATURE REVIEW

4.1 Introduction

Reviewing the literature in product development and manufacturing system design is certainly an overwhelming challenge. Manufacturing system design incorporates numerous research disciplines such as manufacturing strategy, organization design, and detailed process engineering. Moreover, product development includes manufacturing system design as just a portion of it. Research fields within product development range from customer requirements investigation and creativity science to a study on the economic consequences of product maintenance programs and a research on product recycling plans. This chapter focuses on the existing approaches to smoothen the transition from product design to production. A brief introduction to manufacturing system design and product development is also provided to suggest reference reading in those areas. The literature review shows that few approaches are available that address the issues of manufacturing system design in product development.

Before reviewing the existing literature in the interface area of product design and production, some terms are defined first to avoid the confusion in the use of terms.

4.1.1 Systems

A system is typically defined as a combination of elements with definite relationships between the elements to behave as a whole. A number of authors define a system in their own ways but the main idea seems to be similar. Some examples of different system definitions are:

- Bruns [1988] defines a system as a set of elements embodying specific characteristics. Between the elements are relationships representing the functional connections of the elements. A system has a defined boundary to its environment and all elements exist within this boundary. Each element itself might be a subsystem. An open system has inputs from and/or outputs to the environment through the system's boundary. A dynamic system changes its status with the time. The purpose of a system is to achieve defined goals.

- Blanchard and Fabrycky [1998] define a system as a set of interrelated components working together toward some common objectives or purpose. According to them, systems are composed of components, attributes, and relationships [Blanchard and Fabrycky, 1998, pp. 2].

- Wu [2000] defines a system as a collection of components which are interrelated in an organized way and co-operate towards the accomplishment of certain logical and purposeful ends.

- Hitomi [1996, 1971] claims that a system has four basic attributes: assemblage, relationship, goal-seeking, and adaptability to environment. He provides four essential definitions of systems: abstract (or basic) definition, structural (or static) definition, transformational (or functional) definition, and procedural (or dynamic) definition [Hitomi 1996, 1975].

Characteristics of the different definitions of a system are shown in Table 4-1. Considering most of the system definitions cover more or less the same characteristics of a system, the working definition of a system within this thesis's context is:

> *"a system is defined as an assemblage of interrelated components working together towards the accomplishment of certain goals."*

TABLE 4-1 CHARACTERISTICS OF DIFFERENT DEFINITIONS OF A SYSTEM

	Elements	Attributes of elements	Relationship	Boundary	Purpose
Bruns [1988]	x	x	x	x	x
Blanchard & Fabrycky [1998]	x	x	x		x
Wu [2000]	x		x		x
Hitomi [1996]	x	x	x	x	x

4.1.2 Manufacturing Systems

Different authors propose different definitions of a manufacturing system according to their experience and perspective (see [Arinez 2000, pp. 27]). Some of the definitions are:

- Wu [2000, pp.25] defines a manufacturing system as, "the collection of physical resources within the system, whether directly involved with the actual transformation and/or distribution of materials or as part of the supporting infrastructure, the collection of human resources, and the collection of controlling and information system resources." Accordingly, manufacturing represents "the conversion of a design into a finished product. This involves a series of value-adding, interrelated activities and operations such as the design, materials selection, planning, manufacturing production, quality assurance, management, marketing and distributing activities, devoted to the transformation of raw materials into marketable goods [Wu 1994].

- Cochran and Lima [1998] define a manufacturing system as, "a subset of the production system – is the arrangement and operation of elements (machines, tools, material, people and information) to produce a value-added physical, informational or service product whose success and cost is characterized by the measurable parameters of the system design."
- Gershwin [1994] defines a manufacturing system as, "a set of machines, transportation elements, computers, storage buffers, people, and other items that are used together for manufacturing." He defines manufacturing as "the transformation of material into something useful and portable."
- Chryssolouris [1992] defines a manufacturing system as, "a combination of humans, machinery, and equipment that are bound by a common material and information flow."

However, there are common elements among the definitions found in the literature [Linck 2001]. The objective of a manufacturing system is to produce a valuable good by transforming input materials through processing them. The elements of manufacturing systems are resources that are necessary for this transformation such as people, equipment, material, and information. The relationships between the system elements are defined by material and information flows through the system and the relationships represent the organization of the system. The boundary of the manufacturing system, however, varies depending on the definitions. Cochran [1994] distinguishes manufacturing systems from production systems. Production systems include the manufacturing system along with other enterprise functions such as marketing, finance, supply chain management, and product development [Cochran 1994]. Wu [1994, 2000], however, does not distinguish production system and manufacturing system.

The working definition of a manufacturing system in this thesis is:

> *"A manufacturing system is the arrangement and operation of elements (machines, tools, material, people and information) that are related to each other to produce a valuable or useful product."*

On the other hand, manufacturing system design refers to a plan to integrate a number of elements of a manufacturing system into a smoothly functioning whole to achieve the objectives of a manufacturing system. Arinez [2000] provides a comprehensive review on different definitions of manufacturing system design. According to him, the definitions of manufacturing system design available in the literature can be categorized into four groups: 1) the layout and structural organization of physical elements, 2) procedural design approaches that suggests a sequence of activities that constitute the manufacturing system design process, 3) a decision process whereby tradeoffs amongst the variables associated with resources, structure, and processes are made, and 4) system control and information flow management.

In this thesis, a mixed definition of Arinez [2000] and Cochran and Dobbs [2001] is used. Manufacturing system design is, *"the specification of the attributes of the manufacturing system, namely the resources, processes, and its organization. Manufacturing system design covers all aspects of the creation and operation of a manufacturing system. Creating the manufacturing system includes equipment selection, physical arrangement or equipment, work design (manual and automatic), and standardization. The result of the creating process is the factory as it looks during a shutdown. Operation includes all aspects, which are necessary to run the created factory (i.e., problem identification and resolution process)."*

4.1.3 Product Design and Development

Ulrich and Eppinger [2000] define a product as "something sold by an enterprise to its customers," and product development as "a set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product."

This definition is used in this thesis for product development. Therefore, product development covers from the initial market research to the production, sales, and delivery of a product.

As for the definitions of design, several different views are observed in the design literature. Few design articles define design in a strict way and in fact, design can be viewed differently from different perspectives [Phal and Beitz 1996] or in different fields [Suh 2001]. Ulrich and Eppinger [2000] see design as defining physical form of the product to best meet customer needs. Phal and Beitz [1996] cites Martyrer [1960] to refer to design as an engineering activity that: 1) affects almost all areas of human life, 2) uses the laws and insights of science, 3) builds upon special experience, and 4) provides the prerequisites for the physical realization of solution ideas. Suh [2001] defines design as, "an interplay between what we want to achieve and how we want to achieve it," in his Axiomatic Design theory. Pugh [1996] describes designing as "a highly manipulative activity in which the designer has to continuously and simultaneously pay attention to and balance several factors that impinge upon and influence design." All these definitions reflect a certain aspect of design. The definition of product design according to Merriam-Webster's Collegiate® Dictionary (10^{th} edition) is, "the arrangement of elements or details in a product."

Within this thesis, product design refers to a conceptual arrangement of elements or details in a product that is a result of interplays between the objectives of a product and their solutions. The term, "product design," is distinguished from "process design." Process design refers to defining how to physically realize the product design.

4.2 Literature Overview – Manufacturing System Design

Numerous articles on manufacturing system design are available. Dounmeingts et al. [1987] suggest the 'Graphe a Resultats et Activities Interlies' (GRAI) for the design of production management with an emphasis on decision making and control activities. Rao and Gu [1997] propose a serial seven-steps for a manufacturing system design process. Black [1991] proposes a new design approach in his book, 'The Design of a Factory with a Future'. Wu [2000] suggests a general manufacturing system design approach. Cochran et al. [2000a] propose a decomposition-based approach to manufacturing system design. In the study of lean manufacturing systems, Shingo [1989] and Ohno [1988] elaborate the philosophy of the 'lean' production and describe the characteristics of the lean production. Monden [1998] propose a bottom-up approach to design a lean manufacturing system.

Wu [2000], Arinez [2000], and Linck [2001] provide classification of the manufacturing system design methods in terms of level of completeness and details, manufacturing system design activities, and time horizon (phases) respectively. Please refer to the above authors for further explanation of each of the manufacturing system design related literature.

However, few authors in manufacturing system design field address the issue of the impact of product design on manufacturing system. Compared to manufacturing related literature, product development literature discusses more extensively the issue of interactions between manufacturing and product design.

4.3 Literature Overview - Product Development

Vast literature is available in the product development processes. Clark and Hujimoto [1991] explain the strength of Japanese auto companies in their product development compared to the western auto companies. Ulrich and Eppinger [2000] provide a detailed explanation of the product design processes as well as frequently used tools. Sobek [1995] compares Toyota and Chrysler in terms of their product development processes in detail and proposes the concept of set based concurrent engineering (SBCE). Clausing [1994] proposes to use a structured and organized product development process, and provides a step-by-step guide to world class concurrent engineering as well as the tools to be used during each product development process. Meyer and Lehnerd [1997] show the advantages of applying the concept of product platform with respect to the traditional single product development approach. Wheelwright and Clark [1992] suggest a product development framework including the organization issues such as cross-functional cooperation, learning, and building capabilities. Suh [1990] proposes mapping between four design domains for smooth product development. Altshuller [1988] suggests 'theory of inventive problem solving' (TIPS or TRIZ) as a framework to find out creative solutions to solve the design problems. Table 4-2 shows what objectives of product development are addressed by each method.

TABLE 4-2. PRODUCT DEVELOPMENT LITERATURE REVIEW

		Design a functional product that satisfies the external customer requirements			Design a producible product that satisfies the internal customer requirements	Reduce the overall product design and process definition time	Minimize development cost	Continuous improvement
		Ensure that external customer's requirements are mutually understood	Design product to achieve customer's requirements	Validate Designs				
Andreasen and Hein	1987	(+)	(+)		+	+	+	
Clark and Fujimoto	1991	(+)	(+)	+	(+)	+	(+)	(+)
Wheelwright and Clark	1992	(+)	(+)	+	(+)	+		+
Nevins and Whitney	1989				+			
Martin and Ishii	1997				+			
Clausing	1994	+	+	+	+	+	(+)	+
Boothroyd et al.	1994				+			
Sobek	1997	+	+	+	(+)	(+)	(+)	(+)
Pugh	1996	+	+		(+)	(+)		(+)
Ulrich and Eppinger	2000	+	+	+	+	+	+	(+)
Cunningham	1998				+			
Ulrich	1995		+		(+)	(+)		
Krishnan	1996				(+)	+		
Thornton	2000	(+)	+		+	(+)		
Feitzinger and Lee	1997		(+)		+		(+)	
Suh	1990	(+)	+		(+)			
Pahl and Beitz	1996	(+)	+		+	(+)	(+)	
Altushuller	1988	(+)	+					(+)
Meyer and Lehnerd	1997	(+)	(+)		(+)	+	+	
Cusumano and Nobeoka	1998				(+)	+		(+)

(+) abstract, process description
\+ detailed description of what to do, how to do

As is seen in Table 4-2, almost all literature addresses the issues of designing a producible product that satisfies the requirements from manufacturing from the beginning of product design. It is observed that there are two major streams to address the manufacturing issues during the product development. The first stream is to facilitate the communication between manufacturing and product development. In this approach, organizing people (i.e., cross-functional product development team, matrix organization [Ulrich and Eppinger 2000]) and coordinating complex information flows (i.e., parallel development, critical-path model) are important to design producible products. Authors such as Andreasen and Hein [1987], Clark and Fujimoto [1991], Wheelwright and Clark [1992], and Clausing [1994] explain different aspects of this approach in detail. The other approach is to study how the product design itself affects manufacturing. For example, Nevins and Whitney [1989], and Cunningham [1998] address the issue of product tolerancing and assembly. Boothroyd et al. [1994] propose several methods to estimate the cost and time of machining and assembly along with material selection issues. O'Grady [1999] explains the concept of modularity, and Meyer and Lehnerd [1997] describe the benefits of the product platforms. Both concepts can lead to simpler manufacturing systems with given product variety. Suh [1990, 2001] proposes to match process variables with product design parameters during product design in his Axiomatic Design methodology, which consequently leads to the consideration of manufacturing issues during product design. Sohlenius [2000] proposes a model for concurrent design of product, process, and manufacturing system. In summary, this approach tries to convey the content of issues that can arise during the transformation of conceptual product design to physical implementation.

However, many of these authors are either explaining their methods in a very high level of abstraction without providing details of the methods (i.e., [Wheelwright and Clark 1992], O'Grady [1999], Sohlenius [2000]), or limit the discussion to specific manufacturing process engineering issues (i.e., [Boothroyd et al. 1994]). Furthermore, manufacturing system issues are rarely addressed even though the manufacturing system plays a significant role during the actual production of the new product.

In the following sections, four approaches are described in detail: concurrent engineering, product platform/architecture, Design for X (DFX), and Axiomatic Design. These approaches are not addressed in isolation, however. Most product development literature deals with the first three approaches at the same time in a mixed way. Axiomatic Design literature also addresses the first three issues.

4.3.1 Concurrent Engineering Approaches

According to Clausing [1994], products in the U.S. were traditionally developed based on partial designs, structured for complex products by phased program planning, and encumbered with a management bureaucracy that adds insufficient value [Clausing 1994]. The traditional product development processes are often represented by 'functional silos (or chimneys)' in the organization or 'throw-over-the-wall' style serial development. Clark and Fujimoto [1991] pointed out the disadvantages of this traditional approach: difficulty in designing for simplicity and reliability, failure to pay enough attention at the design stage to the likely quality of manufactured product, weak consideration for manufacturability, longer development time, weak involvement of suppliers, and neglect of continuous improvement. To overcome the disadvantages associated with the traditional product development processes, concurrent engineering proposes to do a concurrent process carried out by a multifunctional product development team.

Concurrent engineering (CE) has received much attention from the early 1980s, and the attention given to it has been intensified since about 1988 [Clausing 1994]. The idea of concurrent engineering gained its popularity by the great success of Japanese automakers in the U.S. market in the 1980s. Sometimes concurrent engineering is referred to with different titles such as 'simultaneous engineering (SE)' or 'integrated product and process development (IPPD).' However, the main idea is similar – collaboration of different functional parties within a company during the product development processes to address the issues in downstream and upstream processes simultaneously in order to provide a successful product at the market price. Therefore, simultaneous and parallel execution of different phases of product development through collaboration of different functional groups may be seen as the essence of concurrent engineering.

Two things are important for successful implementation of concurrent engineering. First, concurrent engineering aims for parallel processing of different phases of product development rather than serial processing. Therefore, it is very important to define the dependencies between design activities and to organize the activities according to the dependencies and the timing. In other words, clear identification and careful control of information flows among product development activities at different phases of product development are essential. Second, there are a large number of people involved in product development. Therefore, organizing the people according to the identified information flows is important. Since it is people who perform the actual product development activities, it is crucial to organize them properly so that the necessary information flows freely between them in a timely manner.

Therefore, in concurrent engineering literature, the smooth transition from product design to manufacturing is ensured by the above-mentioned two factors: information flow control or/and organization management. However, in terms of the smooth transition from product design to manufacturing by considering manufacturing system design issues, concurrent engineering approach shows weaknesses in revealing the actual content of the interactions between the manufacturing system and product/process design. In other words, concurrent engineering literature does not provide in-depth knowledge on what information should be exchanged between functional parties to smoothen the transition from product design to manufacturing.

4.3.2 Product Platform/Product Architecture Approach

This approach starts from the assumption that the best way to success is to give customers what they want to have. However, the product variety comes with costs. In other words, this approach is about the strategy and methods to provide a wide variety of products without significantly increasing design and manufacturing costs. Before illustrating how the ideas of product platform and product architecture affect the manufacturing system, the definitions of relevant terms are necessary to avoid the confusion. Product platform is defined as, "a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" [Mayer and Lehnerd 1997]. Consequently, product platform is related to the use of a common structure that can be applied to various products. Product architecture is, "the scheme by which the functional elements of the product are arranged into physical chunks and by which chunks interact" [Ulrich and Eppinger 2000]. There are two types of product architecture: modular architecture and integrated architecture. Product family is, "a set of products that share common technology and address a related set of market applications." [Mayer and Lehnerd 1997] Therefore, a product family can be developed based on a product platform by carefully considering the product architecture.

Mayer and Lehnerd [1997] claim that a platform approach to product development dramatically reduces manufacturing costs. This is true from two perspectives. First, a platform approach enables the reduction of complexity in fabrication with given product variety since many products share the same platform. In addition, assembly takes its benefit in terms of decreased assembly complexity since the variety of components dealt with in assembly is significantly reduced with the given product variety. Second, a plat form approach provides significant economies of scale in the procurement of components and materials, because many of these are shared by various products. Some examples of platform approach are the component sharing program of Black Decker in 1970s and Sunbeam in 1980s. Utterback [1994], Lehnerd [1987], and Meyer and Lehnerd [1997] present the examples in detail.

Product architecture is also closely related to part sharing. In some sense, part sharing through a platform design should be supported by modular product architecture. According to Ulrich and Eppinger [2000], modular product architecture has the following two properties:

- Physical building blocks of a product implement one or a few functional elements in their entirety and,
- The interactions between the physical building blocks of a product are well defined and generally fundamental to the primary functions of the product.

To use a common platform to derive a stream of products, the interactions between platform components and other components should be clearly defined and thus, it should be supported by modular architecture. The platform components can be extremely complex internally but their external interfaces should be clearly defined [O'Grady 1999]. The opposite of the modular architecture is an integral architecture. The characteristics of the integral architecture are as follows:

- Functional elements of the product are implemented using more than one physical building blocks of the product.
- A single physical building block of the product implements many functional elements.
- The interactions between physical blocks are ill defined and sometimes are incidental to the primary functions of the products.

Modularity, however, is a relative property. In other words, an architecture is more or less modular when it is compared with other architectures. An absolutely modular architecture does not exist as an absolutely integral architecture does not exist.

In terms of interaction between manufacturing and product architecture, different product architectures can affect manufacturing systems in controversial ways. First, the number of components can be reduced through component integration with integral product architecture, which can lead to simpler assembly and material handling. Typical Design for Manufacturing and Assembly (DFMA) approach encourages the reduction of part counts [i.e., Boothroyd et al. 1994]. On the other hand, components sharing through modular product architectures can greatly reduce the manufacturing complexity while providing more product variety. For example, modular product design enables the delay of product differentiation within manufacturing systems up to the end of production lines, which significantly reduces the complexity associated with handling product variety at the front of production lines [Andreasen and Hein 1987], [Lee 1993], [Lee and Billington 1994], [Lee and Tang 1997]. Therefore, product architecture decisions should be made after thoroughly investigating the impact of the decision on manufacturing systems.

However, there is some controversial evidence as to the usefulness of the part commonality and part sharing. For example, Fisher et al. [1995] point out that many attempts to increase the commonality of parts eventually failed due to the lack of providing the literal meaning of 'variety' that are recognized by the customers. In the same context, postponing the differentiation point may not work. In other words, reducing complexity of manufacturing systems by part sharing or differentiation point postponement may be possible, but if the real variety of products recognized by the customers is not provided, reduced complexity is meaningless.

In summary, part sharing through product platform or modular architecture has been proposed to save manufacturing costs through the elimination of complexity in fabrication and assembly within manufacturing systems. It also provides the benefit of economies of scale in part and material procurement. In addition to these benefits, modular product architecture makes the delay of product differentiation within manufacturing systems, which leads to the reduction of complexity associated with handling product variety.

4.3.3 DFX Approaches

One of the most widely accepted engineering design philosophies associated with manufacturing is "Design for X" (DFX) approach. Here X can stand for many criteria. For example, in their design embodiment section, Phal and Beitz [1996] enumerate many DFX ideas such as 'Design for Ergonomics,' 'Design for Aesthetics,' 'Design for Production,' 'Design for Ease of Assembly,' 'Design to Standards,' 'Design for Ease of Maintenance,' 'Design for Recycling,' 'Design for Minimum risk,' 'Design for Quality,' and 'Design for Minimum Cost.' Ulrich and Eppinger [2000] claim that the general ideas that apply to methodologies for achieving any of the Xs in DFX are the following:

- Detail design decision can have substantial impact on product quality and cost.
- Development teams face multiple, and often conflicting, goals.
- It is important to have metrics with which to compare alternative designs.
- Dramatic improvements often require substantial creative efforts early in the process.
- A well-defined method assists the decision-making process.

Among these methodologies, the most common is Design for Manufacturing (DFM). Ulrich and Eppinger [2000] view the traditional DFM approach as a means to achieve cost savings. They categorize the DFM activities into components cost reduction, assembly cost reduction, and supporting production cost reduction, and propose five steps for the DFM method as is shown in Figure 4-1 [Ulrich and Eppinger 2000]. The five steps are: 1) estimate the manufacturing costs, 2) reduce the components costs, 3) reduce the assembly costs, 4) reduce the costs of supporting production, and 5) consider the impact of DFM decisions on other factors. In order to support cost savings in components and assembly, Boothroyd [1979], Dewhurst and Boothroyd [1987], Boothroyd and Dewhurst [1990], and Boothroyd and Radovanovik [1989] propose several DFM tools to estimate manufacturing cost and time at the early conceptual design stage as well as design guidelines for ease of manufacturing. According to Boothroyd et al. [1994], DFMA tools are designed to serve as analysis tools to help concurrent engineering teams to study proposed designs and to evaluate them from the point of view of manufacturing difficulty and cost. However, in many cases, these DFM tools focus on the design interactions with manufacturing in the process level or the component level.

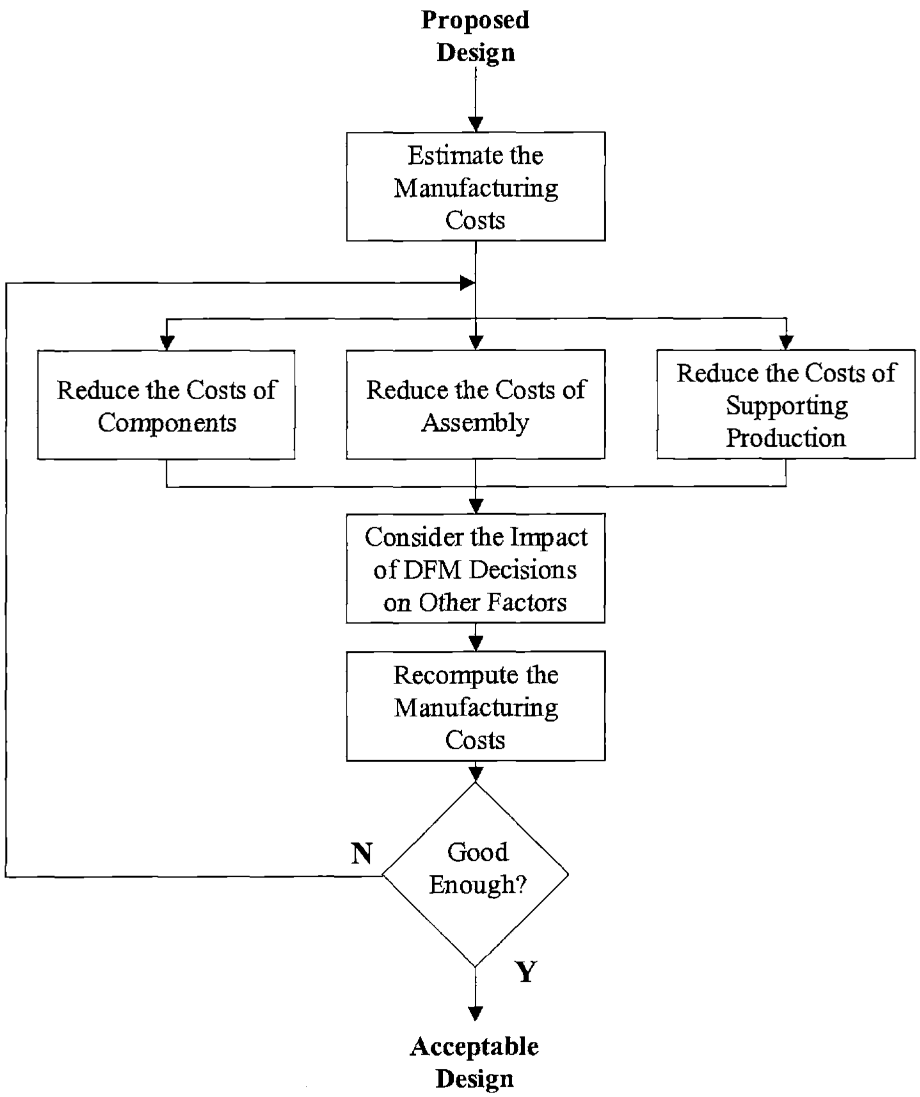


FIGURE 4-1. THE DESIGN FOR MANUFACTURING (DFM) METHOD [ULRICH AND EPPINGER 2000].

Cost savings in supporting production are about saving the overhead of manufacturing. Ulrich and Eppinger [2000] illustrate a series of examples for cost savings in supporting production through DFM. A reduction in the number of parts may reduce the demands on inventory management. A reduction in assembly content can lead to the reduction of the number of workers required for assembly and therefore, reduces the cost of supervision and human resources. The demands on engineering support and quality control can be greatly decreased by standardized components. Still, the DFM approach lacks of a framework to show the consequences of DFM rules on manufacturing systems. Specifically, it is not known whether the application of a DFM 'rule' will bring positive or negative consequences on a manufacturing system's ability to meet its requirements. For example, a part count decrease by applying the DFM rules may require new manufacturing processes to be developed, which may increase cost. Manufacturing systems can be simplified by the reduced number of parts but also can be complicated by the issues such as training of operators for new processes and quality assurance for new processes. Therefore, controversial results may arise from the application of typical DFM rules. This problem suggests that DFM rules should be applied only in the context of the manufacturing requirements.

Another interesting DFX approach regarding its relationship with manufacturing systems is the 'Design for Variety' (DFV) approach. In the DFV approach, Ishii et al. [1995], and Martin and Ishii [1996] proposed metrics to measure the cost impact of product variety. DFV is unique from the perspective that it provides quantifiable indices to measure and compare the costs of product variety. In their research, Martin and Ishii [1997] claim that the manufacturing cost of dealing with a variety of products consists of direct and indirect costs. The direct costs are easy to calculate and include increased capital equipment, more training of personnel, the engineering time required to make new drawings and analyze the new design, run certification or qualification tests, and to find new suppliers. However, indirect costs are more difficult to consider and include raw material inventory, work in process inventory, finished goods inventory, post-sales service inventory, reduction in capacity due to set-up, and the increased logistics of managing the product variety. With these concepts, three indices that measure the commonality of the parts, the differentiation point in manufacturing processes, and setup costs are proposed. The costs related to the increased product variety can be decreased by increasing the commonality of parts, postponing the differentiation point, and decreasing setup costs.

The DFV approach mentions the possible impact of product design on manufacturing systems in terms of various aspects of manufacturing systems such as equipment, training, engineering, and suppliers. However, it does not provide a framework that integrates the impact of product design on various sides of manufacturing and does not show how these relationships can interact with each other.

4.3.4 Axiomatic Design Approach

The approach of Axiomatic Design to integrate manufacturing to product design is unique since it proposes simultaneous consideration of process during the product design processes. The details of the Axiomatic Design methodology are provided in section 6.2. According to Suh [1990, 2001], design is interaction between what to achieve and how to achieve in four design domains of customer, functional, physical, and process. He claims that customer attributes (CAs) should be mapped to functional requirements (FRs), which are satisfied by design parameters (DPs) (Figure 4-2). DPs are physically implemented by process variables (PVs), which are typically quantities such as temperature, pressure, and flow rate that can be changed on equipment to yield a desired output value of a product characteristic. The mapping between elements in different domains is governed by the zigzagging principle that guides the decomposition process from a high system level to lower detailed levels. The zigzagging principle suggests that designers should zigzag between the design domains during the design process. For example, a high level FR satisfied by the corresponding DP can be further decomposed, if necessary, into sub-FRs but these sub-FRs are constrained by the DP. Therefore, during the decomposition process, the higher level DP should be always considered.

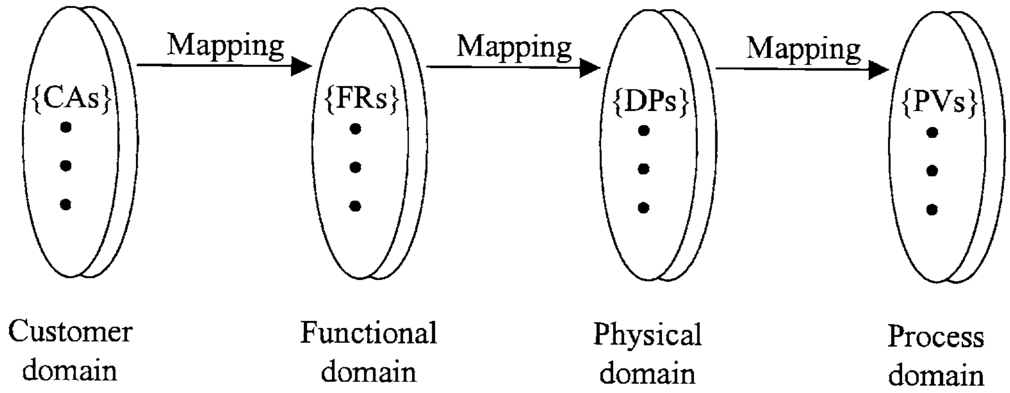


FIGURE 4-2. DESIGN PROCESS OF AXIOMATIC DESIGN

In Axiomatic Design, the manufacturability of design is assured by the zigzagging principle. Since the PVs at the high level of decomposition govern the low level DPs, manufacturing is always considered during the design. Therefore, it can be said that Axiomatic Design supports the design for manufacturing by its inherent design process.

However, it is not very clear how to decompose between physical domain (DP) and process domain (PV). Suh [2001] describes the required design matrices between FRs and DPs, and DPs and PVs but he does not provide the detailed steps for simultaneous decomposition between three domains of functional, physical, and process. Furthermore, few examples are available that show the decomposition across three design domains. With regard to this problem, several authors proposed their own approaches to clarify the physical realization process of DPs. For example, Arinez and Cochran [1999] propose an approach for mapping from the physical domain of product and production system design to process domain. They propose to use both product design decomposition and production system design decomposition to find the PVs in the common process domain. In other words, based on the DPs of product design and the DPs of production system design, PVs in the process domain can be derived. The benefits of this approach are the consideration of both product design and production system design for process design. Furthermore, it enables to trace the requirements for communication between designers when alternative decomposition in process domain exists. Their approach is summarized in Figure 4-3.

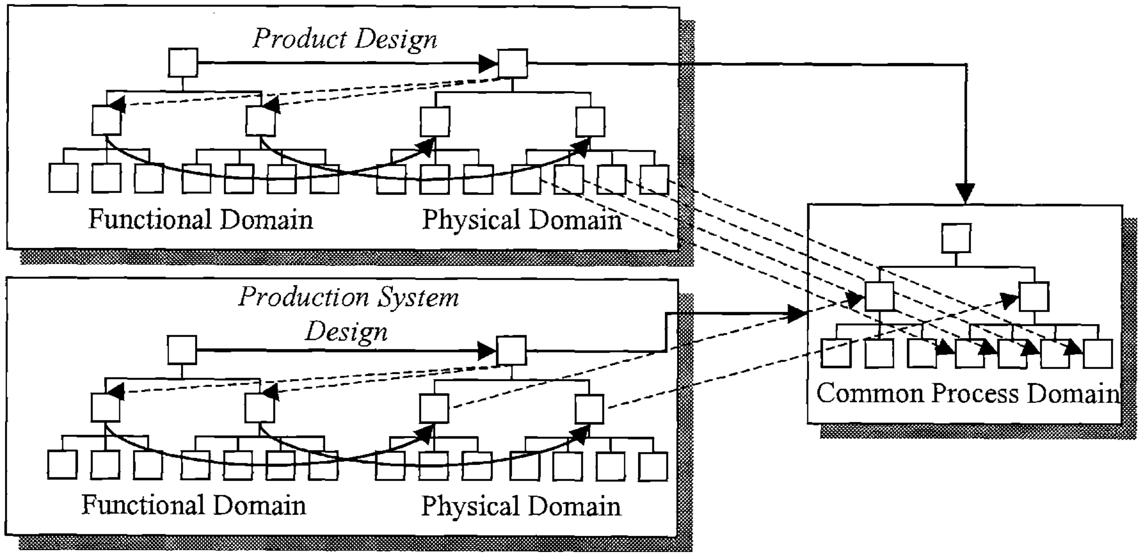


FIGURE 4-3. COMMON PROCESS DESIGN BETWEEN PRODUCT AND PRODUCTION SYSTEM DESIGN [ARINEZ AND COCHRAN 1999].

In their approach, they take an example of compressor crankshaft design, which is shown in Figure 4-4. From the eleven product design FRs and DPs, eight process variables that affect product design are derived. In addition, three more process variables are derived from the three FR – DP pairs of production system design.

Product Design

{FR}PD												{DP}PD
FR1: Mate to clutch plate	X	O	O	O	O	O	O	O	O	O	O	DP1 - Drive spline geometry
FR2: Mate with housing support bearings	O	X	O	O	O	O	O	O	O	O	O	DP2 - Shaft bearing geometry
FR3 - Mate to piston bearing	O	O	X	O	O	O	O	O	O	O	O	DP3 - Piston bearing geometry
FR4 - Minimum torque load	O	X	X	X	O	O	O	O	O	O	O	DP4 - Overall shaft geometry
FR5 - Maximum shaft weight	O	O	O	X	X	O	O	O	O	O	O	DP5 - Shaft material density
FR6 - Maximum shaft deflection	O	X	O	X	O	X	O	O	O	O	O	DP6 - Modulus of elasticity
FR7 - Maximum volumetric wear	O	X	X	O	O	O	X	O	O	O	O	DP7 - Surface hardness
FR8 - Minimum fatigue life	O	O	O	X	O	O	X	X	O	O	O	DP8 - Shaft material fatigue strength
FR9 - Maximum leakage via shaft seal	O	O	O	O	O	O	O	O	X	O	O	DP9 - Seal diameter surface finish
FR10 - Maximum compressor housing space	O	O	O	X	O	O	O	O	O	X	O	DP10 - Shaft (length/diameter) ratio
FR11 - Lubricant flow between shaft ends	O	O	O	O	O	O	O	O	O	O	X	DP11 - Lubricant passage geometry

{DP}PD									{PV}PD
DP4 - Overall shaft geometry	X	O	O	O	O	O	O	O	PV4 - Overall machining process plan
DP1 - Drive spline geometry	X	X	O	O	O	O	O	O	PV1 - Spline generation process variables
DP8 - Shaft material fatigue strength	O	O	X	O	O	O	O	O	PV8 - Heat treat process variables
DP7 - Surface hardness	O	O	X	X	O	O	O	O	PV7 - Quenching process variables
DP2 - Shaft bearing geometry	X	O	X	X	X	O	O	O	PV2 - Bearing grinding process variables
DP9 - Seal diameter surface finish	X	O	X	X	X	X	O	O	PV9 - Polishing process variables
DP11 - Lubricant passage geometry	X	O	O	O	O	O	X	O	PV11 - Machining process plan for passage
DP3 - Piston bearing geometry	X	O	X	X	O	X	O	X	PV3 - Piston grinding process variables

Production System Design

{FR}PSD				{DP}PSD				{PV}PSD
FR1 - Reduce tasks that tie operator to the machine	X	O	O	DP1 - Autonomous operation of machines and stations	X	O	O	PV1 - Level of machine automation
FR2 - Enable worker to operate more than one machine	X	X	O	DP2 - Work loops implemented in a cell layout	X	X	O	PV2 - Cell layout parameters
FR3 - Plan resources for different operating volumes	X	X	X	DP3 - Standardized work loops for different volumes	X	X	X	PV3 - Work content per loop

FIGURE 4-4. CRANKSHAFT DESIGN INTEGRATED WITH PRODUCTION SYSTEM DESIGN [ARINEZ AND COCHRAN 1999].

This approach, however, is somewhat different from the original Axiomatic Design approach in a couple of perspectives. First, Axiomatic Design stresses the importance of one-to-one relationship between FRs, DPs and PVs. Arinez and Cochran, however, provided eight PVs from eleven product DPs in their example shown in Figure 4-4. Additional three pairs of DPs and PVs are derived from the FRs of the production system design. Therefore, some DPs of product design such as DP5 (shaft material density) and DP6 (modulus of elasticity) are not linked to their corresponding PVs. In addition, it fails to capture the feedback relation between manufacturing and product design.

On the other hand, Sohlenius proposes the following framework shown in Figure 4-5, which is a further development of the approach of Arinez and Cochran. In his roadmap for concurrent product and business process design, he distinguishes the product design from manufacturing system design. Each design has functional requirements, design parameters, and process variables of Axiomatic Design. In manufacturing system design, however, functional requirements are called as manufacturing requirements (MR), design parameters as manufacturing parameters (MP), and process variables as manufacturing implementations (MI).

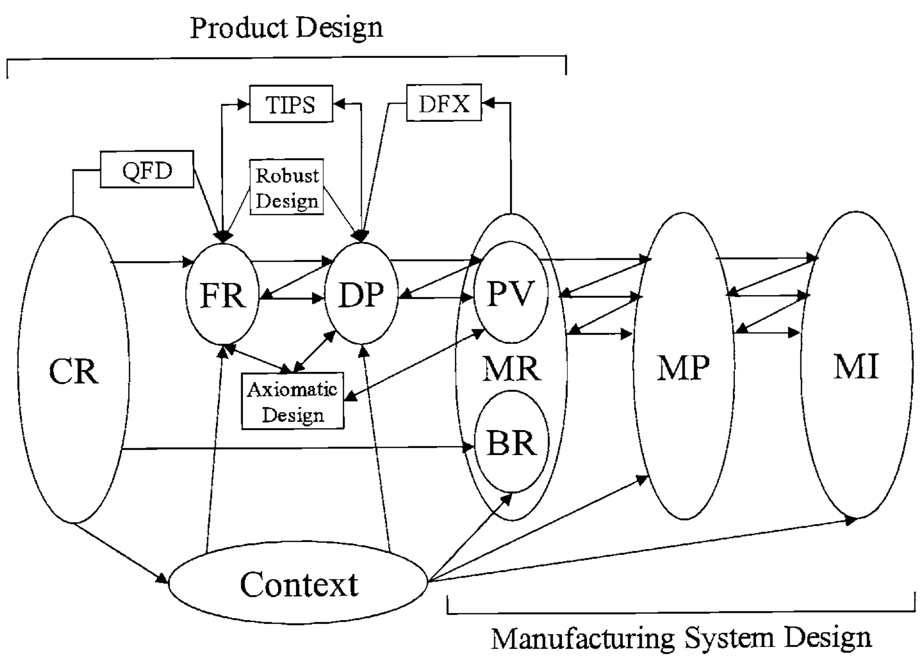


FIGURE 4-5. ROADMAP FOR CONCURRENT PRODUCT AND BUSINESS PROCESS DESIGN (ADAPTED FROM [SOHLENIUS 2000]).

In his approach, design starts from customer requirements (CR), which are mapped to product design FRs and business requirements (BR). The mapping from CR to FR can be facilitated by using tools such as quality function deployment (QFD) [Clausing 1989, 1994]. The FRs are mapped to DPs according to the Axiomatic Design principles. The theory of inventive problem solving (TIPS or TRIZ) [Altshuller 1988], [Kim and Cochran 2000] can help to come up with innovative DPs to satisfy FRs. Robust design principles [Phadke 1989] may also be applied for the selection of DPs. The PVs are derived from the DPs that constitute part of the MRs along with BRs. DFX approach may be applied during the mapping between DPs and MRs. MRs are futher mapped to MPs and MIs. All these elements are subject to the context. Sohlenius' approach is unique in terms that it defines manufacturing requirements derived from product design parameters and customer requirements. However, it does not provide the details of the mapping processes or any example of the whole mapping process. Due to this lack of detail, the actual application of the design roadmap should be classified as under development.

4.4 Chapter Summary

In this chapter, various approaches in the literature to enhance the early consideration of manufacturing systems issues during product development are reviewed. First, the terms such as system, manufacturing system, product development, and design are defined to avoid the mix use of different concepts with the same term. Then, a list of literature in manufacturing system design is provided, which is followed by the literature in product development. Several approaches to integrate manufacturing system issues with product design are explained in detail. They are: concurrent engineering, product platform/architecture approach, DFX approach, and Axiomatic Design approach. Basic ideas of different approaches are presented and their strengths and weaknesses are discussed.

Two problems are identified with the existing approaches proposed in the literature. Many of the proposed approaches are either explaining their methods in a very high level of abstraction without providing details of the methods or are limited to the discussion on specific manufacturing process engineering issues. Furthermore, few frameworks are available to capture the interactions between product/process decisions and manufacturing systems, even though manufacturing system plays a significant role during the actual production of the new product.

5 INDUSTRY PRACTICES CASE STUDIES

In this chapter, the results of the first-round questionnaire are presented. The first-round questionnaire is designed to investigate what industry does to facilitate the information exchange between manufacturing and product design. This questionnaire falls under the research step 2.2 in Figure 3-2. Overall, six companies participated in the first-round questionnaire. The motivation of the first-round questionnaire and its design are also provided along with a brief explanation on the profiles of the participating companies to show the characteristics of their business.

5.1 Introduction

Recently, concurrent engineering gained enormous popularity and has become a norm in product development in major U.S. companies. Concurrent engineering emphasizes collaboration and communication between stakeholders of a product development project early in the product development process in order to minimize the mistakes or iterations in later phases. This technique allows minimization of product development time and costs. In the current volatile market, minimizing product development time and costs to reflect the most recent customer requirements is essential for product success. Therefore, it can be seen that the advantages of concurrent engineering can affect the prosperity of a manufacturing company.

One of most interesting aspects of concurrent engineering is the collaboration of manufacturing groups and product design groups to design producible products in the very early phases of product development. Extensive information sharing between product design groups and manufacturing groups is important for a smooth transition from product concept to production.

The following sections evaluate the various methods used in industry for information sharing.

5.2 Motivation

Companies often use different methods to facilitate the communication between product design groups and manufacturing groups. For example, some companies emphasize cross-functional teams and informal communication among the team members for creative and project-specific solutions. Other companies emphasize the use of standardized written documentation to avoid unnecessary waste associated with trial and error. Therefore, it is difficult to understand exactly why some methods work well for some companies and not for others, and why certain methods are more effective than others. The first-round questionnaire is one step in a series of research activities to determine the effectiveness of each method and propose a general framework for the design for manufacturing systems (DFMS). The list of questions for the first-round questionnaire is provided in Appendix E.

The first-round questionnaire was designed to identify various methods deployed in industry to improve communication between people in product design groups and manufacturing groups. Company A received the first version of the first round questionnaire in the fall of 2000, and a response was received in January of 2001. To increase clarity, modifications of several questions were made after a thorough review of the responses from company A. After the revision, a second version of the first-round questionnaire was sent to five other companies.

The questions of the first-round questionnaire are designed to identify the industry practices with regard to design guidelines for manufacturing, system interface between manufacturing and product design, product design decisions in general, manufacturing system design in general, and performance measures. Although the main goal of this research is to find out the communication processes between product design and manufacturing, questions on product design decision, manufacturing system design, and performance measures are added for better understanding of the communication processes. Knowledge of each company's view on product design, manufacturing system design, and performance measurement is believed to help rationalization of the communication process used in each company.

5.3 General Profiles of Participating Companies

Company A

Company A is an OEM company in the Japanese automotive industry. This company also has several transplants in North America. The main products of company A are cars, trucks, and buses. Respondents to the first-round questionnaire include production engineering planning, vehicle planning, and corporate planning divisions. Many respondents are general managers.

Company B

Company B is a U.S. first-tier parts supplier for the automotive industry. This company was spun off from its mother OEM company several years ago. Company B is a top five automotive supplier in the world. Respondents to the first-round questionnaire are comprised from different product divisions, such as electronics and power train.

Company C

Company C is a German first-tier parts supplier for the automotive industry. Company C operates several transplants in the U.S. Company C is a top five auto supplier in the world. Respondents to the first-round questionnaire are engineers in the U.S. transplants.

Company D

Company D is an OEM company in the automotive industry based in the U.S. The respondent to the first-round questionnaire is an engineer in the die engineering department.

Company E

Company E is a German-based OEM company in the automotive industry. Company E produces high performance, high-end vehicles. Respondents to the first-round questionnaire are engineers from a plant in southern Germany.

Company F

Company F is a Korean-based OEM company in the automotive industry. Company F produces cars, trucks, and buses. The respondent to the first-round questionnaire is a design engineer in the bus division.

5.4 Data Collection Methods

For company A, the first round questionnaire was translated by Prof. Kawada, a Japanese professor in Meijo University. Prof. Kawada interviewed the engineers and managers of company A and translated the responses to English. A complementary interview was held in the summer of 2001 in Japan by the author to increase the understanding of the answers. The responses to the complementary questions were recorded.

From company B, five different answers were received from five different product groups. Their answers are excellent in terms of diversity and details. A follow-up meeting was held at company B headquarters in Dearborn on June 29th, 2001 to clarify the terms used in the answers and get a clear overall picture of the system used in company B. Participants from company B include engineers from interior (instrument panel, doors, seats, etc), exterior (bumpers, etc.), electronics, power train, and climate control.

For companies C, D, E, and F, the first round questionnaire was sent by email. The answers were documented by the engineers of each company and sent to the author by electronic files.

5.5 General Overview on the Received Answers

The answers received from six major players in the auto industry revealed that those six companies are pursuing more or less similar goals and implementing similar tools as suggested by the academia. All of the companies stressed the importance of the communication between product design groups and manufacturing groups (including production engineering groups) in order to streamline product development activities, which results in faster introduction of new products without significant cost increase. The use of cross-functional teams or design for manufacturing guidelines is becoming a norm in the automotive industry. Knowledge management to minimize the repeating mistakes is extensively pursued. All respondents are aware of the disadvantages associated with the traditional 'throw-over-the-wall' approach with functional chimneys. However, for some companies, lower level divisions may not take the advantage of the many tools developed at the corporate level. This may be due to the a loose enforcement of corporate-wide tool use or a lack of continuous support to encourage the propagation of tool use.

Among the answers received from the participating companies, especially interesting are the answers from company B. Five answers from five different product groups were received. According to the received answers, each division pursues different strategies for the integration of manufacturing and product design. This is partly due to the different characteristics of the products that each division produces. However, the major reason is a consequence of the fact that each division worked as an independent organization when company B was a part of its mother company. The division that achieves the best integration is electronics. The electronics division produces circuit board products for automotive vehicles in several plants around the world. The integration between these plants as well as between manufacturing and product design is achieved by the core cross-functional team, 'Copy-Exact' team. This team supports the software tool that is globally used to check the manufacturability of new product designs, the new process technology options, and the availability of new components. On the other hand, in other divisions, a corporate-wide product development manual is often used as a basis to consider manufacturing issues. This manual describes the processes that should be followed for new product development and clearly defines participating groups, their responsibilities, and information flows between these groups. Based on this manual, electronic knowledge databases are currently being developed or are already in use in some divisions. The use of knowledge databases reduces product development time by eliminating the time to solve a problem that had occurred before. The knowledge databases also help product designers eliminate the problem permanently. However, some divisions heavily count on the personal experience and knowledge of its individuals instead of using the standardized knowledge base.

Company A is highly recognized and referred for its excellence in manufacturing as well as product development. The quality of new products from the production line is known to be superior to other companies according to the JD power awards. Therefore, it is expected that company A implements many of the benchmark tools for excellence in product development proposed by academia, such as cross-functional product development teams, knowledge bases to avoid repeating mistakes in product designs, and product design guidelines for manufacturing. These tools are identified in the answers to the first-round questionnaire. For example, a design knowledge base is implemented in company A. This knowledge base is well managed and continuously updated. More importantly, it is extensively used by most of the engineers in the company. In addition, many improvement examples can be found that are the result of enthusiastic collaboration of the product design group and manufacturing group.

Company A, however, seems to be weak in terms of the integration of tools used in different plants. For example, each plant seems to pursue its own modified version of the knowledge base to avoid design iterations caused by poor producibility of the product design, which they believe is more effective than the tools used at other plants. The difference becomes more significant in the case of overseas plants.

A similar trend is observed in the propagation of 'best practices' within company A. Some engineers of the company A believe that standardization is obsolete in company A for its product development related knowledge base. Instead of implementing the same practices and tools, each plant pursues its own, which is believed to be better than the existing best practice. Competition between plants is believed to stimulate the improvement and it is naturally admitted as 'pride of engineers.' This practice is possible because of the relatively loose control from the headquarters in Japan over overseas plants.

This approach is very different from the approach taken by the electronics division of company B. This division pursues maintaining a common best-practice knowledgebase for all of its plants worldwide. A specific team is assigned to maintain and update the software tools and it is their responsibility to make this tool available to all of its plants worldwide. Any best practice developed in one of the plants is thoroughly reviewed by the copy-exact team and then updated to the database as is necessary.

As for company C, it seems that there were not many intensive efforts for the integration between manufacturing and product design at the overseas plant according to the received answers to the first-round questionnaire. However, over the past several years, company C has been strengthening the link between manufacturing and product design groups by deploying several tools such as DFM tools and APQP (Advanced Product Quality

Planning) processes. Company C also intensively works with outside consultants to streamline the time-to-market.

In the case of company D, it may not be appropriate to generalize the practice of company D from a set of answers received from a die manufacturing engineer. For example, the collected answers reported a lack of support for continuous update of the manual they use while company D does have a highly detailed manual for its product development processes. This example may show that it is not an easy task at all to make the communication happen between manufacturing and product design engineers in charge even with the enormous amount of resources spent to support the communication at the corporate level.

Company E seems to maintain some implicit information flow paths between manufacturing and product design. However, there is no written product design guideline available to design manufacturable goods. Instead, manufacturing engineers can affect product designs in various ways. Human network is one way that is frequently used for the information exchange and PC-network tool to which all involved parties have accesses is another way in use. In addition, manufacturing engineers can raise their issues at the periodic quality meetings. Basic principles of concurrent engineering are pursued such as project leaders, temporary project offices, and quality meetings that all involved parties attend.

Company F seems to be heavily influenced by the practices of Japanese auto companies. Several reasons can be inferred such as geographic closeness between Korea and Japan, and its long-term relationship with a Japanese partner company as a technology source. Company F has a documented design guideline and product development schedule standard. However, the design guideline of company F does not capture the manufacturability information. Therefore, manufacturability problems are often solved through negotiation between product design and manufacturing after they have occurred. However, some manufacturing system constraints are reflected in product design. For example, the chassis hard points for different vehicles are set to utilize just one fixed jig instead of developing many different jigs.

5.6 Detailed Answers to the First-round Questionnaire

5.6.1 Design Guideline for Manufacturing

The first-round questionnaire starts by asking questions regarding the availability of written document of product design guidelines from manufacturing people. As is shown in Table 5-1, different companies seem to use different formats of the design for manufacturing documents. However, actual use of the available document seems to be different depending on companies according to the interviews with the engineers. Some engineers showed their concerns on the continuous update and management of the document available.

Questions asked regarding the availability of written product design guideline for manufacturing are as follows:

- Some literature addresses the frequent use of product design guideline originated from manufacturing in benchmark companies. This document contains the requirements from the manufacturing or production engineering side to product design side. Does your company use a formal document like this?

<u>If your company has the equivalent one:</u>

- How has it been developed?
- What is its content?
- How is it related to their manufacturing system design? Is there any good example of design constraints imposed by manufacturing system issues?
- Is there any performance measure for product designers related to this issue? (Are product designers evaluated by being committed to this guideline?)

<u>If your company does not have the equivalent one:</u>

- How are the manufacturing requirements fed back to the product design side?
- Which one is more frequently used for the feedback process, documented (written) information or tacit knowledge through human network?

- If a manufacturing engineer found a product design problem, for example, how would the problem be informed to the product designers? (e.g., product development team meeting, product development process gate review, etc.)
- What activities are done to prevent repeating problems?

TABLE 5-1. THE SUMMARY OF THE ANSWERS TO THE DESIGN GUIDELINE FOR MANUFACTURING QUESTIONS

Company		Availability of written DFM document	Who developed? (if no document, what alternative?)	Content (or substitute method)	PM*
A		Yes	Production engineering	Structural requirements (before a project), general requirements (during a project), improvements by design – manufacturing collaboration.	Yes
B	X	Yes	Slight modification of one used in mother company	Lessons learned, FMEA, content is agreed and audited by product engineering	Yes
	Climate control	Yes	Developed and maintained by cross-functional teams	Lessons learned, best practice, manufacturing feasibility, product design related information	No
	Exterior	No	Human network with tacit knowledge	Feasibility meetings that happen randomly, depend on memories & tacit knowledge of engineers	No
	Powertrain	Yes (design guide based on avoiding mistakes)	Product engineering in consultation with manufacturing engineering	Lessons learned, Do's and Don'ts based on current manufacturing procedures and practices	No
	Electronics	Yes (IT knowledge tool)	Copy-Exact team	Panel size optimization, solder ability, load balance to optimize facility usage, test strategy, equipment specification, material sources, tool design	No / Yes
C		Yes	Product design in consultation with outside consultants	Modified form of the APQP, DFM/DFA workshops	No
D		Yes (but obsolete, not updated)	Feasibility dept. used to own and maintain the guideline – no longer has the resources for this task.	Manufacturing feasibility reference based on past experience with sections & sketches by part types	No
E		No	Human network with tacit knowledge	Periodical quality meetings, PC-network based change-request system	No
F		No	Human network, engineers' experience and tacit knowledge	prototype building is done by designers, production engineering reviews the design with the beta prototype.	No

* PM: Performance Measurement

In the following section, detailed information regarding the written DFM documents used in each company is described.

5.6.1.1 Company A

Company A has a product design guideline originated from manufacturing that is called *Yoken-sho* (requirement sheet). There are two types of *Yoken-sho*. One defines the general structural requirements applied commonly to all the models; the other regulates the requirements applied to each individual model. Both are formal documents.

The general structural requirement means a general solution applied to any vehicle regardless of the model. General requirements are submitted from the manufacturing to the design side at the earlier stage of product design. The answers to these general requirements are *Ippan-kai* (general solutions). For global standards, *Ippan-kai* should be universal, not unique to the problems, so that designers can easily check their drawings. Countermeasure ideas of the current vehicle problems are recorded in *Ippan-kai*. For example, once the position of the fuel inlet is decided to be at the right (or left) side of the body, designers of any vehicle must observe these regulations without any exception as to the general structural requirements.

The specific structural requirements are incessantly issued from the manufacturing or production engineering side to the product designers in the development process of any specific model. Upon receiving the requirements, product designers are required to decide as early as possible whether to accept the requests, or stick to their original ideas although they contradict to what the other party claims. When both parties disagree, they meet together and discuss thoroughly until they reach some specific solution or some optimal compromise.

Some plants within company A use a different tool called a Pre-Product-Check (PPC) instead of using *Yoken-sho*. PPC is an advanced version of *Yoken-sho*. However, PPC is not thoroughly formalized. Additionally, every plant within company A develops and implements its own version of PPC. This separate development of PPC by each plant is due to the loose control over the plants from the headquarters of company A. PPC was originally developed in a format of written documents but now an electric database version is available. Product designers can easily access and search the data in many different categories with this electronic database. For example, the part number can be used for data search since company A has a unique part numbering system. Every part used in company A has a 10 digit part number. The first five numbers indicate part type (e.g., bumper, display panel, etc.) and the rest shows model. Therefore, if an engineering designer is designing a bumper, he can easily learn about the previous mistakes made and the problems that have occurred with bumpers of other similar models as well as those of previous models. In addition, the possible solutions to the problems are recommended by the database. According to the interviewed engineer, 90% of the mistakes made during the product development are repeated mistakes. By using the PPC, these problems can be prevented.

In company A, a designer's commitment to problem solving with manufacturing engineers is promoted by performance measure. Acceptance ratio is the ratio of the number of indications the design side admitted as rational to all the number of indicated items reported by manufacturing.

Company A, however, seems to suffer from the lack of integration of the tools used in different plants. Some plants claim that they use different sets of tools, which they believe is more effective (than tools used in other plants) to avoid iterations at the phase of production realization due to lack of producibility of product design. Improvement activities in different plants are also done in different ways and the best practice cases are not implemented in every plant. Instead of implementing the same practice, each plant pursues a better one. The difference becomes more serious when it comes to the case of oversea plants. Each plant seems to pursue its own version of best practices. This practice is not far from what engineers of company A believes. For example, the view of the engineers of company A is that standardization is obsolete in the company in terms of PPC. This results from relatively loose control from the company A headquarters in Japan over overseas plants. For example, company A does not have a standardized single cost accounting and thus, cannot effectively compare costs of different plants. Most of the engineers of company A, however, did not seem to be concerned a lot about the level of integration within company A in terms of tools used. A general manager commented about the different tools used as follows:

> "It is like a pride of engineers. Company A engineers do not think that there exists any best practice. If they see some 'good' practices, they compete with those who developed the good practices by developing 'better' practices."

5.6.1.2 Company B

Five answers from five different product groups were received from company B. Respondents from company B include engineers from interior (instrument panel, doors, seats, etc), exterior (bumpers, etc.), electronics, power train, and climate control.

It is interesting to see that some divisions of company B implement their own version of tools to stimulate the information sharing between the product design group and the manufacturing group. The use of different tools is caused by the fact that company B is a spin-off company from the mother OEM company. Each product division of company B had worked for a different organization of the mother company in different environment and thus, it had developed its own version of communication tools that was adequate to their situation. However, this difference caused the problem of a low level of integration throughout the company. For example, significant achievement of one division in terms of time and money saving in product development is not likely to propagate to the other divisions of the company. Company B is trying to solve this problem by encouraging each division to use the company wide manual for product development.

Within a division, however, the level of integration seems to be high. A very high level of integration is observed in the electronics group, for example. The electronics group forces the use of the Copy-Exact tool to its plants worldwide and supports this activity by assigning a designated team to update and maintain the tool. In addition, the Copy-Exact tool is available as a software tool, which allows easy use of the tool by its plants. They claim that this tool covers every aspect of circuit board manufacturing and test, mechanical assembly, and shipping best practices. This tool is developed and maintained by a central Copy Exact team focusing on each step of the electronics manufacturing process. This Copy Exact team is a cross-functional team that includes representatives from each functional group involved with product development. Every plant establishes a lead in one of the areas of the process to create refined equipment, maintenance, material and design requirements, and is responsible to feed the central Copy Exact Team with the requirements to ensure all plants benefit. Much of the knowledge is captured in continually updated IT knowledge tools that layout new circuit board designs.

Other divisions use similar tools. The power train group, for example, uses a Design Guide to avoid mistakes. It is developed by the product engineering group as a result of lessons learned and in consultation with manufacturing engineering. This guideline describes "Do's" and "Don'ts." The Design Guide is based on current manufacturing procedures and practices. For example, the design of corners or radii of blow-molded components is critical to prevent excessive thinning in the corners of the product. The design guide specifies the minimum radius required to avoid excessive thinning in those corners. There is a manufacturing feasibility sign-off process required in the product development process. However, the manufacturability feasibility review result does not necessarily affect the performance review of product design engineers.

The climate control group also uses a Design Guide that includes manufacturing lessons learned through product launches and manufacturing best practices. It is developed and maintained by cross-functional teams through experience of design validation testing, product launches, and concern resolution processes. This guideline contains primarily product design related information with manufacturing best practices and manufacturing feasibility information. The results of the use of the Design Guide are more manufacturable product designs. For example, heater core connector tubes with bends are designed with oval ends at tank connection to insure correct orientation. Another example is that radiator end tank designs include sufficient spacing between the crimp surface and connectors to allow for tooling to properly crimp. There is no specific performance measure related to the use of the Design Guide, but problems related to designs would reflect negatively on the designers' performance evaluation.

Another division (division X) in company B directly counts on the corporate-wide product development manual, in which cross-functional product development teams maintain specific product development milestones to ensure design for manufacturability, production feasibility, tooling buyoff, and lessons learned. As is previously described, this manual is an extension of the manual used in the mother company of company B. It requires the review of lessons learned to feed the product FMEAs (Failure Mode and Effect Analysis), which feed the process FMEAs which culminates into a manufacturable product controlled by a dimensional control plan agreed to and audited by product engineering. Product engineers are evaluated by their performance and participation in product development teams.

Exterior / Interior division, on the other hand, does not use any written design guideline. Often verbal communication of requirements is ignored. The manufacturing requirements fed back to product design side in the feasibility meetings when manufacturing engineers are invited. The meetings occur randomly. Therefore, the feedback process counts on manufacturing engineers' tacit knowledge and their human network in product design groups.

5.6.1.3 Company C

Company C does not seem to have enjoyed the luxury of well supported communication between manufacturing and product design. Since company C is a U.S. operation of a major German company, a lot of products are designed and validated in Germany. However, company C maintains quite a significant product design capability – around 200 product design engineers in the U.S. In addition, over the past couple of years, company C has been actively involved with activities to strengthen the link between the manufacturing group and the product design group by deploying several tools such as DFM tools and APQP (Advanced Product Quality Planning) processes. The deployment of those tools is done as a part of a focused effort to streamline the product development process to minimize the time-to-market. A result of the efforts may be the new integrated air fuel manifold of which complex wiring harness was completely redesigned by assembly concerns. Still, no performance measure of product designers related to design manufacturable product is established. Company C is working to establish baseline metric information.

5.6.1.4 Company D

It may not be appropriate to generalize the DFM practice of company D from a set of answers received from a die manufacturing engineer. In fact, the respondent does not seem to be aware of company D's manual for product development that the author is aware of and is frequently discussed by academia. However, this fact itself shows that it is not an easy task at all to make the communication happen between manufacturing engineers and product designers even with the enormous amount of resources spent to support the communication.

In the die engineering group of company D, manufacturing feasibility reference books are available. They are somewhat old but still relevant according to the respondent. However, the feasibility department which owned and maintained this book no longer has the resources for this task. The feasibility reference books are developed based on past experience, and include sections and sketches by type of part. However, the feasibility book assumes a standard type of stamping process and is not specific enough to go beyond basic formability, trim, flange issues, etc. No performance measure is there to encourage product designers to design truly manufacturable products.

Overall, the respondent claims that the product design group is not very interested in what makes a part truly manufacturing friendly. If the parts meet their engineering design requirements, and are "feasible" to be manufactured, no other changes are likely to happen to make the part truly manufacturing friendly.

5.6.1.5 Company E

Company E does not have a documented design guideline for manufacturable products. However, there are several other methods implemented to facilitate the communication between product design and manufacturing. One of them is periodical quality meetings. There are various sources of information related to manufacturing requirements that should be reflected in product design. For example, suggestions for ease of installation may be raised from the assembly track. In addition, some relevant information may be provided by the sales departments or quality audit teams. All this information is collected and presented in the quality meetings, where the representatives from relevant functional parties including product design are present. The participant list at this meeting and the ideas/solutions generation is based on the human network. The participants are assembled for each unique case. However, the concrete information is passed on in a written form.

In addition to the quality meeting, manufacturing engineers have other paths to provide manufacturability information to design engineers. A manufacturing engineer has direct personal contact that a design engineer uses to redesign the part. Furthermore, a manufacturing engineer can raise a change request through a PC-network-based solution to which product design engineers and other involved parties have accesses. Still, however, human network plays a major role in preventing same types of problems from occurring again.

5.6.1.6 Company F

In company F, a design guideline for engineering design is available. For example, the range of allowable natural frequency is dictated in the guideline for a suspension design. In a similar way, tire geometry design standard for designing tire clearance from the body are pre-defined. However, company F does not seem to have a written product design guideline for manufacturing.

Instead of relying on a documented design guideline for manufacturing, product designers get their feedback from manufacturing by personal contact. For example, when the drawing is released, a manufacturing group reviews the drawing and gives such feedback as the given tolerance cannot be met. In addition, the production engineering group solves manufacturing problems with product design group with a beta prototype, which is typical in auto industry. Other design problems are solved by team meetings or discussion between relevant parties over the telephone when they arise. Therefore, company F seems to focus on solving problems after they occur instead of preventing them from occurring.

However, some important manufacturing information is available from the beginning of the design. For example, chassis hard points for different vehicles are set to utilize one fixed jig instead of creating many different jigs according to the vehicle types. Furthermore, product designers participate in building the alpha prototype in order to solve manufacturability problems in the early stage of product development. In addition, product designers have personal experience in manufacturing in many cases and thus, they understand basic constraints in manufacturing through their hands-on experience. Still, this type of knowledge and information is not documented and captured in a knowledge base.

5.6.2 Interface between Manufacturing and Product Design

The second group of questions asked in the first-round questionnaire is about the interface between manufacturing and product design. The questions are intended to capture the actual practices in the company such as communication processes between manufacturing and product design, types of documents shared or exchanged, contents of the information transferred between product design and manufacturing, and use of performance measurement to support the activities.

Questions asked regarding the interface between manufacturing and product design are as follows:

- What is the system interface between manufacturing and product design during the product development processes?
- Is there any standardized information exchange between two parties? For example, when designing a steering gear, is there exchange of standardized (e.g., information contents are pre-specified) information such as manufacturing rate, capacity of existing line, process capability, etc.?
- How is that information (capacity of existing line, process capability, etc.) reflected in product design?
- What kind of information is transformed and shared between two functional parties?
- What does your company do to make that information exchange really happen?
- Is there any performance measure to enhance this information exchange?

- What is the problem solving process if the transplant overseas finds some manufacturing problems associated with product design? Does she ask for design modification to product designers in the mother company?
- When is it decided during the product development processes where to produce the new product? Even in case that there is only one plant available for a certain type of product (for example, your company may have only one plant for a bumper production), it should be decided which production lines/machines within the plant will product the new product).

Table 5-2 below shows the summary of the answers for the questions about the interface between product design and manufacturing. Interestingly, most companies count on cross-functional product development teams as a primary way for enhancing communication between manufacturing and product design. Some companies, however, complement cross-functional product development teams with pre-specified product development processes, which are available in a form of manual.

Detailed information on the actual practices of each company is described in the following section.

TABLE 5-2. THE SUMMARY OF THE ANSWERS TO THE INTERFACE BETWEEN MANUFACTURING AND PRODUCT DESIGN QUESTIONS

Company		Interface between PD and MFG	Standardized information exchange	Content of information exchange	PM	When to decide production line?
A		QIR and DIR, product development team	Yes	Both parties aggressively exchange information	No	Early in the product development
B	X	Cross functional product development team	Yes	Any pertinent production data, tooling diagrams, machine drawing, 3d simulation models, container sizes, etc.	Yes	Early in the product development
	Climate control	Varies. Core product development teams / domain experts	Yes	Feasibility studies, FMEA, control plans, quality forecasts, cost reduction opportunities, etc.	Yes	Preliminary sourcing in the early, final decision before purchase of special tooling
	Exterior	PD asks for feedback if PD knows where production takes place	Yes if a company B facility, no if tier 2 supplier	Little or no information is reflected in design	No	It is typically manufacturing's problem to find the capacity
	Powertrain	Cross functional product development team	Yes	Volume, timing, tooling, facilities, labor, bill of materials, make/buy assumptions, etc.	Yes	Prior to initial quote by strategic business planning
	Electronics	Collocation of manufacturing & product design	Yes	Corporate-wide product development manual specifies the contents	Yes /No	At the time of quote, manufacturing plant is identified
C		Production development team and DFM workshops	Yes	Drawings, specifications, and DFMEA	No	Early in the product development
D		Dedicated representative	CAD release event only	Product design data from product engineering and proposed changes from manufacturing	No	Early in the product development but press line and plant changes are common
E		Manufacturing experts in design module meetings	No except drawings	Drawings	No	Varies from project to project.
F		Beta prototype, project teams	No except drawings	Drawings	No	Very beginning of the product development

5.6.2.1 Company A

In company A, there are two types of interface for formal communication between manufacturing and product design. One is for manufacturability and called as DIR (Design Investigation Requests). This form is used when manufacturing finds some problems associated with the product design and asks for appropriate changes. The other is for quality assurance and called a QIR (Quality Investigation Requests). QIR is the same problem information sheet as DIR, but QIR is for suppliers or in-house production departments. These two requests forms were called as "Mon-ren-syo," which means "problem reporting sheet," but now they are called as "Mon-tei-sho," which means "problem sheet with proposal." It implies that manufacturing is encouraged to propose possible solutions to the identified problems rather than just reporting them. DIR and QIR are applied to all groups of company A regardless of geographic locations.

For any project, engineering designers are supposed to check the PPC or *Yoken-sho* when they design. The result of product designers' checking is reviewed by production engineering engineers. If there is any issue associated with the checking of product designers, production engineering engineers issue DIR to product designers. However, the scope of DIR is not limited to the checking of the PPC or Yoken-sho. DIR covers design issues during prototype development or production trial stages.

Mon-tei-sho is different from *Yoken-sho* in several points. *Yoken-sho* contains general requirements used even before the start of design. There is no why to *Yoken-sho* and designers are supposed to know the reasons behind the requirements in *Yoken-sho*. Before the start of detailed design, production engineering group sends *Yoken-sho* to engineering design group, which contains structural requirements. Then, before the release of the drawings, problems are reviewed and recorded in *Mon-tei-sho*. *Mon-tei-sho* is a claim for designers after the design is done in this sense. Engineering change request (ECR) is made based on the review. Still, negotiation always exists and in some sense, this negotiation is more important than the exchange of *Yoken-sho* or *Mon-tei-sho*. Since short time length of development time cause an overlap of manufacturing and product design, collaboration between designers, production engineering engineers, and manufacturing engineers is very important. The engineers of company A stressed that collaboration is more important than any documentation. *Mon-tei-sho* is just a report. Moreover, in fact, the product design drawing itself is the result of co-work of engineering design, production engineering, and manufacturing. Big three companies in the U.S. are known to use similar tools. Examples of *Yoken-sho* and *Mon-tei-sho* (DIR) are available in the appendix.

In addition to the DIR and QIR, there is a standardized format applied to each stage of product development in which pre-specified checkpoints such as the 'capacity of the existing line,' 'processing time,' etc. are described. Details of drawings are thoroughly re-examined and solutions are sought when problems are identified on each checkpoint. Company A has five stages for the design information to be exchanged with manufacturing. They are:

1) No drawing stage
2) Virtual design stage (simulation by means of 3-D CAD etc.)
3) Real drawing
4) Semi-trial production (not on real production line)
5) On-the-line final trial

Different checkpoints are established at each of these stages. At each stage, drawings are checked out by the discussion of two parties with prescribed checkpoints in a standard format. These standardized checkpoints are pre-specified. Some of the examples are, 'capacity of the existing line,' and 'processing time.' The details of drawings are under strict surveillance, and solutions are sought when problems are identified on each checkpoint. Their contents, interestingly, are not fixed at all. They are subject to continuous improvement through kaizen activities.

Even with these well-standardized communication channels, company A has a different attitude towards two groups (product design and manufacturing), compared to its western competitors. Company A regards both groups as an inseparable, integrated part for product development that interact and collaborate with extensively shared information as if they are one group, standing on the slightly different perspectives. Consequently, both parties aggressively exchange information. Problems are proposed from the standpoint of manufacturing – for example, the 'size,' the 'kinds of color,' and the 'number of parts' that could incur additional costs or hamper manufacturability. Once the manufacturing side insists that special considerations for high quality in some portion of drawings could increase product costs, or some drawings lack the considerations for ergonomics in workers' motion in the assembly line, and then detailed discussions on why and how to do with the problems follow. For example, manufacturing insists to make the workers' motions easy in assembling dashboards in terms of ergonomics. Product designers reflect this issue to the product design. Aggressive exchange of information and enthusiastic collaboration in problem solving of manufacturing and product design are a natural and established custom in company A.

However, there is no particular performance measure associated with the use of standardized processes at the interface between manufacturing and product design. Again, concurrent and close information exchange between manufacturing and product design is viewed as an established custom in company A as is previously described.

The system of DIR and QIR is applied to overseas plants as well. DIR is issued from an overseas plant to company A in Japan, on whatever problems associated with product, for the new model or for the current model, body fabrication, and assembly line. There, however, was a learning period on a trial-and-error basis for the very first time. Language problems were significant and there was a problem of different time zone. No emails were available at that time. It took almost two weeks to solve even a small problem and three months when the problem was just a little bigger. Occasionally, a large number of technicians from the overseas plant directly visited company A in Japan to solve technical problems. At present, however, thanks to the development of latest technology in communication such as video conferencing and emails, a much higher level of communication is kept. Technologies like virtual review of the mock-up through 3-dimensional CAD also helps a lot for smooth communication. Now, the motto of company A in communication is 'visual and virtual communication.'

5.6.2.2 Company B

The system interface between manufacturing and product design of company B is typically cross-functional product development team. Collocation of engineers and product development meetings are considered important for the communication. To some extent, the process and content of information exchange seem to be standardized in the corporate-wide manual for product development, and many of the divisions follow the standardized processes. The issue might be the level of understanding of the manual of each division and how aggressively each division uses the manual.

As is previously described, in the electronics division, the integration between manufacturing and product development is achieved by the core cross-functional team, 'Copy-Exact' team. Electronics division counts on collocation of manufacturing engineering with the design team to ensure first time right implementation of the manufacturing design rules. In addition to informal communication within a team, the Copy-Exact team supports the software tool that is globally used to check the manufacturability of new product design, the new process technology options, and the availability of new components. For example, this software tool prevents mistakes from occurring by making a complete scan of the circuit board layout. After the scan, a list of issues with the layout design is generated by the software tool based on the rules developed by the Copy-Exact team. Designers are supposed to look at this list and double check the listed issues. However, since this system is based on the rules developed by the Copy-Exact team, sometime problems occur when new process technologies or new components are used. When a problem occurs, it is stored in the knowledge database and a new rule is generated to prevent this problem from occurring again. A separate E-CAD team supports the use of this software tool and updates it. The use of this software tool is possible partly because of the unique manufacturing environment. Manufacturing of the electronic circuit board products within company B consists of three general steps (Figure 5-1).

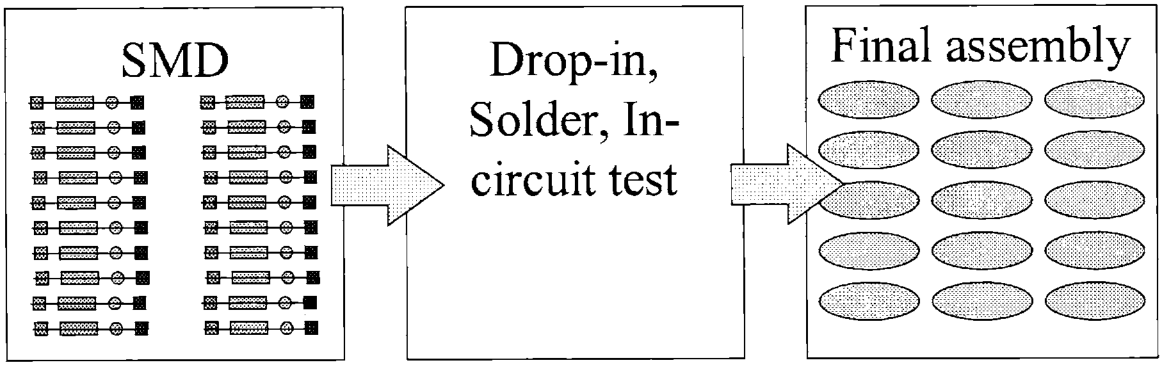


FIGURE 5-1. SCHEMATIC VIEW OF THE MANUFACTURING SYSTEM FOR CIRCUIT BOARD PRODUCTS

The first step is SMD (surface mount device) process. This process is a common process for all different types of products and thus, machines with a high level of flexibility are used. This process is expensive because expensive flexible machines are used, though. Therefore, design rules are heavily applied during the product design phase to minimize the mistakes when the parts are actually produced in the line. The second step is a drop-in manual insert process. More like dedicated machines are used in this process. The third step is the final assembly and a large number of small assembly cells are used. Each assembly cell is not very flexible but the large number of different assembly cells ensures the necessary flexibility. Each cell costs not so much and the design rules do not matter so much.

With this unique type of manufacturing system, a lot of information related to manufacturability issues is fed back to product design groups using the 'Copy-Exact' tool. For example, capability (e.g., throughput time, quality, inventory, etc.) of the production line is known for each of design steps. Capacity is generic for process centric aspects like component placement but product specific for final assembly and test. Eventually, this information drives the overall design. All plants around the world have basically the same manufacturing systems and the best practices found in one of the plants are updated to every plant through the 'Copy-Exact' tool. In this sense, the Copy-Exact tool is the keeper of the best-known methods for approved equipment.

Other information is shared such as benchmarks for operating efficiency, throughput of processes, and poka yoke best practices for different design alternatives. These factors are weighed to provide the best total cost solution. The content, timing and standards of information flow between all departments, and aspects of product design and manufacturing are all specified in the corporate-wide manual for product development.

There is no specific direct performance measure for individual product designers for their performance in designing manufacturable products even though 'Green, Yellow, Red' process monitors the programs for specific high level of timing and cost. Event timing and cost management are reviewed monthly. Manufacturing plant for the production of new product is considered early in the product development. The business plan includes a manufacturing strategy for each product and for each plant. At the time of quote, however, the manufacturing plant is identified.

In the powertrain division, cross-functional product development team is the system interface. Both product design and manufacturing engineers are team members throughout the product development processes and are responsible for deliverables of the product development manual. These two groups work together to prepare the design and manufacturing assumptions worksheet, which contains information such as volume, timing, tooling, facilities, labor, bill of materials, make/buy assumptions, testing, assembly, packaging, product complexity, among other things. These assumptions are reviewed prior to submission of the initial quote, and then again at the 'design freeze and release to manufacturing' gateways.

In this division, the product development processes described in the corporate-wide product development manual are faithfully followed. Manufacturing site is decided at strategic business planning stage prior to initial quote, as is dictated by the manual. Performance of the engineers is evaluated by the program managers at the gateway reviews.

In the climate control division, the system interface between manufacturing and product design varies depending on product. Some groups use core product development teams with design, manufacturing, and purchasing representatives on the teams. In addition, domain experts in manufacturing disciplines are available and used as resources for designers. Most of the manufacturing issues except production rates and capacities are already reflected in the Design Guide or the KBE (Knowledge Based Engineering) tool and product designers are required to meet Design Guide criteria and KBE rules while satisfying customer requirements. Production rates and capacities are considered with manufacturing and sourcing strategy. Information such as feasibility studies, FMEA, control plans, quality forecasts, and cost reduction opportunities (TQCM – total quality and cost management) is shared between product design and manufacturing. Information exchange is ensured by requiring product development teams to follow the processes described in the product development manual of company B. The documentation required by this manual is audited by program managers, internal and external audits, and management program reviews, which are all directly reflected to individuals' performance.

Preliminary sourcing decision is made at the quote stage and final sourcing is determined prior to purchase of special tooling. When a problem associated with product design is found in the plant after the start of production, a concern system is used to help divisional cross-functional teams to identify problems and resolve them. All plants regardless of their locations use the same concern system.

In the division X, the cross-functional product development teams utilizing all of the engineering tools such as design models and simulations are the primary system interface between manufacturing and product design. The product development teams are the first level of problem solving and are empowered to solve their issues within financial constraints. The product development teams are complemented by the product development manual of company B, which contains regular program reviews in which issues requiring additional management intervention can occur.

In the product development team meetings, issues like customer requirements, and current production capacity and capability are discussed to find opportunities and to avoid potential problems in the program direction. For example, throughout these meetings, product designs may be redirected to accommodate an existing production process that has open capacity in order to achieve investment efficiency. Furthermore, information such as pertinent production data, tooling diagrams, machine drawings, 3D simulation models, product math models, and container sizes is exchanged between manufacturing and product design to ensure the smooth transition from design to production.

This information exchange is enforced by two ways. The first way is to require product development teams to follow the product development manual which describes the standard product development processes. The other way is to have performance measures designed into the system such as first-time-through design changes, engineering costs as a percentage of revenue, and on-time delivery of prototype parts.

Manufacturing sourcing is decided at the first phase of the development processes, which is strategic intent. Therefore, it is possible to reflect plant specific constraints in product design. After the start of production, an on-site resident engineer who is an expert on the product requirements takes care of product design problems. This resident understands the product requirements, makes decisions, and documents the decisions with the manufacturing and production team at the plant.

In exterior division, if product design group knows where production will take place, they will ask for feedback. However, product design group does not typically consider where to produce when developing a design. Therefore, the feedback from manufacturing side often happens only after the design, which is pointed out by academia as a typical problem with the traditional functional chimney organization of product development. Historical process assumptions typically prevail and no or little information is reflected in the design. Another problem is that there is no standardized decision process for selecting manufacturing site. For example, sometimes, product designers work with a supplier and source a product with them, even a competitor, without determining if process could be done internally. The design engineers may know someone who did it before and they simply direct the product to that company. In this case, no standardized information exchange between product design of company B and manufacturing of the suppliers is done unless the suppliers have residents on-site. If it is made internally within company B, it is typically the manufacturing site's problem to find capacity. However, when the new product is produced internally, standardized information is shared between manufacturing and product design even though it is not done early in the product development.

In case that the plants outside of the U.S. found some product design problems, they would ask for design modification to product designers in the U.S. since those plants typically do not have any design support.

5.6.2.3 Company C

In company C, the system interface between manufacturing and product design lies in the production development team and the DFM workshops. Standardized information such as test specifications, manufacturing guidelines, projected volume requirements, similar process capacity information, and process capability requirements, is shared through this interface. To make the information exchange really happen, company C has weekly product development team meetings and joint workshops.

One interesting and unique approach of the company C that defines the relationship between manufacturing and product design is that manufacturing plants financially support product design groups. In other words, product design groups are supposed to solicit the support from manufacturing and manufacturing budgets the funds. In return, there are licensing fees and royalties paid to product development groups by manufacturing plants. With this unique relationship between manufacturing and product design, a high level of manufacturing involvement in product design is assured.

After production, the 'lead plant' system of company C supports the information exchange between manufacturing and product design. All company C products are identified with a 'lead' plant.' Then, that plant has overall responsibility for product design after start of manufacturing. If there were a request for product design change, that request for modification would go through the 'lead' plant of that product.

Location decision for initial production of new products is based on the location of the largest market share (e.g., North America vs. Europe) and availability of capacity for appropriate core plants, which are plants with core competencies. The organization of company C is structured around core competencies. For example, plant A is the center of competence in North America for electronics. In addition to these considerations (market share and capacity of core plants), product cost calculations are made for plants that are interested in manufacturing a product. All this information is considered together and a decision is made at the Board of Director level.

5.6.2.4 Company D

Company D uses a dedicated representative for information exchange between manufacturing and product design. For large programs, a dedicated representative makes feasibility assessments. This feasibility engineer uses his reference materials and draws expertise from the core process groups as necessary to guide product during vehicle development. The feasibility is done around the exterior clay (class one surface), master section (early inner panel geometry), and structure review meetings (3d inner panel geometry). However, the feasibility analysis is not standardized. The only standardized exchange of information between product design and manufacturing is from product to manufacturing in the form of CAD drawing release events. There is no performance measure to enhance the information sharing.

At the process decision stage, surrogate processes are evaluated for known issues and that information is used to help to drive feasibility decisions. However, more significant drivers of product design are part function and knowledge that some other OEM is making a similar part. In addition, outside stamping sources are usually very willing to accept difficult designs and are used as leverage.

Initial consideration of production site is done at the SC (Strategic Confirmation) milestone (36 months before production), and the final decision is done at the program approval for the approximate costing (30 months before production). However, press line and plant changes are common up to and beyond initiation of die design.

5.6.2.5 Company E

The system interface between manufacturing and product design in company E is design meeting. Manufacturing experts are represented in design module meetings from the early phases of the development processes and thus, manufacturing system issues can be considered from the start of the product development. Especially, manufacturing planners attend early stage design meetings and have the ability to influence product design. Various kinds of information are exchanged in various formats such as verbal conversation, written documents, and drawings. To ensure the information exchange, several methods are implemented. For example, all involved parties have accesses to the PC-network based system and temporary project offices are used for collocation of relevant engineers. In addition, project leaders play as integrators of various functional parties including product design and manufacturing. However, there is no performance measure in use to enhance the information exchange.

The timing of the manufacturing site decision for a new product varies from project to project. The aim is to maintain maximum flexibility to allocate the product to a plant at the latest feasible stage, bearing in mind the design support that factory representatives give to the design departments.

5.6.2.6 Company F

The formal system interface between manufacturing and product design in company F is the prototype development. Product designers develop the first prototype by themselves with the help from the model shop workers. In this process, many manufacturability problems are solved and product designs are modified accordingly. The second prototype is built with the tools that will be used in the mass production. In this stage, production engineering group reviews every aspect of product designs and uncovers manufacturability problems that can arise in the plant such as ergonomic issues of assembly workers. Then, production engineering issues an official product problem report to product design group and product design group makes modification on product design through official engineering order.

In addition to the prototyping activities, a project team is established for each vehicle development program. This project team manages product development schedules and layout packaging. Furthermore, the project team organizes various team meetings to solve arising problems and invites engineers from involved functional groups whenever necessary. In this sense, company F does not rely on standardized information exchange between functional groups to prevent problems from occurring. Rather, company F solves arising problems with a case-by-case approach.

The manufacturing site is planned from the very beginning of the product development. Usually, one assembly line is capable of dealing with two or three variations of the vehicles.

5.6.3 Product Design Decision in General

Four general questions on product design strategy of each company are asked in the first-round questionnaire for extra information to help the understanding of the practices of the design for manufacturing. They are:

- What is the basic strategy of your company in product design? How are the products of your company different from those of your competitors in terms of external design, performance, etc.?
- How is you company different from others on its design decision processes?
- What are the decision criteria for product variety? How does your company decide product variety?
- What is your company's perspective on customer desire for product variety? How does your company optimize between customer requirements and manufacturing constraints? Is there any optimization strategy?

Due to the limitation of the knowledge of the respondents, some respondents did not answer the questions. However, the received answers show each company's unique view on product design especially in terms of product variety and differentiation.

TABLE 5-3. THE SUMMARY OF THE ANSWERS TO THE PRODUCT DESIGN DECISION IN GENERAL QUESTIONS

Company		Basic design strategy	Design process differentiation	Variety decision criteria	Optimization: variety vs. manufacturing constraints
A		Offer cars welcomed to customers timely	Chief engineer controls the development	Investment efficiency, target costing	The higher the number of kinds is, the higher the cost becomes
B	X	Total systems engineering approach	Cross functional product development team	Product complexity	Flexible manufacturing technology
	Climate control	Design systems first then components	Marketing to direct customers toward its best-in-class technology.	Meet customer requirements, quality, and cost targets; reduce complexity	Meet customer requirements as much as possible
	Exterior	Design to satisfy customers; limited responsibility for performance to budget	N/A	Satisfying the customer is paramount	Typically manufacturing is expected to deliver whatever it is asked to deliver
	Powertrain	Safety first; minimum cost; performance; meet regulations	N/A	Customer demand and business sense for company B	Customer gets what they ask for. More complex product, higher price
	Electronics	Modularity; driving part commonality; first time through design	Quality performance standards	Complexity of a product	Commonality where customer does not see and variety in appearance
C		Fill a niche around high tech products – strive for the highest quality product	Development group must solicit financial support from manufacturing locations	Customer requirements are dominant	Try to build flexibility into the product design based on feedback from different customers
D		Draws are typically deeper for body sides, doors, etc.	N/A	N/A	Give the customers what company D think they want as long as feasible
E		N/A	N/A	N/A	Customers have a maximum desire for variety, trying to increase the scope of variety
F		N/A	N/A	Customer requirements are dominant	In bus production, customization such as painting and seat layout is very important

5.6.3.1 Company A

The basic product design strategy of company A is to offer cars welcomed by customers, on time. Company A has four centers of external vehicle design around the world. Usually, all of these four design centers participate in the competition of the best design for a specific model and the winner is chosen among four proposals. In the time of globalization, however, the sensitivity toward localism seems to be gaining importance. In other words, the design sense relevant to each individual marketing area is considered most important. In addition to the localized design, company A is trying to keep designer's intention to the final end while encouraging designers to make bold adventure in terms of their design concept.

Company A uses a unique design process. Its design decision is made by CE (chief engineer), who has the authority on the overall features of the particular model. CE provides the conceptual design and the business plan based on the demand forecast of the model. The number of units to be produced, unit price, and other major factors are proposed by CE as a 'vehicle plan.'

The vehicle plan mirrors the CE's thoughts and desires about the vehicle. Occasionally, top down policy is enforced on the CE's plan, like safety, the specifications for the air bag, for example. Target costing is the tool that materializes the vehicle plan. Staffs from all the related functions such as corporate planning, finance, production engineering, and manufacturing get together to review and discuss the vehicle plan that CE proposed. There are pre-determined vehicle plan assessment items according to the type of the vehicle for big, medium, small, and special cars, respectively. Assessment items and the assigned weight factors vary according to the type of the planned vehicle.

In making decisions on vehicle variety, "the higher the number of product types is, the higher the cost becomes" is the basic belief reflected on the vehicle plan. Through target costing, investment efficiency is estimated in order to identify the optimum correlation between the number of kinds and the associated vehicle costs. Besides, the target costing, production engineering engineers conduct similar calculations to assess the investment efficiency from their own engineering perspective. These evaluation processes and the negative view on the variety of product which once company A was famous for seem to be the result of their learning on product variety. The respondent of the questionnaire claimed, "What is the rationale of the remaining 17 models among 20 models if only three models represent the 90% of the total sales of the 20 models?" In the past, however, the marketing group of company A tended to increase the number of kinds for ease of sales, and the design side accepted that request too faithfully. The result was additional cost. For example, about 10 years ago, when a new model was introduced to the market, remaining stock of service parts of an old model was surveyed to close the old model. What they found was some first-lot service parts from suppliers remained intact, which means that those parts had never been used to serve customers during the past four years. Still, company A believes that the product variety decision is the most difficult decision to make.

One way to deal with product variety may be modularization. In company A, modules are interpreted as 'sub-assembly' and have been promoted as a natural result of standardization. For example, if the standardization of the structure such as developing a common chassis is promoted, it naturally leads to the sub-assembly or module. Modularization has been sought to optimize the speed or the takt time within each individual cell. However, the characteristics of a module vary according to the concept of a production line, production scale, available space of a factory site, and even the difference of nationality.

Two categories of module characteristics are recognized in company A: module for manufacturability and module for design efficiency. Characteristics of modules are to be diversified according to its purpose.

5.6.3.2 Company B

The electronics division of company B tries to take a full advantage of the characteristics of electronic goods. Core mechanical and electrical circuits are used as proven building blocks, which results in part commonality for manufacturing efficiency and first time through designs (error free designs). The electronics division has quality performance standards for electrical, mechanical, thermal, and durability, which is an inherent base line in all its product designs.

The decision criterion for product variety is complexity. Platform designs are employed for commonality where the customer does not see, touch or feel while variety is provided by differentiating in the appearance items. This variety is supported by flexible manufacturing represented by dedicated lean assembly cells with poka yoke (error proofing) devices. The electronics division sees the inefficiency associated with variety mainly in the purchased incoming material and required inventory by the customer.

From the practices of the electronics division described in the previous paragraphs, it can be inferred that the division is effectively dealing with product variety. The electronics division is faithfully following the methods proposed by academia to deal with increased product variety such as product platform for commonality, modular designs, and flexible manufacturing. The result is successful product development and production while limiting penalties of product variety to incoming material and finished goods inventory.

In the division X, products are highly engineered products designed for specific applications. It seems that company B's advantage is to take a total systems engineering approach to product application, which is enabled by its past history as a complete vehicle manufacturer. As for variety, chassis division tries to minimize product variety by thoroughly reviewing customer requests based on its experience with specific sub-system design requirements. In addition to this effort, flexible manufacturing technologies are pursued to negate the process differences dictated by product variety. For example, changeover can be reduced or, ideally, eliminated by the flexible manufacturing technologies. Furthermore, manufacturing technologies can make a component such as a gear stronger through greater accuracy thereby encompassing a greater torque range, which results in one gear size instead of two gear sizes required in the past.

The climate control division sees advantages over its competitors as a full-service supplier with global engineering and manufacturing capability. Based on this advantage, climate control division tries to design systems first and then components second. Its view on design decision is slightly different from some other divisions. Instead of just following customer requests, the climate control division tries to direct the customer toward its best-in-class technologies and systems approach through marketing strategy. Still, however, meeting customer requirements is a most important decision criteria for product variety along with meeting quality and cost targets, and reducing complexity. It seems that complexity problems arising from variety are partly solved by outsourcing components of which requirements are beyond its manufacturing capability.

In fuel storage and delivery system of the powertrain division of company B, safety is considered first due to the product characteristic, followed by minimum cost to meet customer expectations. In addition, emission performance is seriously taken to meet regulations. Usually, customers get what they ask for, but if a cost reduction is available for reduced complexity by minor modification of customer requirements, it is offered to customers.

In the exterior division, their basic design strategy is the design to satisfy the customer while limited responsibility for performance to budget is assumed. Suppliers are invited to solve problems together. Product variety is also decided by the customer requirements since satisfying customers has the highest priority. The problem with this practice, however, is that manufacturing constraints are not considered with this practice. Typically, manufacturing is expected to deliver what it is asked to do.

5.6.3.3 Company C

The product strategy of company C is to fill a particular niche market around high technology or cutting edge products. Ultimately, company C strives to create the highest quality product designed to give superior functionality at a competitive price. Therefore, traditionally functionality of a product has earned priority over manufacturability. This preponderance for functionality seems to be balanced by the company C's unique development process, in which product development groups must solicit financial support from manufacturing locations. However, in recent years, product variety is largely determined by customer requirements and customers tend to increase their appetite for variety. Therefore, the traditional system is not working effectively and thus company C tries several new methods to overcome the problems of variety. For example, company C tries to build flexibility into its design based on feedback from different customers regarding their potential specific needs, which can decrease the total variety. Company C uses a quite effective product development process that balances manufacturing constraints against the need for a product capable of being easily adapted to various customer needs.

5.6.3.4 Company D

From a sheet metal perspective, the draw design of company D is typically deeper than that of Japanese competitors for body-sides, doors, etc. As unique products with lower demand volume are becoming more the norm rather than the exception, company D now tries to give what company D believes the customer wants as long as it is deemed feasible. To support this strategy, design for manufacturing earns a lot of attention within company D, but in practice, this approach has not been so successful.

5.6.3.5 Company E

The respondent refuses to reveal the strategy of company E in product design as well as its unique design decision process, claiming that they are strategic and confidential issues. The only answer is available for product variety issue. Company E believes that customers have a maximum desire for variety. Therefore, company E individuals try to widen the scope of variety beyond the capabilities that are possible for series production.

5.6.3.6 Company F

The respondent is an engineer in the bus division of company F. The respondent was not aware of product design strategy of company F but it seems to be partly because the respondent works in the bus division that does not deal with high volume customers. In other words, the bus division produces according to customer specific requirements. Company F designs a bus platform and makes variations such as express bus and local bus. The differences between these variations are seat arrangement, interior designs, painting, and suspensions. Customer requirements decide many features such as painting operation and seat arrangement. In other words, customized buses are designed and produced.

5.6.4 Manufacturing System Design in General

It is important to understand the manufacturing system design processes of each company in order to understand the communication between manufacturing and product design, since interactions of manufacturing with product design should be reflected in manufacturing system design. Several questions were asked to capture each company's view on manufacturing system design. They are:

- Does your company have pre-defined manufacturing system design steps?
- What are the general processes of designing a new manufacturing system or modifying an existing manufacturing system?
- How does your company do the capacity planning?
- What feedback is used from the previous manufacturing system design projects?
- What efforts are made to enable a 'vertical/super-fast' ramp up?
- How does your company decide on the mix-capability of each production line?
- What kind of role does product design or product variety play in the decision process of detailed manufacturing system design?
- Is there any special strategy or methodology pursued to maintain manufacturing flexibility?
- What are the challenges your company sees from the mix production? How does your company handle them?
- How does your company schedule the mix of production?
- How does your company optimize between the cost of system and the simplicity? For example, how is the number of cells decided? (if your company has many cells, your company can have focused flows to each customer but in that case the system cost may not be minimized)

As is the same with the previous questions on product design, due to the limitation of the knowledge of the respondents, some respondents did not answer the questions. In addition, the answers are subject to the respondents' personal understanding or expectations of manufacturing systems. However, the received answers show somehow each company's unique view on manufacturing system design. Some representative results are summarized in Table 5-4.

TABLE 5-4. THE SUMMARY OF THE ANSWERS TO THE MANUFACTURING SYSTEM DESIGN IN GENERAL QUESTIONS

Company		Pre-defined MFG system design steps	Feedback from previous project	Manufacturing flexibility	Simplicity vs. cost decision
A		No	Yes	Yes (level production)	Simplicity is the norm and total cost is considered
B	X	Partly yes	Yes – process FMEA's, lessons learned, etc.	Lean manufacturing principles and tools	Investment efficiency is compromised by the characteristics of manufacturing process technology
	Climate control	No	No formal feedback system	No other than lean manufacturing principles	Depends on cases but meeting customer requirements is most critical
	Exterior	Yes but varies	No formal feedback process	No due to the lack of funds	Varies depending on plant and department
	Powertrain	Yes	Lessons learned and best practices	Lean manufacturing principles	N/A
	Electronics	Yes	Yes	Yes, software changeover, removable fixtures, etc.	Part commonality for simplicity
C		Partly yes	Minor feedback	No formal decision process yet but developing one now for more flexibility	Simplicity and flexibility are seen as better total cost solution
D		Yes	Quality, productivity, maintainability from the production plant	Not pursued in die design	Simpler design costs less
E		Yes	Yes	Yes	Simplicity is secondary to cost
F		N/A	Minor	Yes	N/A

In the following section, various aspects of manufacturing system design of each company are described in detail. Some descriptions may not be directly related to the asked questions but are necessary to draw a big picture of manufacturing system design process of each company and thus, provided.

5.6.4.1 Company A

Company A does not have any standardized manufacturing system design steps. However, some engineers participate in the design process repeatedly and thus, they have their own way of managing the processes. In a formal sense, gate way/milestone review during the product development processes is related to manufacturing system design. These reviews are standardized as well as output of each phase.

In the following sections, several unique characteristics of manufacturing system design of company A are addressed.

5.6.4.1.1 General Manufacturing System Design Concept

Basic principle of manufacturing system design of company A is to design a product oriented flow, which is achieved by linked cells. Sometimes, transfer machines are used within a cell but still basic characteristics of a cell such as U-shape, process after process type machine line up, single piece flow, machine cycle time to match the takt time, and man-machine separation are kept. In other words, a cell is always used in all situations except a special process such as heat treatment and casting. For special processes such as heat treatment, stamping, and casting, a principle of single piece flow may not be followed and a process layout is used. There are several guidelines for production flow designs. They are:

- Product oriented flow with U-shaped cells
- Machining cells should be located as close to the assembly lines as possible.
- One cell does all necessary processes
- Locate input and output of a cell close to each other

5.6.4.1.2 Manufacturing System Design Process in General

A typical manufacturing system design project takes about 27 to 30 months, which can significantly vary depending on the case. The approximate time line is as follows:

- Planning: 6 months
- Design: 9 months
- Equipment Preparation: 6 months
- Installation and Adjustment: 6-9 months

The planning and design phases consist of four sub-steps. The first step is process design in which operation drawing by production engineering group and tooling group is released as a basic output. An example of an operation drawing is shown in Table 5-5.

TABLE 5-5. AN EXAMPLE OF OPERATION DRAWING

Op. No.	Operation	Cycle Time
10	Drilling 1.5 inch holes	7 seconds
20	Milling ...	2 seconds
...	...	...

Detailed process design steps are:

(1) Basic product design concept (input)

(2) Process design

(3) Sequence design

(4) Tooling design

(5) Basic machine specification based on (2), (3), and (4)

(6) Type of manufacturing system – transfer or flexible

(7) Number of machines

(8) Simultaneous engineering

(9) Automation

The second step is plant layout design and physical layout of production site is decided as well as machine specification on dimensions. The output of this step is layout drawing. Along with operation drawing, this layout drawing goes to equipment vendors for equipment development. Equipment vendors usually get general specifications such as equipment dimensions on the plant layout, cycle time, and process capability. Vendors will decide how to build a machine. In addition, manufacturing group starts to design the operations, which do not affect plant layout design but do affect detailed layout design (see Figure 5-2).

The third step is detailed line layout design and details of plant design such as the orientation of input/outputs are completed. The final step is real detailed design and the small details of plants such as tool locations, lights, and garbage can locations are designed.

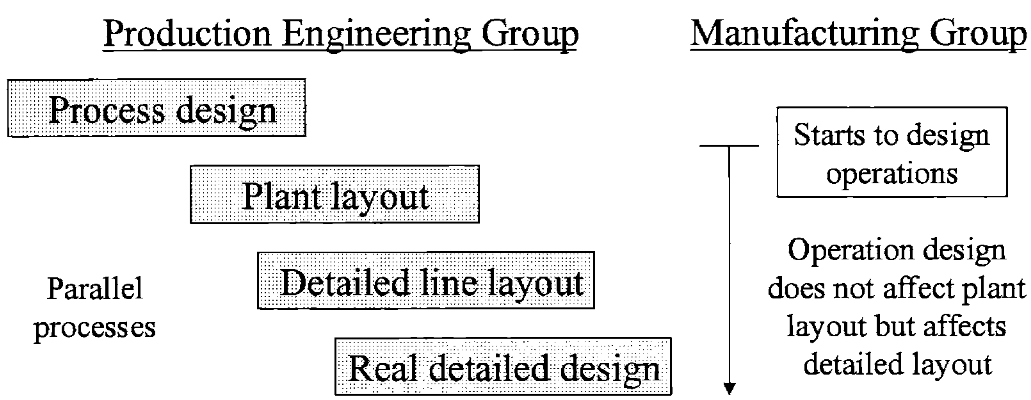


FIGURE 5-2. PLANNING PHASE OF MANUFACTURING SYSTEM DESIGN

Feedback from the previous project is not formally taken into account. During the SE (simultaneous engineering) study phase, there are some feedbacks from the people in the plants in terms of quality, maintenance, and manufacturability. However, this feedback is based on individual experiences rather than knowledge captured in documents.

5.6.4.1.3 Capacity Planning

Capacity planning starts from a make vs. buy decision in which various factors must be considered. Availability of suppliers is a basic requirement for a buy decision and the technology used for the outsourced products should not be critical. Company A wants to keep a critical technology inside to prevent the competition from other makers as well as to maintain its core capability. Internal capacity is also an important factor to be considered.

A decision on the takt time considers many factors but one of the most important factors is operators. A balance between worker's capability and interests is important. If the takt time is too short, keeping the work interesting is very difficult. On the other hand, if the takt time is too long, it is hard for a worker to remember all processes that should be done. In this sense, a takt time shorter than 40 seconds or a takt time longer than 10 minutes is not usual. In addition, if the takt time is too short, it is difficult to have enough time for trouble-shooting.

A capacity of a production line or a cell is decided by considering sales as well as lower limit of takt time. A cell is seen as a unit of capacity. Therefore, if the demand steadily goes up, cells can be duplicated to meet the increased demand. In fact, company A exploits a few different strategies to deal with the demand volume fluctuation. They are summarized in Table 5-6.

TABLE 5-6. CAPACITY ADJUSTMENT METHODS ACCORDING TO THE LEVEL OF REQUIRED ADJUSTMENT

Required adjustment	Methods
Small	Overtime work
Medium	Change takt time, change manual work allocation
Large	Modify equipment capacity / add a cell

For a small size volume fluctuation, usually overtime work is used. In company A, two shifts operation with overtime is preferred over three shifts operation. Three shifts operation is not typical since it is very difficult to manage three shifts operation and three shifts operation does not give a lot of addition to the capacity. It is believed that a three shifts operation gives less than 20 % increase of capacity compared to a two shifts operation with overtime work due to many practical difficulties in managing three shifts operation (e.g., less motivated workforce, minimum support from engineering, etc.). Within company A, three shifts operation is used in limited cases such as casting (huge investment required) and heat treatment (long cycle time). Small and medium size adjustments can be done anytime after the start of production and they are easily adjustable. Large size adjustment, however, can be done only before the line changeover installation since it requires equipment capacity modification. Still, constantly adjusting the planned capacity to the real situation is considered as the basis of company A's operation. Therefore, capacity adjustment frequently happens. For example, production schedules are changed on a daily basis

Another factor that affects the capacity of a production line greatly is product allocation. In company A, products are grouped and assigned to each production line with the principle of bridge production, which is level production in large scale. Bridge production principle designs support capacity to fill in demand volume gaps as is shown in Figure 5-3. For example, assume that component A or B is attached to component C to build a sub-assembly part. Component C is supplied from the outside vendors. In Japan, 90 % of the sub-assembly parts are composed of component B and C, and only 10 % of the sub-assembly parts consist of component A and C. In the US, however, the reverse is the case. In this case, a cell producing component B is constructed in Japan and a cell producing component A is implemented in the US in order to minimize the investment required. Then component B will be exported to the US from Japan and component A will be exported from the US to Japan. The decisions, however, will depend on the ratio of component A and B that need to be supplied in each country, logistics costs, and the expected investment savings.

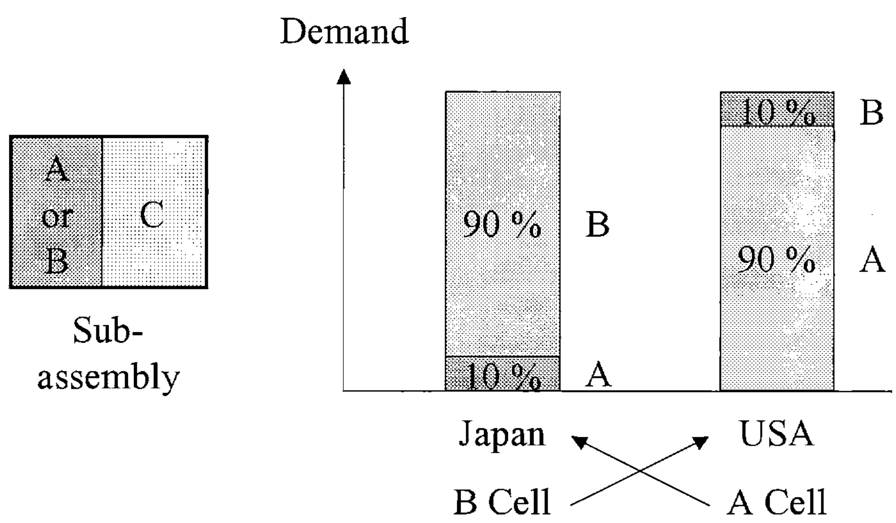


FIGURE 5-3. BRIDGE PRODUCTION CONCEPT

5.6.4.1.4 Process Planning and Routing

Manufacturing processes are decided by the production engineering group and tooling group as briefly explained in section 5.6.4.1.2. As for routing (designing possible material flows for a product), there is no back up routing planned, which puts a lot of pressure to upstream processes since their failure to feed the downstream processes directly affects the final production. This pressure, however, has worked so far and there are not so many cases of supply failure of upstream processes. Sometimes, manual backup plans are prepared for the assembly line but in machining, there is no back up plan. There should not be any problem and that is why company A puts a lot of effort (e.g., preventive maintenance) to prevent a problem from occurring.

5.6.4.1.5 Equipment Design

There are many factors considered for equipment design, including ergonomics, power, emission, noise, manpower, etc. However, detailed design of equipment is done by equipment vendors as is previously explained. Company A provides only operation drawing and layout drawing, which specifies necessary processes and physical dimensions of the equipment. There is one more thing with the equipment design that company A controls. It is a line control methodology that specifies how machines are connected to a signal board for failure cases.

For example, different machine vendors can supply different machines (e.g., company X for machine #1, company Y for machine #2, and company Z for conveyor belt). Even in this case, a standardized interface is implemented to each equipment and thus, each machine can communicate with a programmable line control unit of which logic is designed and specified by company A. For instance, at the machine #1, it can be checked whether enough torque was given to the part and the machine tool came back to the original position. If these two check points turned to be ok, an ok sign goes to the conveyor so that the conveyor can move the part to the next machine. It is checked again if the part arrives to the machine #2 and the machine #2 is allowed to start to work on the part. Therefore, operation control can be conducted as company A's way regardless of the machine suppliers.

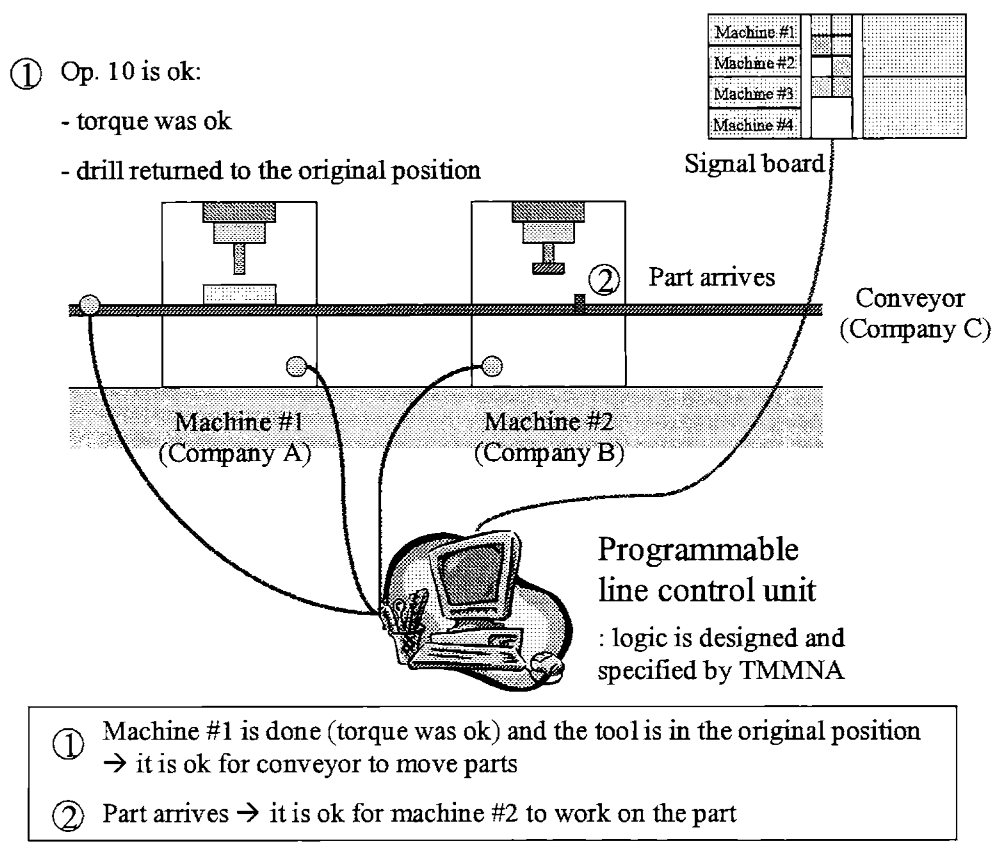


FIGURE 5-4. A SCHEMATIC VIEW OF LINE CONTROL AT COMPANY A.

Equipment is usually designed before material container size and material supply frequency is determined. In fact, the material container size decision is an in-house engineering decision.

5.6.4.1.6 Operation and Supply

In company A, run size is not optimized but decided by the final assembly. An exact sequence from the final assembly dictates the sequence of production in upstream cells. Therefore, virtually the run size is one. Some exceptions exist, though. For example, stamping and casting process have a run size more than one because of long die change over time.

Information technology (IT) is viewed as important for cell operation but not very important for overall plant operation. In cell operation, IT provides an easy way for trouble shooting. However, in overall plant operation, trouble shooting using IT is difficult considering the level of system complexity. Developing a simpler system is the key in the control of overall plant operation, rather than applying IT heavily to a complex system. In company A's plants, materials are supplied according to actual consumption, and operator's work is designed and standardized. The training process is also standardized.

5.6.4.1.7 Inventory Level

Typically, company A does not design in buffers. Therefore, only standard WIP exists as pipeline WIPs in processes and logistics channels. The number of Kanban is decided by factors such as a desired standard WIP level and container sizes. A target number of Kanban is always a theoretical minimum but in real situations, small safety factors are considered (about 10 %).

5.6.4.1.8 Vertical Ramp-Up

Company A is famous for its almost instant ramp-up process. This fast ramp up process is a result of careful coordination of various activities toward actual production. For the vertical ramp up, company A uses a "degree of perfection" system in the development stage. The items of this system include the depth of trained skill of workers and suppliers.

The degrees of perfection are carefully monitored throughout the development processes in terms of the "proceedings of development schedule," "readiness for production," "maturity of workers' skill including temporary helpers," "procurement relations," "degree of completion of drawings including the design revision through DIR or QIR," and "degree of precision of fabricated parts." All items to be checked are aligned and executed to achieve the required operating ratio and the takt time in real production on predetermined D-day (product launch). Under the basic principle that every item required for the real production should be completed until the D-day, the gate is installed at each node of the processes toward the D-day. The actual progresses in product development are constantly checked at each gate, which is called the gate control, of which central target is to assure the performance of the vehicle. The ramp up lead-time represents the generic capabilities of a company as well as all the agents including the suppliers to identify problems and make solutions as fast as possible. The result of this effort is enormous. Company A was able to decrease its ramp up time from 60-70 days to only 10 days.

5.6.4.1.9 Investment Criteria

The basic idea behind investment decision criteria is not to spend more than the similar previous project. According to this basic idea, company A keeps a lot of records of past projects in a database format and uses these stored data to compare the new project plan with previous experiences. Items such as costs are subject to the comparison. If the proposed design is revealed to require higher costs, production engineering and product design work together to make new designs. This decision, however, is not made in an individual machine level. It is made in a cell or production line level, which helps to avoid maximizing efficiencies of each machine instead of the total system. Figure 5-5 briefly shows how this approach works.

During the process design phase, exact values are not available and thus estimated values are used for this purpose. Other factors such as required man-power are also compared to those of past projects and benchmark results are often used to set up a goal/target (Figure 5-6). The final decision is made based on the comparison result of many factors.

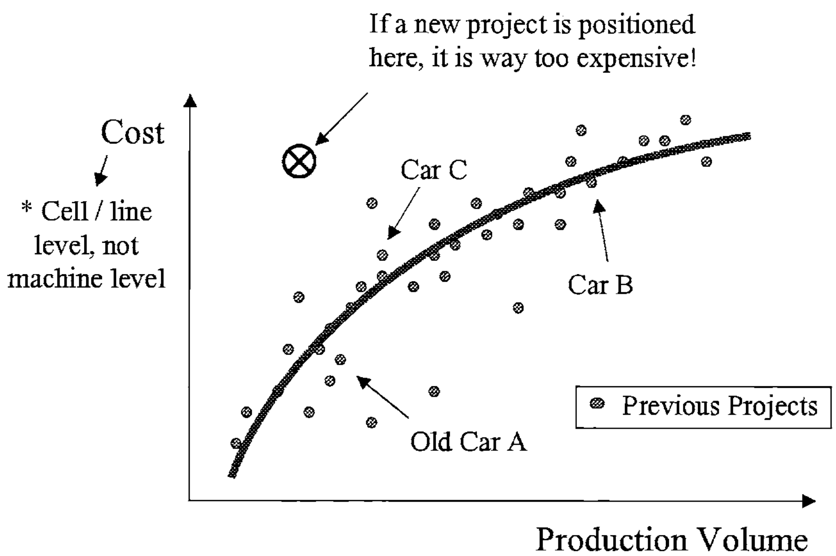


FIGURE 5-5. INVESTMENT FEASIBILITY ANALYSIS AT COMPANY A.

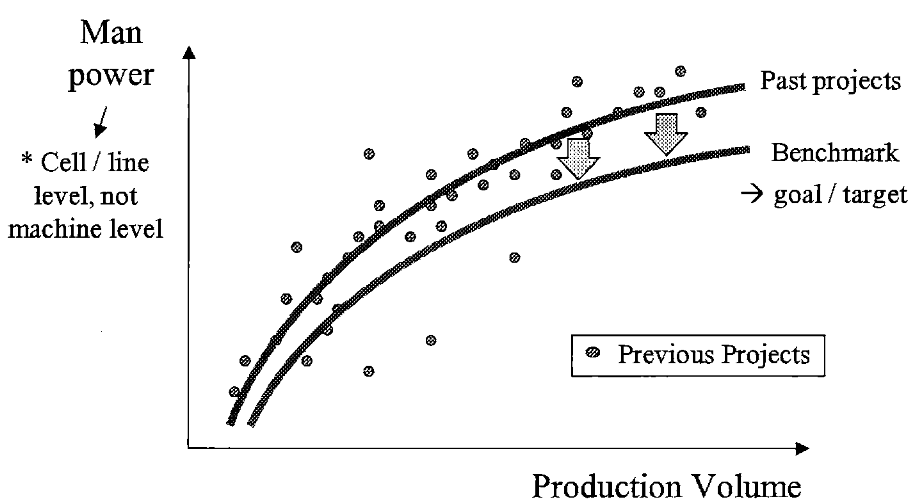


FIGURE 5-6. INVESTMENT FEASIBILITY ANALYSIS AT COMPANY A – THE USE OF BENCH MARK RESULT

5.6.4.2 Company B

The response from each division varies again for the manufacturing system design related questions. Therefore, the response from each division is provided separately.

The electronics division uses pre-defined manufacturing system design steps that are a part of the Copy Exact process. The general process of manufacturing system design is identifying, developing, and experimenting with equipment to provide information on its reliability, serviceability in conjunction with its capability to produce capable high quality product. This usually entails new technologies for which significant characteristics are defined and capability is established. Capacity planning process starts from estimating the volumes from customer over the life of the product. Then the volumes are meshed with planned new business to create a percentage of utilization rates for each equipment or cell. Floor space is allocated and booked in the same way. During these processes, feedback from the previous manufacturing system design projects heavily affect the decisions so that much is copied forward as is appropriate based on the type of product.

As is stated previously, manufacturing systems of the electronics division are very flexible to handle a large number of product types. In the upstream, flexible equipment is implemented to handle the product variety while dedicated assembly cells are used for the same purpose in the downstream. If the upstream equipment runs at a pre-determined speed, then it indicates that the process is optimized. Boards with the common parts run down the same line using different placement programs. The final assembly cells are dedicated and run at the takt time of the customer. Interestingly, the equipment and processes are considered first over product variety decisions and these drive design requirements for commonality and standards. The flexibility of manufacturing systems is maintained through quick software changeovers, removable fixtures with common test equipment, and assembly fixtures that can be replaced within minutes to build a different product. Still, customer demand instability is seen as a challenge to the flexibility since it affects more through the supply chains as the division becomes leaner.

In the division X, the corporate wide manual for product development is extensively utilized. The manual has built-in deliverables for manufacturing required at each of the product development process milestones. These deliverables are directly related to the manufacturing system design steps and linked to the product design phases. The manual has nine phases from strategic intent to launch readiness in which manufacturing works with the cross functional product development team to achieve each milestone while satisfying the APQP (Advanced Product Quality Planning) requirements.

Capacity planning is performed at the staff level using plant data related to each product family and production system. Faster ramp up process is achieved through information sharing on shared resources such as company intranet. The shared information includes process FMEA, dimensional control plans, manufacturing process sheets, and lessons learned.

Flexibility of each production line for a specific product application is assessed by the manufacturing engineering. Manufacturing flexibility is further reinforced by pursuing lean manufacturing principles, and utilizing lean tools such as value stream mapping and reliability techniques. Mix capability of a production line is ensured by pursuing lean principles. Customer focused lean manufacturing system with linked cells is considered as the most effective tool in achieving customer mix requirements. However, the challenge is to achieve the flexibility with the existing equipment designs. Most plants use MRP (Manufacturing Resource Planning) based system to schedule customer mix requirements. Newer production systems are directly linked to the customer and have a single point of scheduling in which continuous flow to the customer is achieved.

Investment efficiency may be compromised when the equipment cycle time and customer takt time are not in concert with each other due to the nature of certain processes. Sometimes, cells that are larger than desired may be required when volume fluctuation reaches peak demand before additional cells are added to production. Specific decisions are made according to customer requirements.

The climate control division does not have any pre-defined manufacturing system design steps. However, lean manufacturing principles and manufacturing system design steps are being implemented and taught throughout the division. Many of the manufacturing problems are approached from the lean manufacturing perspective. For example, the respondent pointed out that fast ramp up process or flexible mix-capability of a production line would be ensured through the extensive application of lean principles. On the other hand, it seems that the continuous improvement aspect of lean principles has not been fully exploited yet even since no formal feedback system is in use. However, the newly formed Lean group attempts to distribute lessons learned. Capacity planning is done by a special cross-functional team that is responsible for periodic capacity studies.

No special strategy is implemented for flexible manufacturing other than the implementation of lean manufacturing principles. The production mix is handled through scheduling due to required changeover and labor variation, and existing mass production equipment. The scheduling of production mix is based on customer forecasts and releases.

The powertrain division uses manufacturing system design steps that are pre-defined as part of corporate-wide product design manual and production system design manual. Still, there is no integrated step-by-step design manual for manufacturing system design. Capacity planning is done through the strategic manufacturing and business planning activities with the help from plant industrial engineers. The mix capability of each line is determined by capacity and customer complexity requirements. Required product complexity drives the manufacturing process design. In the process design, product variety plays a key role. In the past, manufacturing lines tend to be dedicated to individual product lines with the design driven by the product complexity determined by customers. Now, lean manufacturing principles are applied to manufacturing system design. However, major challenges are recognized for this change including the potential for mixed stocks and lost capacity for changeovers. Considering these challenges, production schedules are developed to minimize the number of changeovers and optimize delivery while based on customer demand.

The exterior group has manufacturing system design steps defined. It uses a corporate-wide guide manual for manufacturing system design that provides only principles. Therefore, the design steps vary a lot, and each plant and product design department has its own processes. Exterior group seems to suffer from the lack of standardization. A significant number of critical decisions are made plant-by-plant on a department-by-department basis. For example, capacity planning is done differently depending on the organizations doing the planning and there is no formal feedback from the previous projects. In addition, no standard process is available for mix capability decision for production lines. The mix schedule is typically decided based on what the customer requires and what parts are available to produce. A typical reason for a low level of standardization is claimed to be a lack of fund. For example, there was an attempt to standardize molds in late 90s but failed due to the lack of funds.

5.6.4.3 Company C

Company C does not have pre-defined steps for overall manufacturing system design. However, there are organizations within company C specializing in equipment building, of which expertise has typically been used to design the manufacturing process. In addition, these organizations have processes that they use to develop the manufacturing system. Local plants have begun to exert much more influence in manufacturing system design and are beginning to use some tools proposed from academia.

5.6.4.3.1 Manufacturing System Design Process in General

A cross-functional team works together to design the manufacturing system. Generally, a project gets started by determining how to build a part in an informal place such as private garage. Then, about hundred parts are tried. In this trial, a time defining process is used to determine a natural cycle time that cannot naturally be broken down further. Based on this experience, capacity is planned, equipment is designed, and physical layout is determined

5.6.4.3.2 Capacity Planning

Previously, the estimated volumes and plan for a capacity 15% above the maximum sales forecast would be taken for a necessary capacity. In recent years, the concept of natural cycle time that cannot be naturally broken down further is considered for a capacity planning and manufacturing cells are reproduced according to actual sales. With this approach of the incremental capacity through manufacturing cells, no learning curve effect exists as production volumes increase.

5.6.4.3.3 Mix Capability of a Production Line

In the past, the objective of line mix capability was to run as many part types on a line as possible so that ultimately, all products can be run on a single line. If large hardware changes are needed, the line may be split up into families. In recent years, however, an analysis is made to determine the best possible mix per cell. Sometimes, it is determined that no changeovers should be made and a simple cell should be dedicated to a product. Mostly, high levels of flexibility are pursued in order to changeover in less than one minute regardless of the product.

5.6.4.3.4 Equipment Design

Two basic design philosophies are pursued for manufacturing system design and they are simplicity and flexibility. Simplicity means simplicity of equipment used in manufacturing systems and it often results in low level of automation in the initial equipment. This simplicity in equipment contributes to fast learning curve and prompt problem solving. Automation is added later, as necessary, mostly to solve quality problems. Error proof devices (poka yoke) are specified into the line from the beginning of development to avoid the need for visual inspection for quality control. More devices are added as knowledge is accumulated through the experience with the product.

During the equipment development, product engineers also participate in the equipment design. For example, product design engineers attended the initial equipment design workshop. Company C is now trying to invite design engineers to every equipment design workshops. The timing of the equipment design workshop is as follows:

1st DFM → 1st prototype build
→ 2nd prototype batch build → 2nd DFM
→ "equipment design workshop" → 3rd prototype build

Still, company C is in its early stage of restructuring its product development processes and thus, there is no established formal follow-up structure available to ensure flexible equipment design.

5.6.4.3.5 Operation and Supply

In general, a weekly mix is reviewed and a schedule is created for the assembly line. Some areas are trying to go toward daily mix management. A pull system with customers is not yet established even though some of its suppliers are connected with company C by a pull system.

It is planners at company C who are responsible for receiving information from the customers and transferring that into a schedule for the manufacturing process. They are also responsible for giving orders to suppliers, based on customer releases and long term forecasts, depending on supplier lead times. Planners update schedules as the orders from customers change. In some areas, however, there are still a significant number of expediting activities based on the MRP (Manufacturing Resource Planning) system but this varies greatly depending on the customers' ability to minimize significant demand swings.

5.6.4.3.6 Investment Criteria

In the past, cost was the key requirement for a design. Today, however, simplicity and flexibility are seen as better total cost solutions. Therefore, simplicity and flexibility are prioritized over costs as long as they make sense.

5.6.4.4 Company D

Company D has pre-defined manufacturing system design steps. For stamping, the rough steps are such that the engineers identify and review the surrogate processes, propose a process that improves on the surrogate processes, review it with the production plant, and proceed into design.

Product design affects the selection of surrogate process that will drive the process and the estimated production volume affects class of dies. Due to the characteristic of stamping process, flexibility is not considered much during the die design process. However, stamping machines are subject to flexibility. For example, single minute exchange of die (SMED) can improve the flexibility of stamping process by minimizing the die changeover time. The press loading group determines press line using various criteria including the size and tonnage constraints. Information such as quality, productivity, and maintainability are collected from production plants and fed back to die engineering group.

All vehicle programs have plans that are intended to track various key milestones, which die engineering group currently has difficulty in delivering on the many of the plans. The performance of engineers is assessed by their level of achievement of the planned objectives, which affects pay, bonus, and potential promotion.

5.6.4.5 Company E

Company E has pre-defined manufacturing system design steps in a form of planner handbook and pro-planner. These documents describe the general manufacturing system design processes. Lessons learned from the previous manufacturing system design projects are documented through Lessons Learned meetings held after every project. At company E, a long-term model capacity planning is performed with all factories involved, while factory specific capacity planning is done together with unions and factory planning departments. For each line, planned times for model-specific activities are summed to give critical line capacities. Internal and external suppliers limit the absolute maximum capacity for individual models.

Several methods are in use to shorten the ramp-up time such as virtual tools, sufficient pre-production vehicles, early supplier involvement, strict project dating, and detailed vehicle scheduling in launch and volume production.

In company E, a manufacturing system is designed to offer maximum flexibility, not only for current models, but also for future models, especially with regard to new logistics concepts such as just-in-sequence delivery of parts and modularization. However, the variety in the mix needs to be controlled throughout the process chain, starting from the design engineers, involving the supplier control, vehicle scheduling, process control, and ultimately the production workers. For example, production workers need to receive clear communication, which part should be fitted to which vehicle. These things are recognized as a challenge toward the mix production. Mix production is scheduled by random scheduling of vehicle production within the constraints of the planned time per activity. For example, no three convertibles can be built in sequence because the planned time to assemble the roof is longer than the same activity for other models.

As is traditionally thought, at company E, simplicity is recognized to be secondary to cost. Solutions are sought to satisfy customer needs to the maximum and most cost-efficient extent, even if the solutions are not the simplest.

5.6.4.6 Company F

The respondent of company F was not familiar with manufacturing system design processes of company F. However, the respondent has some experience in the assembly line as an observer and as a line worker. According to his/her experience, final assembly lines of bus division are flexible to deal with two or three different models simultaneously. Furthermore, due to the characteristics of bus business, typical order number is in two digits and thus the production run size is. In other words, since the exterior painting and seat arrangement should be different for each order from different companies, the final assembly lines should be flexible enough to deal with this type of variation. Scheduling of mix production is usually done by the customer order, which becomes the run size of the final assembly lines.

5.6.5 Performance Measurement

Performance measurement system is important to achieve the objectives of a manufacturing firm because performance metrics drive the behavior of the system. Several questions were asked to capture each company's view on performance measurement in general. They are:

- What is your company's financial accounting system used for the internal control purpose?
- What does your company have as performance measures for a plant as a whole?
- How are those performance measures different from each level of plant management? (operator level, engineers level, line managers level, and plant manager level, etc.)

- What efforts are made to keep your company's employees fully motivated? (For example, some companies make a lot of effort to keep its people's sense of 'emergency' for everyday operation. Is there any equivalent effort in your company?)

Due to the limitation of the knowledge of the respondents, some respondents did not answer certain questions. However, the received answers show the each company's own view on performance measurement and employee motivation (Table 5-7).

TABLE 5-7. THE SUMMARY OF THE ANSWERS TO THE PERFORMANCE MEASUREMENT QUESTIONS

Company		Accounting for internal control	Plant-wide performance measures	Optimized PMs measures according to the level of organization	Motivation of employees
A		General expense control monthly; no accounting for day-to-day operation control	Labor productivity, lead time to customers, due day observance ratio, safety, waste control	N/A	Special skill master system; 'no change is evil' philosophy
B	X	Cost accounting based on allocations	Safety, overall equipment effectiveness (OEE), dock-to-dock time, on time delivery, total cost	N/A	Team based approach; safety, health, and wellness programs
	Climate control	Accounting information system and finance manual	Quality, delivery, premium freight, inventory, labor and overhead	Different measures at different levels	Quarterly performance review, initiatives such as 6 sigma and lean
	Exterior	Varies by location	Varies by location (however, safety has the highest priority)	Varies by location	Hourly operators by punishments for failure and profit sharing; salaried people by bonuses
	Powertrain	Total cost approach as a part of QOS (quality operating system)	Safety, quality, cost, and delivery	No measures for operators, engineers & managers have some limited by their areas of control	Try to keep them informed and involved

	Electronics	Several methods are used to estimate costs, overall project profitability	Safety, quality, cost, delivery, people	Cascaded into objectives that have meaning and is measurable at each level	Focusing each team toward a customer and product – pride and team awards
C		Traditional accounting system (profit = sales price – (material + labor + overhead)	Productivity, defect cost, monthly production to schedule, piece price, indirect material cost, headcount, safety, gross margin	The measures are the same for all levels of management	Profit sharing system
D		A system to provide payment and tack stamping tool cost	Specific objectives on safety, quality, delivery, cost, and morale	The objectives of each employee are aligned with the higher level plant objectives	Reward and recognition program to highlight extraordinary effort
E		N/A	Budget adherence, personnel absence rate, product quality	General measures are identical across all levels but quality goals are specific to a department	Financial rewards, part-taking in desirable projects, and promotion possibilities
F		N/A	N/A	N/A	N/A

5.6.5.1 Company A

Company A keeps financial accounting and day-to-day factory operation separate. In other words, company A focuses on continuously improving itself with the non-financial indicators in everyday factory operation. After achieving the non-financial indicators, company A tries to minimize the controllable cost drivers such as energy and defects cost. There is the general expense control on monthly basis by the financial department. Cost improvement targets are assigned to each section of a plant in terms of controllable expenses such as materials, payroll, energy, defects cost, and so forth. However, the factory's day-to-day operation runs autonomously with non-financial indicators such as first time through rate, dock-to-dock time, and on time delivery.

The managerial indicators of company A are generated from each functional organization such as sales, engineering, procurement, manufacturing, and quality control. This brings multi-performance measures that are linked to each managerial function. With these performance measures, the performance of a plant is evaluated from various perspectives. There is no single most important indicator that represents the performance of a plant.

For example, corporate wide quality target is announced by the top manager of quality control function and delivered to each related organization in the factory. Two ratios are considered as the most important with regard to achieving given quality target; direct run ratio and final assembly run ratio. The direct run ratio by assembly lines and by major fabrication departments represents the percentage of units that pass through the line without off-line repair work before reaching the end of the line. The final assembly run ratio is the ratio of vehicles produced to the number required to meet customer orders. These two major indicators are monitored and updated in real time and is reported on big electronic boards throughout the plant, and complied into monthly trend analysis. However, there is no authorized decree that these two measures are the most important indicators for the plant. There is no specific coordination, from the aspect of the factory-wide optimum, among all the indicators from each functional department. In this sense, as far as the integration of managerial indicators is concerned, company A still has a room for improvement. Under these circumstances, various indicators are used to measure such functionally assigned performance of a plant. For example, such performance measures are used as labor productivity (human performance), stroke per hour (facilities performance), lead time to customers (production control), due day observance ratio (production control), injury and accident ratio (safety), and industrial waste control ratio (green factory). All these indicators are accepted by the frontline managers, supervisors, and workers, and faithfully followed. In addition, these indicators are the objects of *kaizen* activities.

Even though the above-mentioned measures are widely accepted and used for improving the operation, company A does not have any formally arranged performance indicators list categorized by the level of management. However, they seem to be aware of this problem. Corporate planning division of company A is now working on developing a systematic framework of managerial performance measures starting from the top management down to the frontline operators.

With regard to competence management, company A has 'special skill master' system, in which individual workers are assessed in terms of the degree of their multi-work capability and the depth of skill in each respective work. Those who mastered all the designated skills are nominated as *Kogi*, which represents the highest skill rank in company A. Climbing up the ladder of the skill rank is not necessarily directly linked to pay, but strongly motivates frontline operators and technicians as the symbol of invaluable honor. Acquiring higher grade of skill is appreciated in human assessment system. General qualitative measures are added to assess the capability of individuals as a team member such as leadership, collaboration, and inter-organizational coordination.

Maintaining the sense of emergency is very important in managing a factory. Company A believes the key to keep tension in work is *kaizen*, continuous improvement, and their deep-rooted philosophy of "no change is evil." For example, if engineering managers came to the factory floor after one or two months of absence, the layout or something in the plant would have been changed.

5.6.5.2 Company B

In the electronics division, several methods are used to estimate resources and costs for quotes in order to enable budgeting once business is sourced, and overall project profitability. As for the plant evaluation, plants are evaluated in terms of such criteria as safety, quality, cost, delivery, and people. These general evaluation criteria are cascaded into objectives that have specific meanings and can be measured at the operator level. Number of days without an accident may be a good example of safety measures.

Employees are motivated by focusing each team toward a customer and product. For this, a lot of product training is provided, and teams are exposed to the customers. Team members are even sent to customer operations to better understand customer needs and expectations. Taking through this type of activities, employees establish a pride in knowing their customer and delivering perfect quality parts on time. Team awards are given as one way to keep teams motivated with other various actions taken by plants.

In the division X of company B, cost accounting based on allocations is the primary financial accounting system used. Activity Based Costing (ABC) is being considered for the future implementation. However, plants are evaluated by metrics established in the production system design manual of company B. In addition to the safety metrics, these metrics include overall equipment effectiveness (OEE), first time through quality, dock-to-dock time, on time delivery, and total cost. To motivate the employees, several methods are in use. Employee involvement teams and communication meetings are used to keep the employees informed on critical information required. Safety, health, and wellness programs are supported at al the manufacturing locations.

The climate control division of company B counts on the AIS (Accounting Information System) and FM (Finance Manual) of the mother company of the company B as its financial accounting system. These systems are implemented in software to which new organization of company B is reflected. However, not only financial measures are used to evaluate the performance of its plant, but also quality measures are exploited. Examples of financial measures are labor and overhead, launch, premium freight, inventory, and capital spending cost. Quality measures include on-going PPM (part per million), delivery metrics, launch performance, stop shipment alerts, owner notification and recall, and customer warranty.

There are different performance measurables applied to different level of management. Operators are evaluated in terms of their responsible part (narrowly focused) quality and production rates. Engineers are assessed by process results in quality, productivity, and warranty. Labor and overhead cost performance, and quality metrics are important for line manager while total cost and overall quality matter for plant managers.

To keep the employees fully motivated, several methods are used together. They are; quarterly performance reviews, initiatives such as six sigma and lean, and special team building events days.

The powertrain division of company B uses a total cost approach as a part of the QOS (Quality Operating System) process. QOS is a package of procedures that plants use. It has a set of measurables through which the plant can be analyzed. Among the performance measurables, safety is considered as the most important one, followed by customer satisfaction (quality and delivery) and then cost. Within this system, however, operators do not have any performance measure. Engineers are judged on their individual performance relative to their areas of responsibility and relative to their objectives. Line managers and plant managers share the same performance measures limited by their areas of control. To motivate employees and keep their sense of emergency, there is an effort to keep them informed of and involved with continuous improvement. However, the result is considered as mixed.

In the exterior division, financial accounting system and performance measures of a plant vary by manufacturing locations. However, some common efforts are made to keep employees fully motivated. The way to motivate employees is slightly different according to their status – hourly employed and salaried. Hourly employed personnel is motivated by punishments for failure to perform to individual job standards and profit sharing from the mother OEM company. Company B does not have an incentive/motivation system for hourly employed personnel. Salaried employees are motivated by performance bonuses, stock options for a few, and re-organization.

5.6.5.3 Company C

Company C uses a traditional accounting practice, which may be represented by the following well-known equation; profit = sales price – (material cost + labor cost + overhead cost). Traditional metrics for plant performance measures include productivity, defect cost, monthly production to schedule, piece price, indirect material cost, headcount, safety, and gross margin. Some 'lean' metrics are in implementation process such as dock-to-dock time, first time through rate, and overall equipment efficiency (OEE). In addition, company C is in its early stage of implementing total plant cost metric. However, performance measures are same for all levels of management. To overcome this problem, company C is conducting baseline studies on metrics designed for specific levels in the organization. Employees are motivated by a profit sharing program based on the traditional metrics. The bonus pay is visible in real time and is regularly reviewed by all associates including management.

5.6.5.4 Company D

Die engineering division of company D has a mainframe computer system to provide payment and track stamping tool costs. The plants have very specific overall objectives in the SQDCM format (safety, quality, delivery, cost, and morale), in terms of which plants are evaluated. The objectives of each employee are aligned with these higher level plant objectives and adjusted to be job specific. There is a reward and recognition program to highlight extraordinary effort for improvement.

5.6.5.5 Company E

Plants of company E have performance measures such as budget adherence, personnel absence rate, and product quality. Generic performance measures for individuals are identical across all levels of management but quality goals are specific to the department.

There are no efforts to keep the sense of emergency among its employees. Motivation is achieved through encouraging the use of the suggestion scheme, financial rewards, part-taking in desirable projects, and promotion possibilities.

5.6.5.6 Company F

The respondent of company F refuses to answer the questions related to the performance measurement system of company F.

5.7 Conclusion

In this chapter, different interfaces between manufacturing and product design of different companies are identified and reviewed. It is recognized that various methods are in use in different companies but all methods share the same common objective of smooth design-to-production process in order to save costs and time while ensuring quality products. It can be also identified that many tools proposed by the academia such as cross-functional product development teams, design for manufacturing tools, and the knowledge management database, are becoming a norm in the companies in auto industry. Almost all companies report their dedication to the cross-functional teams in use for product development, for example. On the other hand, some company-specific unique methods are identified such as 'Copy-Exact' and 'DIR/QIR.' Those unique methods seem to be the results of product characteristics and the dominating culture within the companies. However, they are all same from the perspective that they are developed and used to achieve the goals of minimum development time and cost of quality products.

In addition to the communication interfaces between two groups, general information on the product design decisions, manufacturing system design processes, and performance measurement is provided for easier understanding of the rationale behind the implemented communication interfaces. They are all very closely linked to the communication interface designs. For example, the company-specific strategy of the product design heavily affects the characteristics of the product designs and thus, influences manufacturing systems design. Therefore, the communication between design groups and manufacturing groups is essential to set the strategy and modify it. Manufacturing system design decisions will significantly affect the manufacturing capability of a company and thus, will decide the constraints to be met by product designs. Manufacturing system design even can be seen as a part of product development in a broad sense. In addition, performance measurement system influences the behavior of system constituents. Therefore, it is often insightful to look at performance measurement system to indirectly understand the rationale behind the product development system design.

A question arising from the investigation is how to compare and evaluate those different communication methods described in this report. There can be several ways to assess their effectiveness. One way may be to compare the performance of each company's product development in terms of losses occurred due to the ineffective communication between two parties. For example, total product development time span or the number of design iterations made due to the miscommunication between two parties can be one of the comparison criteria. However, the problem with this approach is that objective comparison based on one criterion is very difficult to be made because of numerous factors involved with the product development. In fact, the companies of which examples are provided in this report develop and produce very different products with various levels of complexity. In addition, collecting associated performance data is not an easy task at all. It would be very time consuming to count the number of design iterations caused by lack of effective communication or to assess the difficulties and costs that manufacturing has to bear for inappropriate product designs. Most importantly, this method does not show why a certain communication method works better than the other does.

Another way is to focus on the issues that each communication method covers. In other words, it can be investigated whether the design-manufacturing communication method in use at each company covers the necessary items for design for manufacturing systems. For example, it can be studied if the method in use at a certain company asks the product designers and manufacturing engineers to see the consequences of proposed designs in terms of manufacturing issues such as operator training, problem solving practices in the plants, material flows in the plants, and scheduling of mix production. For this purpose, a new framework based on the MSDD (Manufacturing System Design Decomposition) is proposed to clearly identify the manufacturing system issues that should be considered in the product development. Based on this newly proposed framework, the second-round questionnaire has been developed and distributed to the same respondents for their answers. The second round-questionnaire is to evaluate the collective exhaustiveness of the scopes of the different communication methods deployed in different companies. Five points survey type questions are prepared for easier responses.

Except the proposed approach, other approaches are possible. Some human factors such as the loyalty to the given methods and the competency level of the employees can be studied. Or else, the level of details each communication method encompasses can be focused. The adequateness of the tools deployed within the communication methods framework (i.e., DFM rules) may be tested. However, the comparison based on these criteria is out of the scope of this research.

5.8 Chapter summary

In this chapter, the industry practices to facilitate the communication between manufacturing and product development is presented. Additional information on the general practices of the participating companies in manufacturing system design, product design, and performance measurement are also provided to enhance the understanding of company practices from the system level viewpoint. As data collection protocols, the first round questionnaire is developed and used while complemented by observations and face-to-face interviews with the engineers in the participating companies. Six companies participated in the case study around the world. Four of six companies are OEM companies in automotive industry and two are first-tier automotive parts suppliers.

The data collected from the answers to the first round questionnaire from six companies, personal observations, and face-to-face interviews with the engineers at participating companies are analyzed. The results of the analysis shows that many companies are adopting the newest solutions available in academia and benchmark companies such as cross functional product development teams and knowledge management tools. All companies strive for minimizing manufacturing problems after product design is completed by facilitating the communication between manufacturing engineers and product design engineers. Still, some weaknesses are observed. For example, most of the companies do not pursue the standardization of the content of the information exchanged among functional groups. Some companies do not use any knowledge management tool to avoid the mistakes made in the past. Even the companies implementing knowledge management tools rely too much on the previous experiences instead of using a systematic framework, so that it is difficult to prevent new problems that have never occurred.

In the next few chapters, a systematic approach to capture the impact of product design decisions on manufacturing systems is presented. This approach makes it possible to identify possible sources of conflicts between manufacturing and product design in a systematic way so that manufacturing problems due to new product designs can be prevented.

6 MANUFACTURING SYSTEM DESIGN DECOMPOSITION

This chapter presents the development of the Manufacturing System Design Decomposition (MSDD). The motivation and basic ideas behind the MSDD are provided along with a brief introduction of underlying design methodology, Axiomatic Design, which is used to develop the MSDD. Furthermore, detailed explanation on the high level FRs and DPs are stated in order to facilitate the understanding of the MSDD.

6.1 Introduction

The Manufacturing System Design Decomposition (MSDD) has been developed by Cochran and his colleagues at MIT for last 7 years. The MSDD is a decomposition of the requirements for a manufacturing system, linked to the design parameters. The framework of the Axiomatic Design was applied for the development of the MSDD. The very first idea of the MSDD started from the dissertation of Cochran [1994] but the first version of the MSDD in its current form was first introduced in 1998.

The first version of the MSDD was developed to rationalize the tools of lean manufacturing and to see the inter-relationships among the tools in order to understand how they interact to serve for the high level objectives [Suh et al. 1998]. Therefore, many of the design parameters in the first version of the MSDD were popular buzzwords for the tools such as 'heijunka', 'poka-yoke', and '5S'.

During the development of the second version of the MSDD, the solution neutral environment that the Axiomatic Design theory requires, was faithfully kept. The zigzagging process was loyally followed and true design parameters were sought for associated functional requirements instead of merely adopting lean manufacturing buzzwords. The result was a very different MSDD from the previous version [Cochran et al. 2000a].

In the following sections, Axiomatic Design is briefly introduced and the details of the MSDD are presented.

6.2 Axiomatic Design

Axiomatic Design has been developed by Suh and his colleagues at MIT in the U.S.A. for more than 20 years. The first paper describing the early idea of Axiomatic Design was published in 1978 [Suh et al. 1978] and the current framework was established with the publication of the first Axiomatic Design book by [Suh 1990]. Axiomatic Design is recognized to provide designers with a tool to structure their thought processes in the early design stages using two design axioms. The main driver for developing axiomatic design was to give scientific basis for the field of design [Suh 1990] so that teaching and learning of the design can be more systematic and generalizable [Suh 1995c]. Suh believed that designers should learn how to make a good decision based on the scientific basis. In this sense, one of the primary motivations for axiomatic design development was education. Axiomatic Design has been applied in a number of disciplines including software design [Harutunian et al. 1996], design of systems [Suh 1995b, Suh 1997], quality [Suh 1995c], manufacturing system design [Cochran 1994], and design process roadmap [Tate and Nordlund 1996, Tate 1999].

In this chapter, a brief introduction of Axiomatic Design is provided. For detailed discussion on Axiomatic Design, please consult the references [Suh 1990], [Suh 1995a], [Suh 2001], [Tate 1999].

6.2.1 Basics of Axiomatic Design

The underlying belief of axiomatic design is that there are fundamental axioms that govern the design process. Originally, many axioms were proposed [Suh et al. 1978] but redundant axioms have been integrated or eliminated so that finally only two axioms are survived. Suh [1995c] claimed that these two axioms were identified by examining common elements in good designs of products, processes, or systems.

The first axiom is the independence axiom. The independence axiom indicates that the independence of functional requirements (FRs) must be maintained. In other words, design decisions must be made without breaking the independence of each functional requirement from other functional requirements. The functional requirements must be independent to each other and their number must be minimized to be just enough to characterize the design.

The second design axiom is the information axiom. Information axiom dictates to minimize the information content of the design. Among the design options that satisfy the first independence axiom, the design with the minimum information content is the best design. Axiomatic design defines the information content as the log inverse of probability of success to satisfy the functional requirements. Based on the two axioms, theorems and corollaries are derived [Suh 1990].

Axiomatic design sees the design world as consisting of four domains. They are: customer domain, functional domain, physical domain, and process domain. Figure 6-1 schematically illustrates these four domains. The elements associated with each domain are customer attributes (CAs), functional requirements (FRs), design parameters (DPs), and process variables (PVs). The domain on the left relative to the domain on the right represents the objectives to be achieved (or what the problems are), while the domain on the right indicates the ways to achieve the objectives (or how to solve the problems). For instance, customer attributes (CAs) are to be satisfied by corresponding functional requirements that are the results of mapping customer attributes from the customer domain to the functional domain.

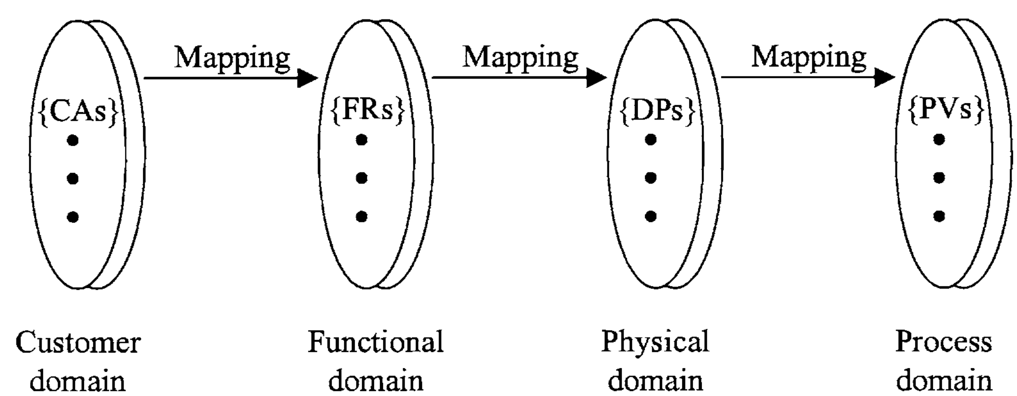


FIGURE 6-1. FOUR DESIGN DOMAINS IN THE AXIOMATIC DESIGN [SUH 1990]

Axiomatic Design dictates to keep two governing rules during this mapping process for a good design. The first one is to follow the two design axioms during the mapping process and the second is to do the zigzagging during the decomposition. The zigzagging is a principle that guides the decomposition process from a high level to low detailed levels. The zigzagging principle guides designers to zigzag between domains when they do designs. For example, during the mapping between functional domain and physical domain, lower level FRs should be derived from the higher level FR while considering the corresponding DP of the higher level FR. In other words, before the higher level FRs are decomposed into sub-requirements, designers must decide the corresponding higher level DPs that satisfy the FRs. The zigzagging process is shown in Figure 6-2.

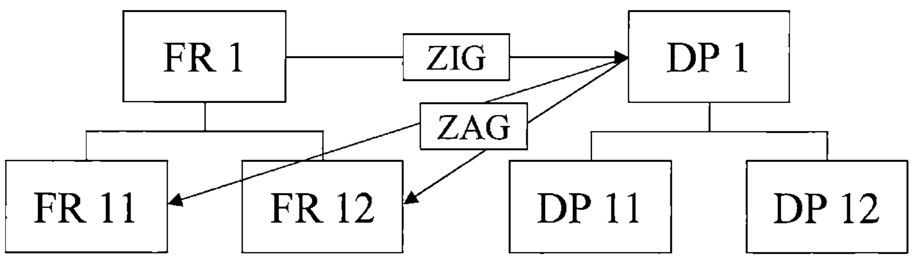


FIGURE 6-2. ZIGZAGGING PROCESS BETWEEN FUNCTIONAL AND PHYSICAL DOMAINS

In the design decomposition hierarchy, design matrix describes the relationships between the elements in the adjacent domains. For example, the relations between functional requirements and design parameters can be described by a design matrix (DM).

$$\{FRs\} = [DM]\{DPs\} \tag{6-1}$$

The elements of the design matrix show the effects of the changes in the DPs on the FRs. For example, consider the following design matrix:

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} \mathrm{X} & \mathrm{O} \\ \mathrm{X} & \mathrm{X} \end{bmatrix} \bullet \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{6-2}$$

The X's of the design matrix indicate the presence of a relationship between a FR and the corresponding DP, while the O's mean that there is no relationship between them. In the design matrix, X's are always present along the diagonal elements since each DP is selected to satisfy its corresponding FR. The lower off-diagonal X shows that DP1 affects

FR2. Therefore, DP1 affects both FR1 and FR2. However, FR1 and FR2 can be satisfied independently since DP2 affects FR2 only. In other words, DP1 can be determined first and then, DP2 can be adjusted to satisfy FR2. In this way, the design matrix provides the sequence of design implementation. If the upper off-diagonal element of the design matrix is X, however, the design is coupled. Therefore, FR1 and FR2 cannot be independently satisfied by adjusting DP1 and DP2. It can be only "optimized" by adjusting DP1 and DP2 with a trial-and-error method. The coupled design matrix indicates that the first design axiom of independence is violated. To keep the independence axiom, design matrix should be either diagonal (uncoupled) or triangular (partially-coupled or decoupled). Figure 6-3 illustrates these design matrices.

$$\begin{pmatrix} X & O \\ O & X \end{pmatrix} \qquad \begin{pmatrix} X & O \\ X & X \end{pmatrix} \qquad \begin{pmatrix} X & X \\ O & X \end{pmatrix}$$

FIGURE 6-3. EXAMPLES OF DIAGONAL (LEFT) AND TRIANGULAR (MIDDLE AND RIGHT) DESIGN MATRIX

The information that a design matrix represents is shown in Figure 6-4 along with the graphical representation of the relationship and the dependency. In the graphical representation of the relationship, an arrow from a DP to an FR indicates the presence of off-diagonal X's in the design matrix.

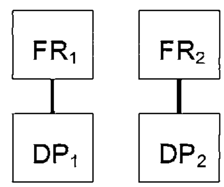
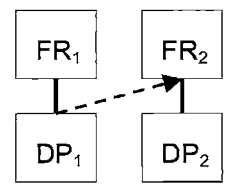
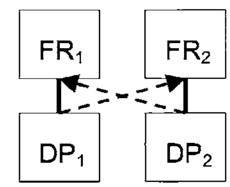
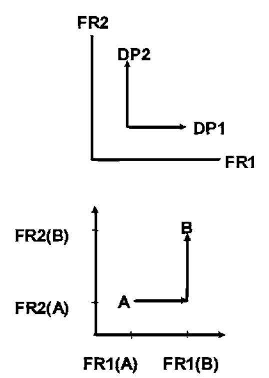
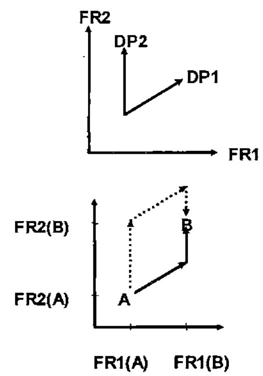
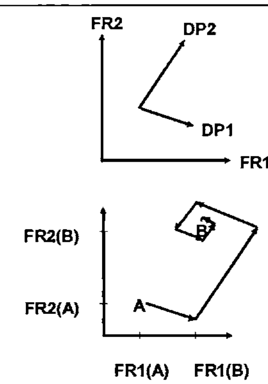
	Uncoupled design	Partially coupled design	Coupled design
Mathematical representation	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \bullet \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$
Graphical representation			
Illustration of path dependency going from A to B			

FIGURE 6-4: THE MATHEMATICAL AND GRAPHICAL REPRESENTATION OF UNCOUPLED, PARTIALLY COUPLED, AND COUPLED DESIGN (ADAPTED FROM [LINCK 2001]).

In summary, from the perspective of Axiomatic Design, 'design' is a mapping process between domains, developing a hierarchy from a system level to a detailed component level with the zigzagging principle, while observing two design axioms. However, the mappings between customer domain and functional domain, and the mapping between physical domain and process domain are loosely defined and structured, compared to the mapping between functional domain and physical domain.

6.2.2 An Example of Axiomatic Design

A good and simple example of the axiomatic design way of thinking is water faucet design. This example is used by many Axiomatic Design advocates due to its clearness and simplicity (e.g., [Suh 2001], [Kurr 1998], [Nordlund 1996]). Not too long ago, even now, faucets that look like the one in Figure 6-5 are often used.

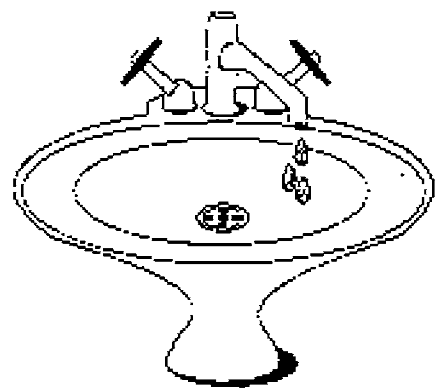


FIGURE 6-5. SINK WITH TRADITIONAL FAUCET [KURR, 1998]

This type of faucet consists of cold and hot water valves that manipulate both the flow rate and the temperature of the water. Therefore, two top-level FRs and corresponding DPs may be stated in the following way.

FR1: control water flow rate

FR2: control water temperature

DP1: cold water valve

DP2: hot water valve

Hence, the design matrix might be represented in the way given below.

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} \mathrm{X} & \mathrm{X} \\ \mathrm{X} & \mathrm{X} \end{bmatrix} \bullet \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{6-3}$$

The design matrix shows that the design is coupled. Whenever a user needs water, the user has to turn on both hot and cold water valves and then adjust the temperature of the water at the tap by adjusting the flow rate of cold and hot water through the valves. If, for example, one wants to have warmer water, one can decide to either turn down the cold water valve or turn up the hot water valve. In the same way, the water flow rate can be adjusted by either turning up or down only one valve or both of them. Therefore, from the perspective of the independence axiom, this faucet design is not a good design and thus can be further improved by changing DPs to eliminate this coupling. There can be several different improved designs and they are presented in Figure 6-6. Among the four available options, the design with the minimum information content is the best design since it has the highest probability to satisfy the functional requirements. A most popular design is presented in Figure 6-7.

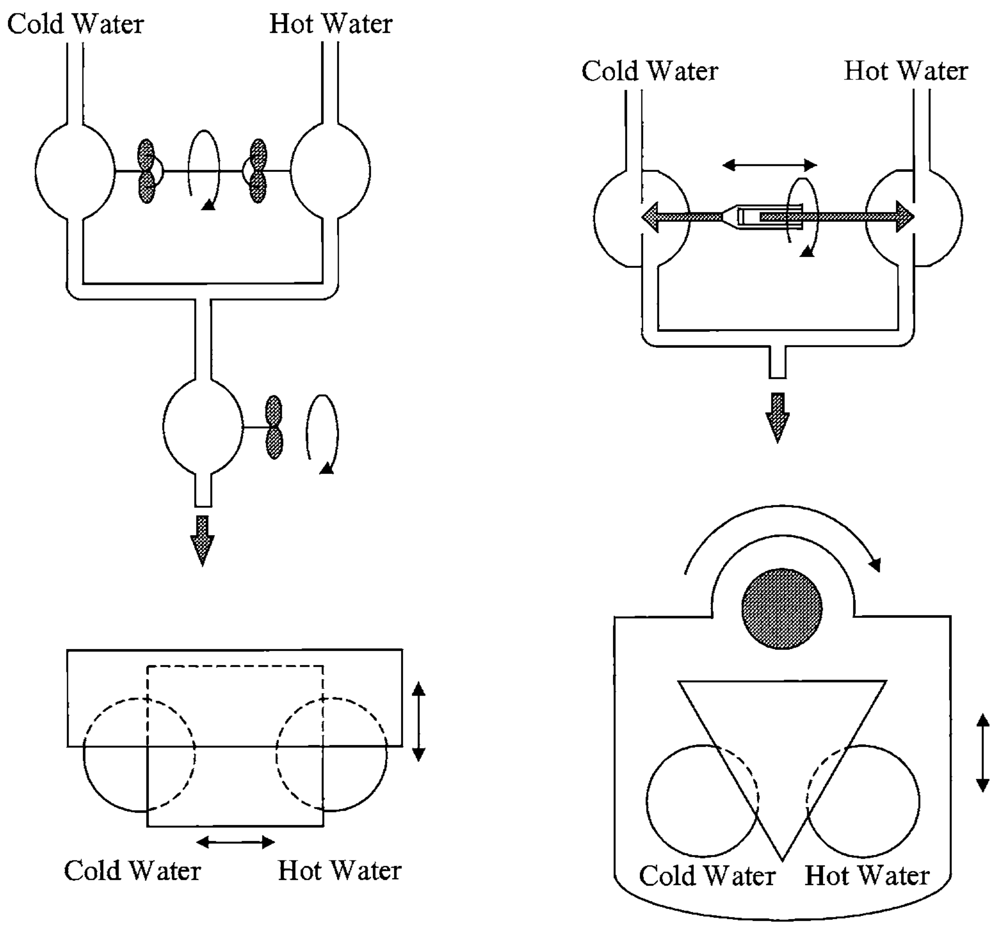


FIGURE 6-6. VARIOUS UNCOUPLED FAUCET DESIGNS [SUH, 2001]

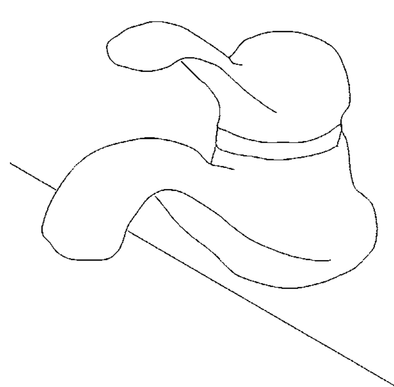


FIGURE 6-7. A MOST POPULAR UNCOUPLED FAUCET DESIGN

6.3 Manufacturing System Design Decomposition

The motivation of developing the Manufacturing System Design Decomposition (MSDD) is the desire to develop an approach to achieve four objectives [Cochran et al. 2000a] in manufacturing system design. These four objectives are:

2) Clearly separate objectives from the means of achievements

3) Relate low-level activities and decisions to high-level goals and requirements

4) Understand the interrelationships among the different elements of a system design

5) Effectively communicate this information across the organization

To achieve these objectives, Axiomatic Design theory is adopted and variety of sources are consulted to generate adequate functional requirements and design parameters. Some of the sources used are: systems engineering literature, Toyota Production System (lean manufacturing) related literature, manufacturing system design literature, industrial engineering literature, and industrial projects in a variety of fields including automotive, aerospace, consumer goods, electronics, and food processing. It was aimed to develop the MSDD general enough to be applicable to repetitive and discrete part manufacturing systems in a wide range of industries.

6.3.1 The Use of Axiomatic Design

As is previously indicated, the fundamental design concept of Axiomatic Design theory and its design methodology are adopted in the development of the MSDD. The design processes of Axiomatic Design start from the identification of customer attributes (CAs) and the conversion of these CAs into a set of functional requirements (FRs). A minimum set of FRs that completely cover all desired function of the design should be developed and these FRs become the highest-level FRs. Then corresponding design parameters (DPs) are identified with guidance from two design axioms. After the design parameters are identified, the high-level FRs are further decomposed into sub-FRs while following the zigzagging principle, if necessary. The design processes used in the development of the MSDD is shown in Figure 6-8.

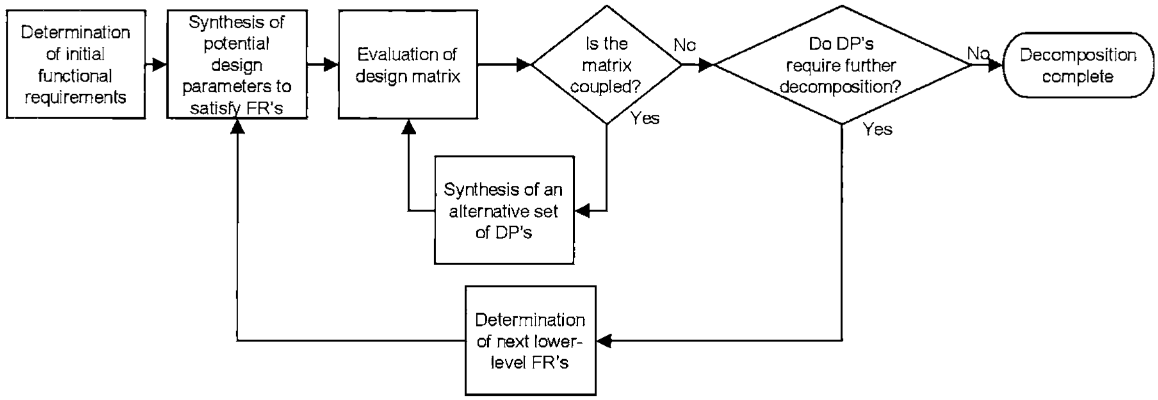


FIGURE 6-8. THE DECOMPOSITION PROCESS USED FOR THE DEVELOPMENT OF THE MSDD USING AXIOMATIC DESIGN [ADAPTED FROM COCHRAN ET AL. 2000A]

During this design process, the formulation of FRs and the selection of DPs are solely a product of creativity of designers. Therefore, to avoid the ambiguity, high level FRs and DPs should be clearly stated before further decomposition. This was particularly important in the development of the MSDD because of the broad context of manufacturing system design. The decomposition process used in the development of the MSDD is described in more details by [Cochran et al. 2000a] and [Linck 2001].

This decomposition process is a simpler version of more precise and rigorous decomposition process proposed by Tate [1999]. Tate [1999] examined the decomposition process and proposed guidelines to aid designers. Compared to his decomposition processes, for example, the decomposition processes used in the MSDD development loosely consider the existence of design constraints. His roadmap of activities in decomposition and the design process roadmap of Tate and Nordlund [1996, 1998] are shown in Figure 6-9 and Figure 6-10 respectively. For detailed discussion on the decomposition processes, please refer to [Tate and Nordlund 1996], [Tate and Nordlund 1998], and [Tate 1999].

The benefits of using the Axiomatic Design instead of other design tools such as Quality Function Deployment (QFD) or IDEF0 are two-fold. First, Axiomatic Design stresses on the separation of the objectives (FRs) from the means (DPs). Second, it provides a structured decomposition process with decision criteria of two design axioms. Combined together, these characteristics of the Axiomatic Design make it well suited to achieve the four objectives of the MSDD [Cochran et al. 2000a]. QFD is a good method to capture customer needs and convert them to engineering requirements but lacks effective guidance on decomposition process. IDEF0 is not very effective to separate the objectives from the means to achieve them. More discussion on different design methodologies can be found in [Tate and Nordlund 1995], [Tate and Nordlund 1996], and [Tate 1999].

The decomposition process resulted in the MSDD with six different main areas of quality, problem solving, predictable outputs, delay reduction, operational costs, and investments (Figure 6-11). The general structure of the MSDD is discussed in the following section as well as the details of each area.

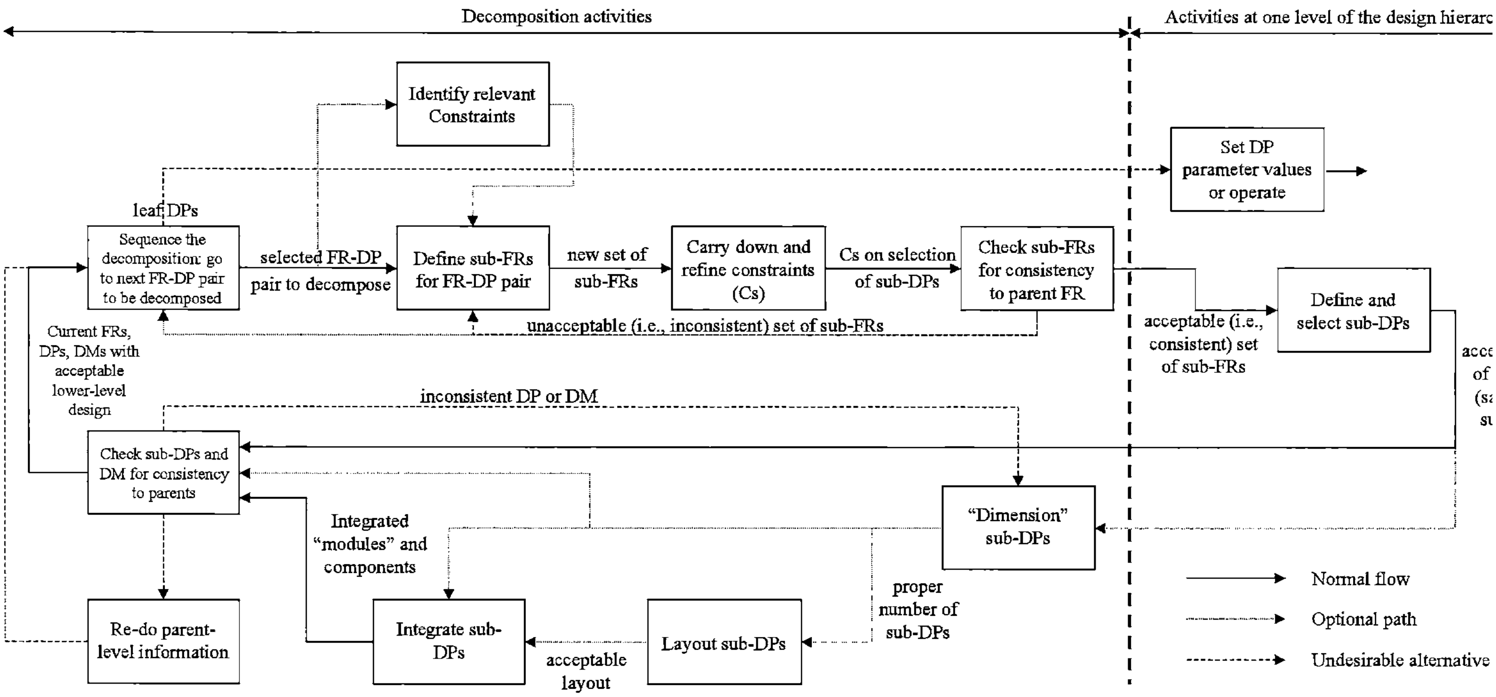


FIGURE 6-9. ROADMAP OF ACTIVITIES IN DECOMPOSITION
[TATE 1999]

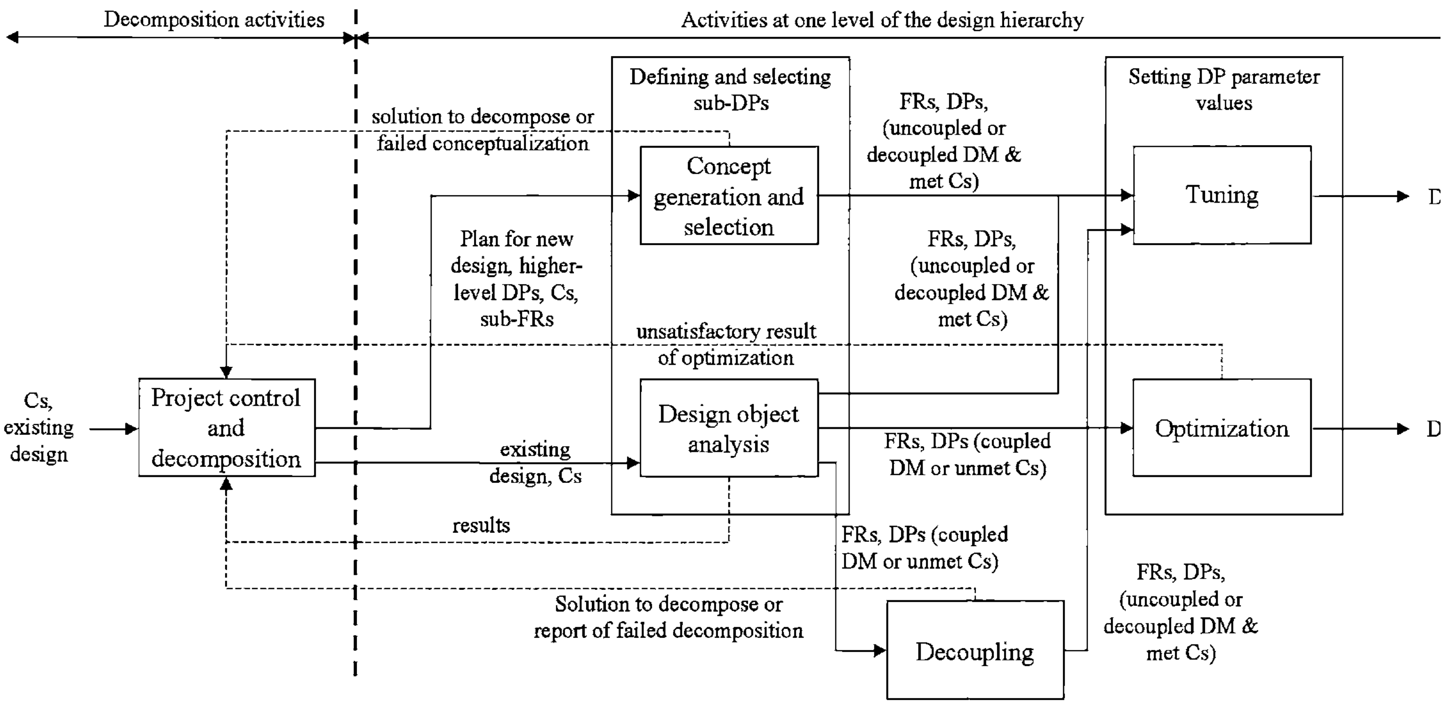


FIGURE 6-10. THE DESIGN PROCESS ROADMAP [ADAPTED FROM [TATE AND NORDLUND (1996), TATE AND NORDLUND (1998)]]

6.3.2 General Structure of the MSDD

A complete version of the Manufacturing System Design Decomposition (MSDD) is available in Appendix A. As is previously described, the MSDD consists of six major branches and the general structure of the MSDD is shown in Figure 6-11.

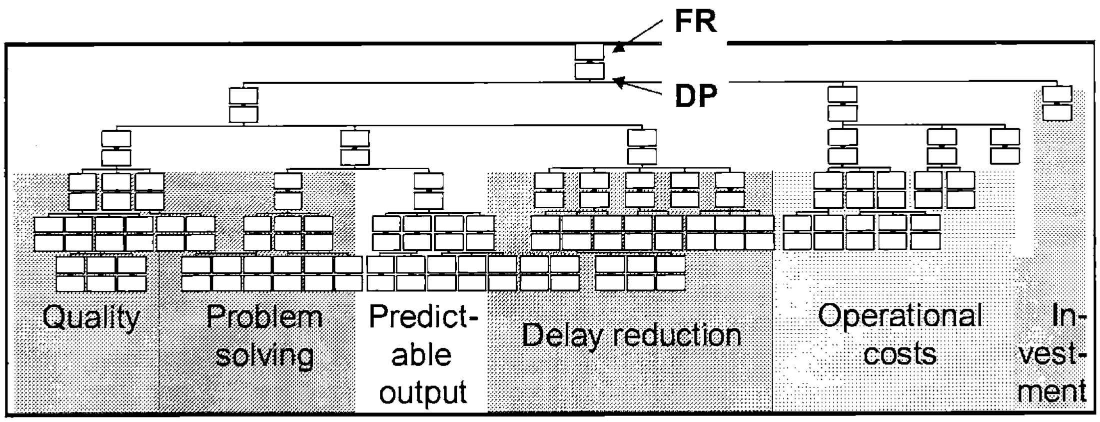


FIGURE 6-11. THE GENERAL STRUCTURE OF THE MANUFACTURING SYSTEM DESIGN DECOMPOSITION (MSDD)

The Manufacturing System Design Decomposition (MSDD) starts from the functional requirement (FR) of “maximize long-term return on investment (ROI),” which is very general managerial objective of a company. To avoid the shortcomings of the ROI [Johnson and Kaplan 1987], the term of ‘long-term’ was chosen. It stresses the importance of long-term improvements rather than short-term profit-seeking thinking. For example, activities to improve customer relationships or to create flexible systems may not contribute to the short-term profit and it is difficult to estimate their benefits in terms of dollar value. However, they are essential to keep the company in the business from a long-term perspective. The corresponding design parameter (DP) is manufacturing system design. This DP implies that the scope of the MSDD is limited to manufacturing and thus, other important functions of an enterprise such as product development and marketing would be excluded during the further decomposition processes. The zigzagging principle of the Axiomatic Design ensures that the characteristics of the lower level FRs and DPs are confined to manufacturing issues.

The first level FR is further decomposed into three sub-FRs of:

FR11: Maximize sales revenue,

FR12: Minimize production costs, and

FR13: Minimize investment over the production system life cycle.

These three sub-FRs are derived from the ROI formula,

$$ROI = \frac{\text{Revenue - Cost}}{\text{Investment}} \quad (6\text{-}4)$$

These FRs are satisfied by the following DPs respectively.

DP11: Production to maximize customer satisfaction,

DP12: Elimination of non-value adding sources of cost, and

DP13: Investment based on a long-term system strategy.

The design matrix that governs the relationship between the FR-DP pairs is as follows:

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} \text{X} & \text{O} & \text{O} \\ \text{X} & \text{X} & \text{O} \\ \text{X} & \text{X} & \text{X} \end{bmatrix} \bullet \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix} \quad (6\text{-}5)$$

The rationale behind the design matrix (6-5) is that if the produced product failed to satisfy the customer, the product would not be sold very well and thus, cause unnecessary costs and investment. Therefore, DP11 affects FR12 and FR13 as well as FR11. In addition, the elimination of non-value adding sources of cost may require a certain amount of investment. Consequently DP12 affects FR13 along with FR12. It can be argued that DP12 may affect FR11. However, FR11 may be satisfied without eliminating non-value adding sources of cost and thus, DP12 would not affect FR11. With the term of non-value adding sources of cost, it is implicitly assumed that the eliminating cost drivers does not affect producing customer-satisfactory products.

As is described above, production to maximize customer satisfaction (DP11) is chosen as a design parameter to achieve the FR11, maximize sales revenue. Having the DP11 in mind, FR11 is further decomposed into three sub-FRs

FR111: Manufacture products to target design specifications

FR112: Deliver products on time

FR113: Meet customer expected lead time

The decomposition is based on the core manufacturing performances that can greatly contribute to the customer satisfaction – quality and delivery (on-time delivery and minimal delivery lead time). The following DPs are chosen to satisfy each FRs.

DP111: Production processes with minimal variation from the target

DP112: Throughput time variation reduction

DP113: Mean throughput time reduction

The design matrix that describes the relationship between FRs and DPs are as follows:

$$\begin{Bmatrix} FR111 \\ FR112 \\ FR113 \end{Bmatrix} = \begin{bmatrix} \mathrm{X} & \mathrm{O} & \mathrm{O} \\ \mathrm{X} & \mathrm{X} & \mathrm{O} \\ \mathrm{X} & \mathrm{X} & \mathrm{X} \end{bmatrix} \bullet \begin{Bmatrix} DP111 \\ DP112 \\ DP113 \end{Bmatrix} \tag{6-6}$$

The design matrix shows that quality should be ensured first to deliver products on time and meet the customer expected lead time. Quality problems cause production disruptions and thus affect the stability of the system performance as well as the lead time.

DP111 is focusing on increasing process capabilities rather than relying on final inspection to avoid the shipment of poor quality products. From a manufacturing perspective, a quality product is a product that is produced to meet all design specifications. Therefore, the quality branch represented by the FR111 and the DP111 provides the FRs and DPs to ensure the product conformance to the design specifications at the first time. In other words, quality should be ensured by perfect first-time processing, not by inspection or re-work. The quality branch suggests the FRs and DPs to ensure perfect first-time processing.

DP112 is about reducing the time variation in throughput time in order to ensure on-time delivery to the customer. There can be numerous sources of time variation in throughput time. For example, unpredictable machine downtime or unavailable component parts can cause the disruption of production, which affects the overall throughput time. To deliver products on time (FR112) by reducing throughput time variation (DP112), two kinds of system capability are required. One is to respond rapidly to production disruptions (FR-R1) and the other is to minimize the production disruptions themselves (FR-P1). Therefore, FR112 is further decomposed into FR-R1 and FR-P1. A standardized procedure for detecting and responding to production disruptions greatly helps to respond rapidly to production disruptions and thus, it is selected as DP-R1 for FR-R1. To eliminate the production disruptions themselves, it is important to ensure predictable production resources such as people, equipment, and information (DP-P1) in terms of their availability and their performance. The design matrix between these two FR and DP pairs are:

$$\begin{Bmatrix} FR-R1 \\ FR-P1 \end{Bmatrix} = \begin{bmatrix} \text{X} & \text{O} \\ \text{X} & \text{X} \end{bmatrix} \bullet \begin{Bmatrix} DP-R1 \\ DP-P1 \end{Bmatrix} \tag{6-7}$$

Compared to the FR112 and DP112 pair that focuses on eliminating sources of variation, the FR113 and DP113 pair stresses the minimization of the throughput time of which predictability is already ensured by the FR112 and DP112 branch. The short delivery time expected from the customer (FR113) can be met through mean throughput time reduction (DP113). Five different categories of delays are identified and thus, FR113 is further decomposed into five sub-FRs while keeping the throughput time reduction (DP113) in mind.

Production costs branch (FR12) mainly deals with the elimination of the non-value adding sources of costs (DP12). This is quite a different approach from the traditional cost-based approach since the MSDD shows that the customer satisfaction through the quality and the delivery should come first than the cost. The underlying thought is that when the FR11 is satisfied by perfect quality, immediate problem identification and solving, predictable outputs from the production resources, and minimum throughput time, operation costs are already reduced as a result of this achievement. For example, no more material and manpower are wasted to produce scrapped parts since quality is ensured. Expensive scheduling software and the manpower to support it will not be necessary due to the simple material flow. In other words, the wastes hided in the inefficient system structure are already eliminated by achieving the FR11. Therefore, the FR12 branch deals with what left such as efficient use of direct and indirect labor, and facility cost (plant wide energy cost, etc.).

As for the investment area, the MSDD does not further decompose the FR13 minimize investment over production life cycles and DP13 investment based on a long-term strategy. This is because the investment decision should be considered after satisfying all previous FRs in the customer satisfaction branch and the operational cost reduction branch. If the project satisfied all those FRs before the investment decision, there would be less room for investment decision and the investment decision would become more or less obvious. In addition, the investment decision is significantly affected by the enterprise strategy since once the investment is made, the enterprise should live with the investment made for a relatively long time. Therefore, investment decision can be too company-specific to be incorporated into the general MSDD. From these reasons, the MSDD proposes to consider the investment from the long-term perspective and does not propose detailed decomposition. For possible further decomposition of the investment branch of the MSDD, please refer to the diploma thesis of Szentivanyi [2002].

Upper levels of the MSDD are summarized in Figure 6-12. As is previously stated, the MSDD considers customer satisfaction as a prerequisite for a successful manufacturing system design over operational costs and investment. In other words, maximizing customer satisfaction determines the basis for minimizing operational costs and investment. Since operational costs and investment greatly vary depending on customer satisfaction through quality and delivery, setting solutions for minimum operational costs and investment is not very meaningful. This dependency is dictated in the design matrices as shown earlier.

In this sense, the MSDD provides a desirable sequence of design implementation in manufacturing system design. According to the dependencies of each branch, quality should be ensured first, then problem solving, predictable output, and delay reduction should be followed. Only after satisfying these four branches, financial target can be met without deteriorating the operational performance of the manufacturing system.

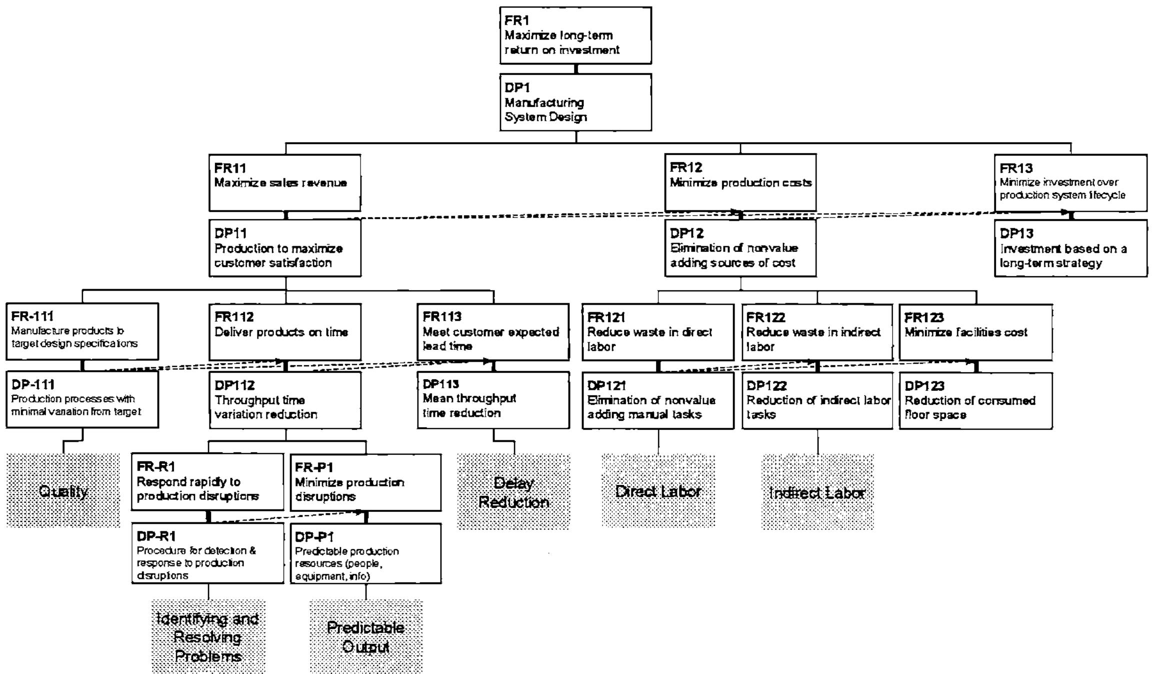


FIGURE 6-12. GENERAL STRUCTURE OF THE MSDD: UPPER LEVELS IN DETAIL

It is noteworthy that problem solving, predictable output, and delay reduction branches are dealing with production interruption problems caused by other timing issues except quality. Quality issues are supposed to be solved with the DPs in the quality branch. In this sense, the MSDD represents the ideal case of manufacturing system design. In existing systems, perfect quality is not guaranteed and the dependencies suggested in the MSDD are not kept. In this situation, sometimes the activities in other branches contribute to the production of quality products. For example, it can be argued that quality can be improved by reducing the delays since faster throughput time can result in faster identification of quality problems and thus, improvement of quality.

Detailed explanation of the decomposition of each branch is provided in the following sections.

6.3.3 Quality

Manufacturing quality is recognized as a norm by today's customers. In today's highly competitive market, no customer will tolerate dealing with defective products. In other words, products are expected to function as they are designed from the very beginning of their usage throughout their entire lifecycle. The quality branch of the MSDD focuses on what manufacturing can do to satisfy customers in terms of product quality. It is to ensure individual manufacturing processes consistently produce products according to the product specifications. A complete decomposition of quality branch is provided in Figure 6-13.

The quality branch consists of three main requirements and they are:

FR-Q1: Operate processes within control limits,

FR-Q2: Center process mean on the target, and

FR-Q3: Reduce variation in process output.

The letter Q indicates the FRs and DPs belong to quality branch. These FRs are chosen based on the traditional quality related research in quality loss function and statistical quality control (SPC) [Taguchi 1989], [Montgomery 1985], [Bothe 1997], [Phadke 1989]. Three FRs stresses first to get the process controllable (FR-Q1) by eliminating assignable causes (DP-Q1), then to get the process mean to the target value (FR-Q2) by adjusting parameter value (DP-Q2), and finally to reduce the output variation caused by process noise (FR-Q3) by reducing the production noise (DP-Q3).

The design matrix of these FRs and DPs are as follows:

$$\begin{Bmatrix} FR-\mathrm{Q1} \\ FR-\mathrm{Q2} \\ FR-\mathrm{Q3} \end{Bmatrix} = \begin{bmatrix} \mathrm{X} & \mathrm{O} & \mathrm{O} \\ \mathrm{X} & \mathrm{X} & \mathrm{O} \\ \mathrm{X} & \mathrm{X} & \mathrm{X} \end{bmatrix} \bullet \begin{Bmatrix} DP-\mathrm{Q1} \\ DP-\mathrm{Q2} \\ DP-\mathrm{Q3} \end{Bmatrix} \qquad (6\text{-}8)$$

The design matrix is decoupled and it shows that the process should be first controllable by eliminating assignable causes since the existence of assignable causes affects other FRs. In some cases, it may be difficult to adjust processes without affecting their robustness to external noises, which may lead to coupling between FR and DP-Q2 and Q3. It is then necessary to determine process parameters that simultaneously shift process means and reduce variation [Arinez 2000].

The FR-Q1 is further decomposed into four sub-FRs and their corresponding DPs are selected to keep the independence axiom of the Axiomatic Design. The four sub-FRs are about equipment (FR-Q11), operators (FR-Q12), process plan (FR-Q13), and the incoming materials (FR-Q14). It should be ensured that equipment is capable of producing to target specifications by efforts such as failure mode and effect analysis (FMEA) (DP-Q1) to analyze and correct machine assignable causes. Operators must be properly trained (DP-Q121) to have knowledge required for their tasks (FR-Q121) and their consistent performance (FR-Q122) should be supported by standard work method (DP-Q122). Researchers such as Monden [1998] stress the importance of the training by calling it as “a key to implementing a successful system.” In addition, their mistakes should not be translated to defective parts (FR-Q123) by mistake proof devices (Poka-Yoke) (DP-Q123). Hirano [1988] discusses the use of the poka-yoke devices in detail. Processes should be designed from the beginning (DP-Q13) to ensure effective conversion of raw material to planned products and thus eliminate the method assignable causes (FR-Q13). Finally, the incoming materials to the process should have perfect quality (FR-Q14) through quality insurance program with the material suppliers (DP-Q14).

FR-Q2 does not need to be further decomposed considering the generality kept in the MSDD. However, FR-Q3 needs to be further decomposed into FR-Q31 (reduce noise in process inputs) and FR-Q32 (reduce impact of input noise on process outputs). These two FRs focus on eliminating the noise itself (FR-Q31) and design the process to be robust to the noise (FR-Q32). The corresponding DPs are DP-Q31 (conversion of common causes into assignable causes) and DP-Q32 (robust process design).

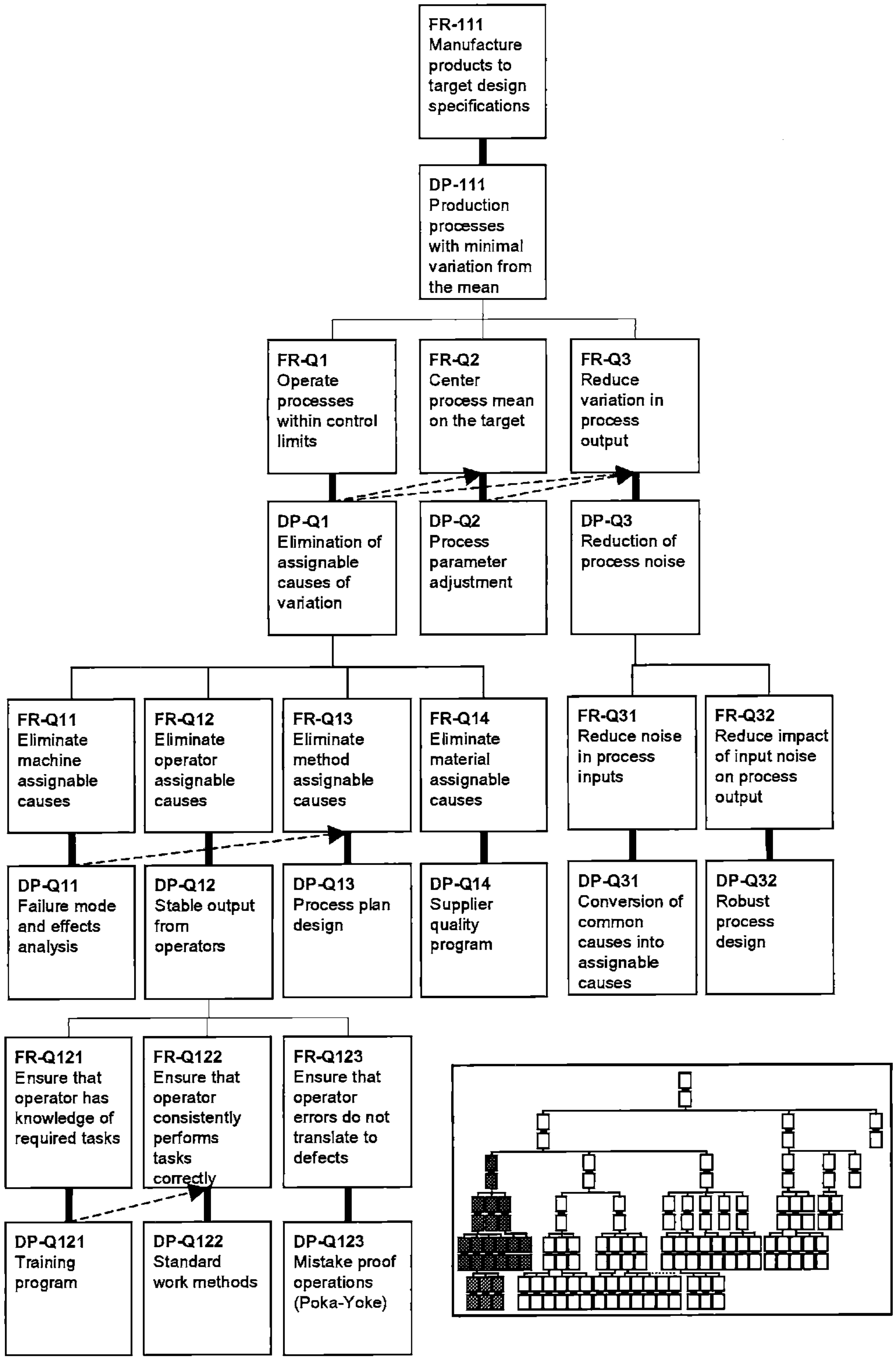


FIGURE 6-13. QUALITY BRANCH OF THE MSDD.

6.3.4 Identifying and Resolving Problems

Identifying and resolving problems branch is one of two branches to reduce the variation of throughput time. Since identifying and resolving production problems affect predictable output of the system, this branch comes before the predictable output branch of the MSDD. The main objective of this branch is to design a manufacturing system to be quick at finding unplanned production disruptions and correcting them. The examples of unplanned production disruptions may be machine down, material shortage, and mistakes from operators affecting production timing. The unplanned disruptions lead to a loss in system availability. Quality problems, though they are disruptive, are not included in the production disruptions since they have been addressed in the quality branch. A complete decomposition of the identifying and resolving problems branch is presented in Figure 6-14. The letter 'R' after the FRs and DPs in this branch stands for responding to disruptions.

The identifying and resolving problems branch starts with the FR-R1 (respond rapidly to production disruptions) and the DP-R1 (procedure for detection and response to production disruptions). Three sub-FRs are recognized from the decomposition process. They are: to rapidly recognize production disruptions (FR-R11), then to communicate those recognized problems to the right people (FR-R12), and finally to solve them as quickly as possible (FR-R13).

To rapidly recognize production disruptions, it is more effective to organize the system itself to support the operators to recognize the problems rather than assigning a special task force to watch and investigate them. Therefore, subsystem configuration to enable operator's detection of disruptions is chosen as DP-R11. The underlying belief of the DP-R11 is that system operators are the ultimate cores to recognize and identify problems, even though technology can be a great help to deal with the disruptions through instant feedback about the state of the manufacturing system. The sub-FRs and sub-DPs of the FR-R11 reflect this idea, and describe 'where, when, and what' aspects of the disruptions and how to recognize those aspects. Again, the idea is that the design of the work tasks and systems should be integrated with the human being inside of the system who performs the tasks in order to achieve fast recognition of the problems.

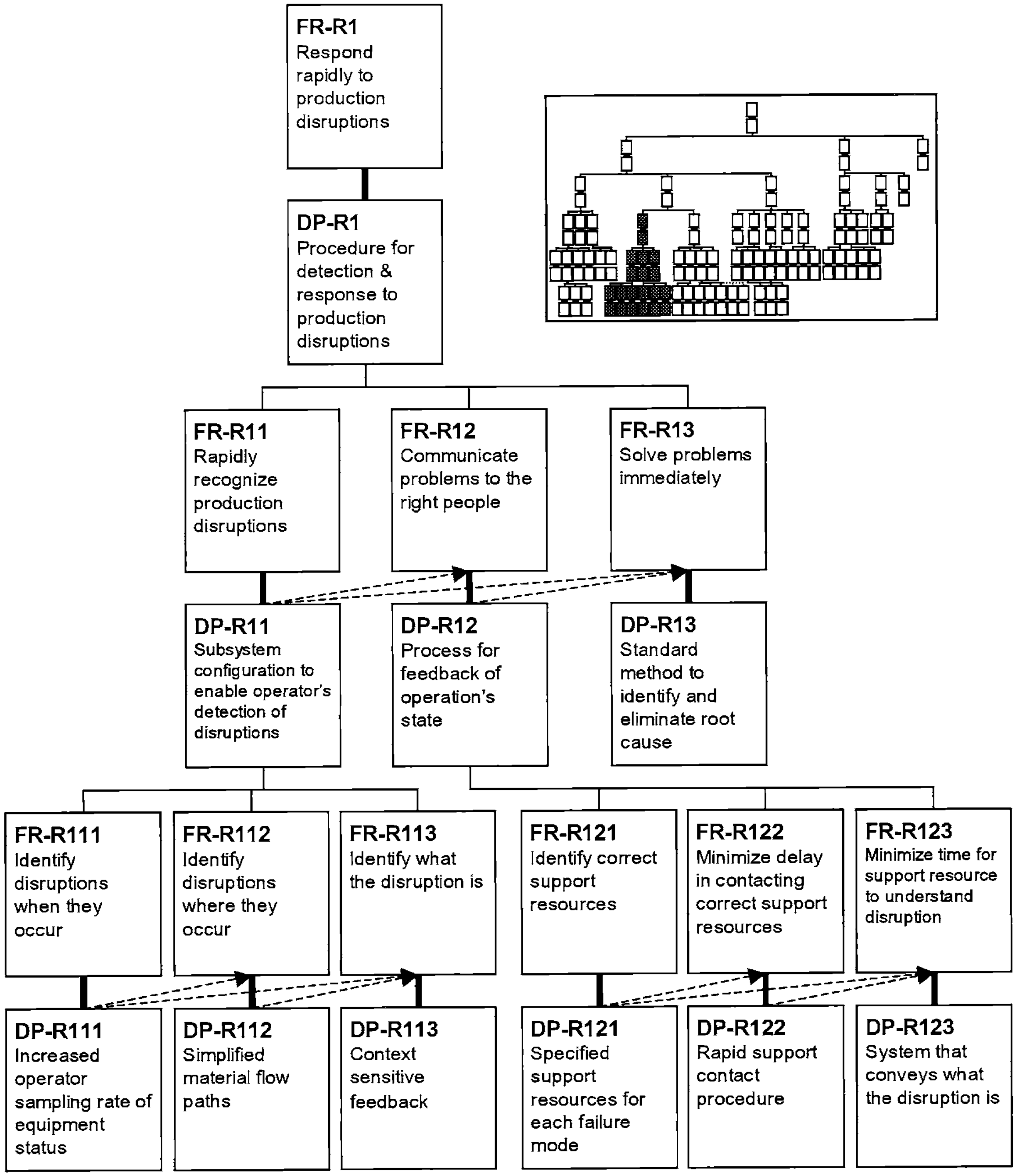


FIGURE 6-14. IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD.

To solve the disruptions immediately identified according to the FR-R11 branch, the disruption information should be transmitted to the right people. The DP-R12 (process for feedback of operation's state) is selected as a solution, stressing the importance of standard communication channels among the constituents of the manufacturing system.

To have the standardized communication channels, specified support resources should be assigned to each failure mode (FR and DP-R121) and contacting the right support resources should be quick (FR and DP-R122). Then, to minimize the time for problem analysis, the content of disruptions should be transmitted along with the disruption report (FR and DP-R123). Eventually, the root causes of the disruptions should be immediately eliminated by following well-defined and standardized procedures.

6.3.5 Predictable Output

Once the production disruptions can be quickly identified and solved, the next step is to eliminate the disruptions themselves. The predictable output branch focuses on minimizing production disruptions (FR-P1) through predictable production resources such as people, equipment, and information (DP-P1). Four sub-FRs are recognized in the area of information (FR-P11), equipment (FR-P12), operators (FR-P13), and materials (FR-P14). A complete version of the decomposition of the predictable output branch is shown in Figure 6-15. The letter 'P' after the FRs and DPs in the predictable output branch indicates 'predictable output'.

Figure 6-15 highlights the importance of the capable and reliable information system (DP-P11) to ensure the availability of relevant production information (FR-P11). The DP-P11 affects all other FRs in the predictable output branch and thus, should be implemented prior to the other DPs in the branch.

Predictable equipment output is ensured (FR-P12) by maintenance of equipment reliability (DP-P12). Therefore, one of the two sub-FRs deals with securing easily serviceable equipment (FR and DP-P121) and the other stresses regular preventive maintenance of the equipment (FR and DP-P122). In other words, after implementing easily serviceable equipment in the manufacturing system, regular preventive maintenance programs should follow to service the equipment. Further details on the equipment maintenance are well described in the total preventive/productive maintenance (TPM) literature [Nakajima 1989].

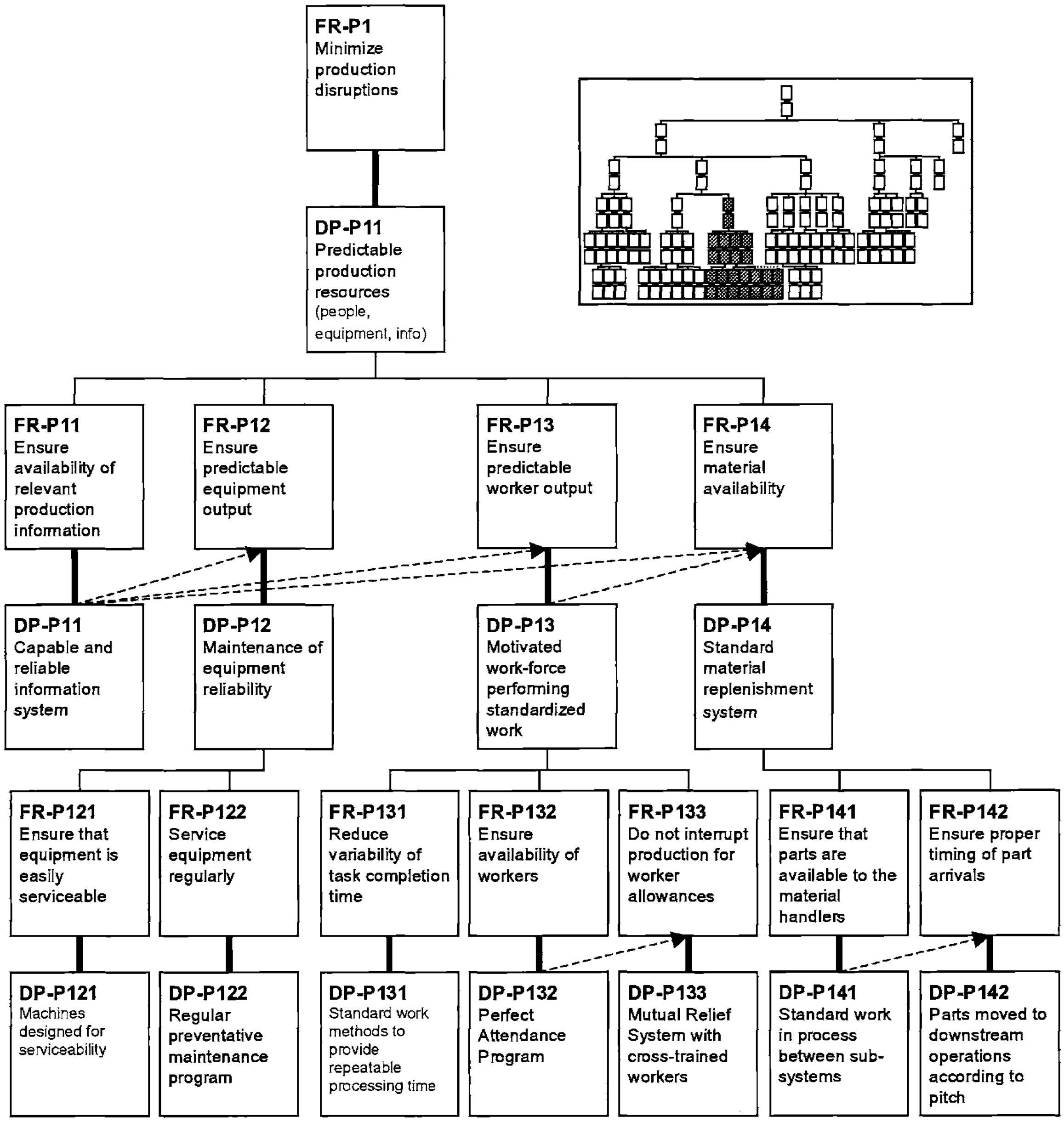


FIGURE 6-15. PREDICTABLE OUTPUT BRANCH OF THE MSDD.

To ensure predictable output from the operators (FR-P13), two factors are important. First, the operators should be motivated to perform their work tasks consistently. They should be well aware of the consequences of their abnormal work completion and should be willing to avoid problems that might be caused by the inconsistency of their work completion time. In addition, this motivation should be systematically supported in their working environment by means of standardized works. Three sub-FRs are recognized for the FR-P13 and they are: reducing variability of task completion time (FR-P131), ensuring worker availability (FR-P132), and not interrupting production for worker allowances (FR-P133). Variation in the task completion time is minimized through defining standardized work methods (DP-P131). The attendance program to draw the perfect attendance from the workers (DP-P132) should be implemented to ensure the worker availability when the production tasks need to be done (FR-P132). Mutual relief program (DP-P133) enables avoiding production disruptions due to worker allowances. Detailed discussion on the design of work systems in terms of ergonomics and psychology is available in [Grote et al. 2000].

There can be many methods to ensure the material availability for predictable output. For example, a manufacturing system can increase its WIP (work-in-process) level to damp any variation in material supply and thus to ensure the material availability. In the MSDD, standard material replenishment system (DP-P14) is chosen as a DP for the FR-P14. There can be two cases when the material is not available. The first is when the upstream production is not finished and thus, material handlers cannot deliver parts to the downstream operators due to the lack of parts. The other case is when the incoming material is not arriving at the right timing. In this sense, FR-P14 can be further decomposed into two sub-FRs. First, the parts should be available when they are demanded by the material handlers (FR-P141) and the parts should be arrived at the production stations at the right timing (FR-P142). As corresponding DPs, standard work in process between sub-systems (DP-P141) and parts moved to downstream operations according to pitch (DP-P142) are selected respectively. Standard work in process (SWIP) between subsystems serves as a buffer against production uncertainties and transportation delays. The emphasis is on keeping defined levels of inventory between processes instead of having uncontrolled levels of inventory. The DP-P142 describes a synchronous material replenishment system in which material handlers regularly replenish the consumed materials following a defined route at defined time. However, low volume and high variety manufacturing may pursue different strategy from keeping SWIP between sub-systems since it may not be feasible to keep standard number of thousands types of materials between manufacturing processes.

6.3.6 Delay Reduction

The decomposition process of the delay reduction branch is about identifying the types of the delays in manufacturing systems and finding possible ways to eliminate the root causes of them. A delay is defined as time that a part spends in the manufacturing system when no value is added to the part from a customer perspective. Therefore, all time that a part spends in the manufacturing system except when they are processed is delay. In the MSDD, five distinctive types of delays are identified and they are: lot delay (FR-T1), process delay (FR-T2), run size delay (FR-T3), transportation delay (FR-T4), and systematic operational delay (FR-T5). The complete delay reduction branch is shown in Figure 6-16. The dependencies between the delays are shown with arrows.

Lot delay occurs when a plural number of parts are transported between operations at a time. Since a plural number of parts are transported, parts that finished their processing earlier than the others should wait for the other parts to be processed. In other words, in case of a lot size greater than one, parts accumulate in a lot, waiting for being transported. Therefore, to reduce lot delay, transfer batch size should be reduced, ultimately, to one (single-piece-flow) (DP-T1). Reduction of transfer batch size (DP-T1) affects other FRs such as FR-T2 (process delay) and FR-T4 (transportation delay). For example, parts transfer frequency affects the arrival rate of parts and if the arrival rate of parts is faster than the service rate of the downstream process, parts are accumulated in front of the process and cause process delay. Parts transfer with a large lot size, therefore, causes process delay since some of the parts in a lot should wait to be processed while the first few parts are processed. In addition, smaller transfer batch size means more frequent part transfers, which may increase transportation delay.

Production delay is a result of faster part arrival rate than part service rate. In other words, if more parts arrive at a process than the instant capacity of the process, some parts need to wait for their turns in front of the process. This time delay is production delay. Therefore, assuming the long-term average part arrival rate is equal to the average service rate of a process, process delays occur only for short time intervals when the arrival rate is larger than the service rate. Otherwise, an infinite number of parts would accumulate in front of the process. The production delay can be minimized by pacing all processes according to a pitch that is sometimes called as takt time. Giving a periodicity into the operation of manufacturing system smoothens the material flow and solves the process delay problems. This is often called as balancing the system [Monden 1998], [Hopp and Spearman 1996].

Pacing all manufacturing operations according to takt time significantly affects the design and the operation of the manufacturing system [Linck and Cochran 1999]. To make all manufacturing operations pace together according to takt time, takt time should be defined first (FR and DP-T21), subsystem should be designed to meet the takt time (FR and DP-T22), and the parts transportation system should be designed to operate according to the takt time (FR and DP-T23). Monden [1998] and Mierzejewska et al. [2000] discuss the takt time calculation in detail. Since factors such as machine down time, setup time, and worker allowances should be considered in the takt time calculation, it is somewhat complicated to get the right number for the pitch that all manufacturing operations can follow.

When processing times vary significantly depending on the types of products, small run size may be required to ensure the balancing within the manufacturing system. Therefore, DP-T2 (production designed for the takt time) may affect FR-T3 (reduce run size delay). In addition, balanced production requires proper timing of material deliveries, which may affect FR-T4 (reduce transportation delay) by increasing the frequency of transportation.

Run size delay (FR-T3) occurs when a plural number of part types are produced but the sequence of production does not match the sequence of the customer demand. Here, run size is defined as the number of products in one type produced before changing over to a different product type. Run size delay is typically a result of efforts to save setup changeover time since setup changeover time usually leads to a loss of available production time. Run size delay usually leads to increased inventory to cover the customer demand while waiting for the next run of demanded part production.

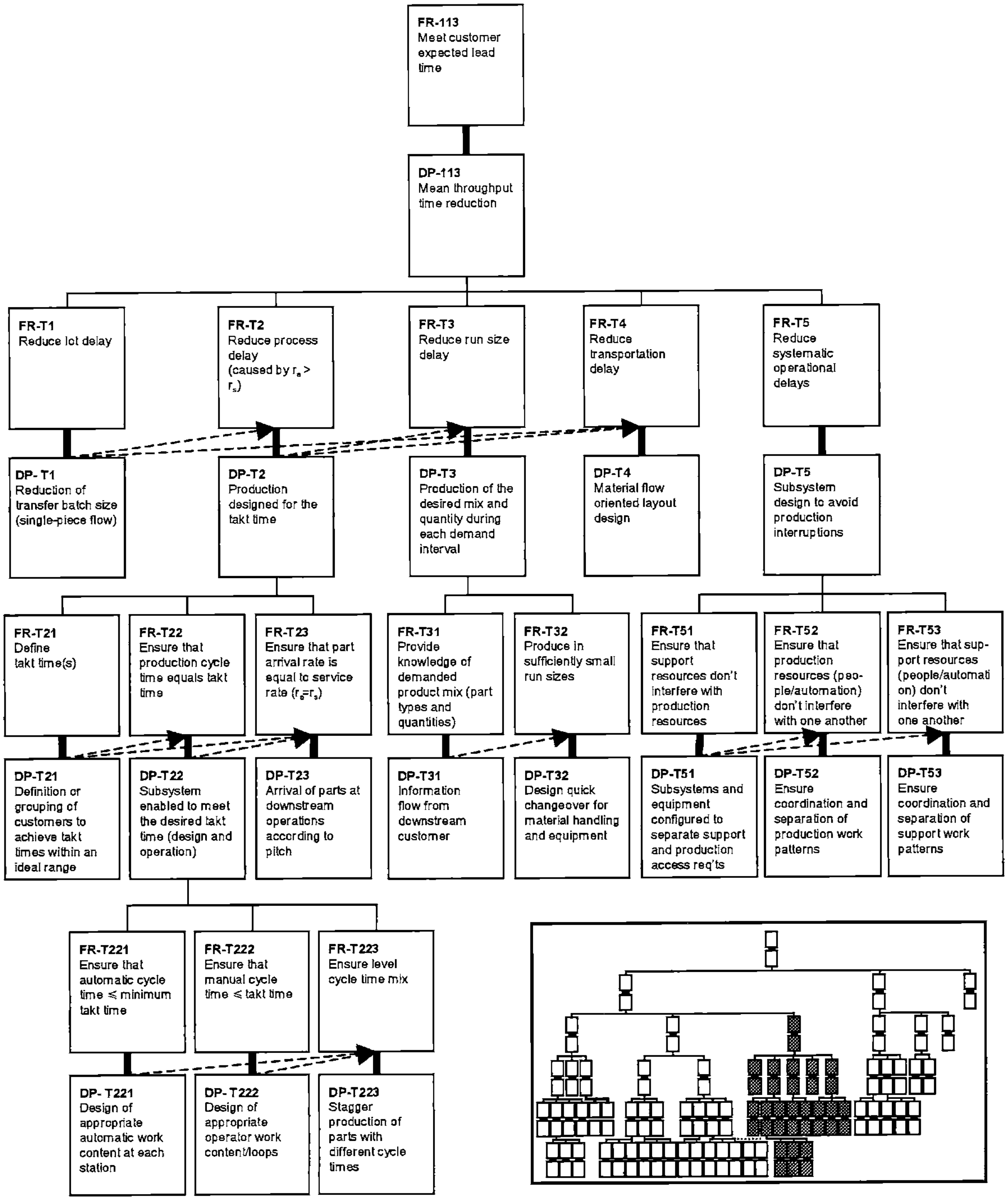


FIGURE 6-16. DELAY REDUCTION BRANCH OF THE MSDD.

To minimize run size delay, production mix sequence should be matched to customer demand sequence during each demand interval (DP-T13). The demand interval is the time interval between deliveries to the customer, which may vary significantly depending on many factors such as transportation cost. To ensure the production of the desired mix and quantity during each demand interval (DP-T3), demanded product mix information (part types and quantities) should be provided to the production (FR-T31) and the run size should be small enough to catch up the required mix production (FR-T32). Information flow from downstream customer (DP-T31), and quick changeover of material handling and equipment (DP-T32) are selected as corresponding DPs respectively. DP-T31 refers to pull system in lean manufacturing literature and DP-T32 reflects the ideas of SMED (single-minute-exchange of die) proposed by Shingo [1985, 1989].

Transportation delay (FR-T4) is defined as the total time from the moment when a full transfer batch of parts is ready to be transported until these parts arrive at the downstream operation and are ready for processing [Cochran et al. 2000a]. Transportation delay includes the time that parts spend for waiting to be transported, the time in transit, and the time for loading and unloading of the parts. To minimize transportation delay, it is best to eliminate the need for transportation itself. Therefore, the material flow oriented layout (DP-T4) is chosen as the solution for transportation delay. Material flow oriented layout indicates that parts should be transported not for non-value adding activities such as temporary storage, but for value-adding activities such as next processing. By arranging equipment according to product flow, transportation distance can be minimized. In this sense, a cell is a good example of material flow oriented layout since the downstream processing machine is located right next to the upstream processing equipment, which minimizes the transportation distance.

Systematic operational delays (FR-T5) are caused by the interference of production resources with each other, which leads to a loss of available production time. The MSDD distinguishes the production resources (operators, equipment, etc.) that add value to the product and the support resources (material supply, maintenance, chip removal, etc.) that support production activities. To eliminate systematic operational delays, a careful planning of operation and a thorough subsystem design (DP-T5) are required. All support resources should be ensured not to interfere with production resources such as people and automated equipment (FR-T51), and the production resources (FR-T52) and the support resources (FR-T53) should not interfere with one another. Various solutions can exist, but the MSDD chose subsystems and equipment configured to separate the access requirements from support and production resources (DP-T51), coordinated and separated production work patterns (DP-T52), and coordinated and separated support work patterns (DP-T53).

6.3.7 Operational costs

The operational costs branch of the MSDD deal with the efficient use of labor and facility. It is noteworthy that the cost branch is located to the next of quality, identifying and resolving problems, predictable output, and delay reduction branches. The MSDD treats customer satisfaction through quality and delivery as a prerequisite for a successful manufacturing system design. In other words, maximizing customer satisfaction determines the basis for minimizing operational costs as is dictated by the design matrix. With the philosophy embedded in the MSDD, many of the cost drivers are already minimized through the design of efficient manufacturing systems to achieve the objectives of quality and delivery. Therefore, in terms of cost reduction from the manufacturing point of view, engineers only need to focus on minimizing facility costs (FR-123) that are not directly connected to quality and delivery (i.e., energy cost, etc.) and utilizing human resources as efficient as possible without deteriorating the system design for quality and delivery (FR121 and FR122).

For example, Linck [2001] discusses the view of the MSDD to the total cost approach proposed by Son [1991]. As is shown in Figure 6-17, Son categorized the cost drivers into three groups of productivity cost, quality cost, and flexibility cost. Among these three groups of costs, quality cost and flexibility cost are addressed and minimized in the customer satisfaction branch. Among the productivity cost items, labor and floor space items are addressed in the operational cost branch of the MSDD. Some cost drivers are assumed that manufacturing does not have direct control (material), since product design is assumed to be given. The use of computer software is minimized through the design of simple but efficient manufacturing systems through the customer satisfaction branch. Depreciation is a result of accounting customs and investment. Tool and machine issues are not directly addressed.

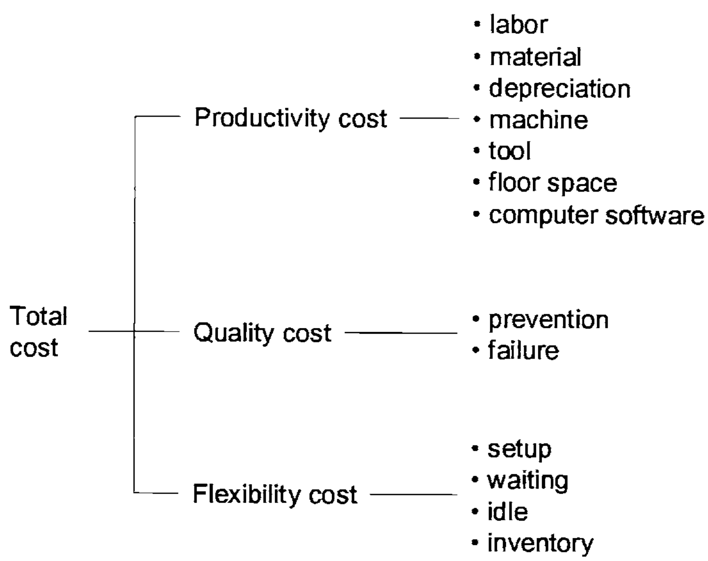


FIGURE 6-17. COST STRUCTURE FOR ADVANCED MANUFACTURING SYSTEMS [SON, 1991]

In the direct labor branch of the MSDD (FR-121), three factors are considered: eliminating operators' waiting for machines (FR-D1), eliminating wasted motion of operators (FR-D2), and eliminating operators' waiting on other operators (FR-D3). Human-machine separation (DP-D1), workstation and work-loop designs (DP-D2), and balanced work-loops (DP-D3) are chosen as corresponding DPs respectively.

In the indirect labor branch (FR-122), effective production management (FR-I1) through self directed work teams (DP-I1) and elimination of information disruption (FR-I2) by visual factory (DP-I2) are addressed to minimize waste in indirect labor.

A complete decomposition of the operational cost branch is provided in Figure 6-18.

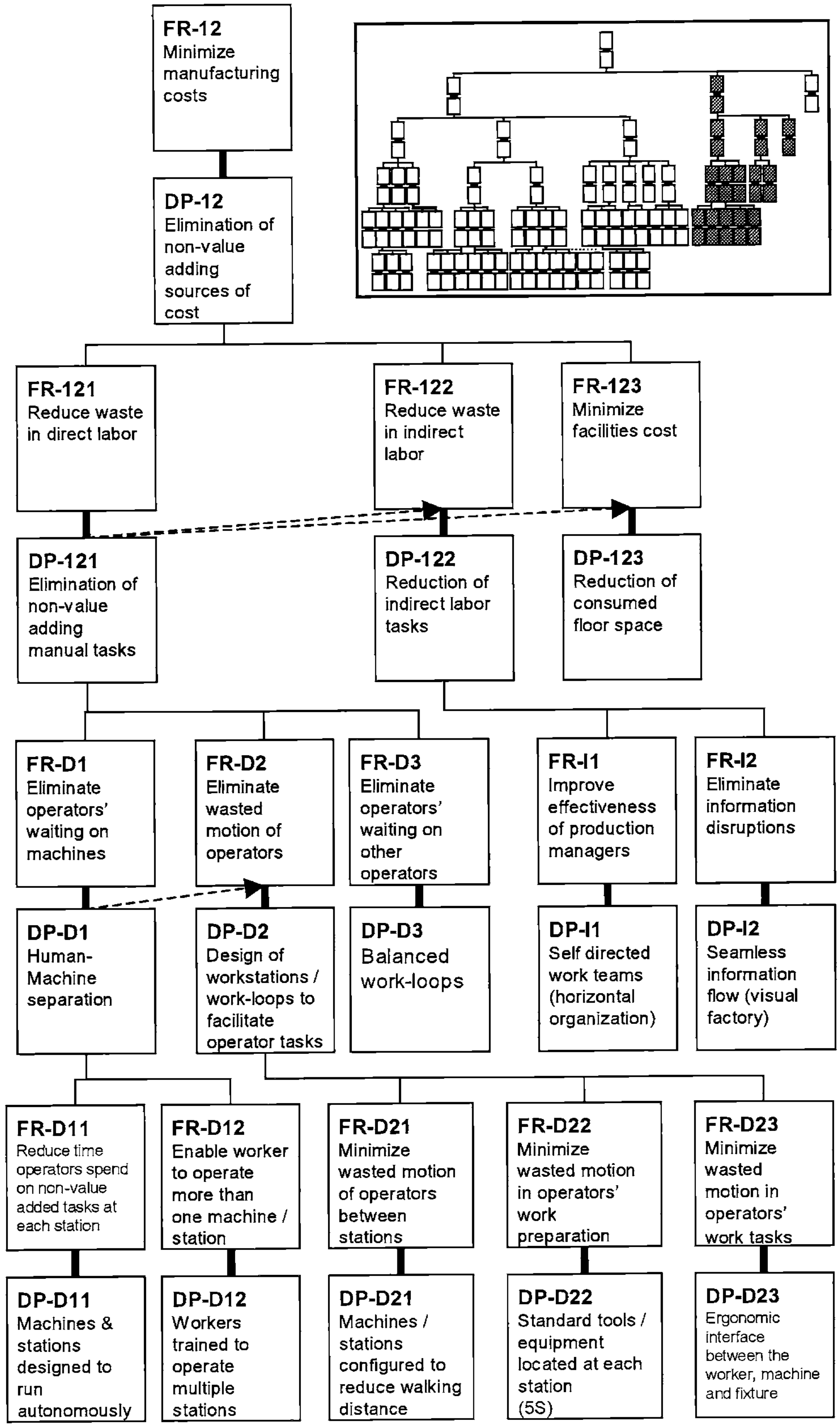


FIGURE 6-18. OPERATIONAL COSTS BRANCH OF THE MSDD.

6.3.8 Investment

As is previously discussed, the MSDD does not decompose the investment branch, mainly because the investment decision is heavily dependent on company specific situation. In addition, the basic idea of the MSDD regarding investment decisions is that the system design should drive the investment decisions. In other words, meeting the FRs of the MSDD in other branches are first considered and then given the solutions, the investment decisions should be made. Therefore, the investment decisions do not drive the system design. This is very different from the traditional approach to design the systems constrained by the budget, which may lead to sub-optimization of the system forced by the budget calculation 'methods' [Cochran et al. 2000b, 2000c]. This is not a right sequence. After identifying the various system design options that satisfy the FRs imposed by the MSDD, the final investment decisions should be made, considering the investment constraint. If the investment constraints cannot be met or modified to accommodate the manufacturing system design options, new designs should be sought to widen the design solution pools.

6.4 Supportive Evidences of the MSDD

The MSDD considers customer satisfaction through quality and delivery as a prerequisite for a successful manufacturing system design. Quality is considered as the first that must be ensured for successful manufacturing system design. Then, delivery aspects of manufacturing system performances are stressed, followed by operational cost and investment. In this chapter, several empirical and theoretical evidences that support the general structure of the MSDD are discussed.

Toyota, as a benchmark of lean manufacturing, has a similar view to successful manufacturing with that of the MSDD. One of the managers in a plant located in Japan developed a decomposition of the roles in plant based on the return on asset (ROA). A schematic view of his decomposition is shown in Figure 6-19. It is noteworthy that the decomposition starts with the ROA (the MSDD starts with the ROI) and sales increase by quality and delivery are addressed first and followed by cost and assets.

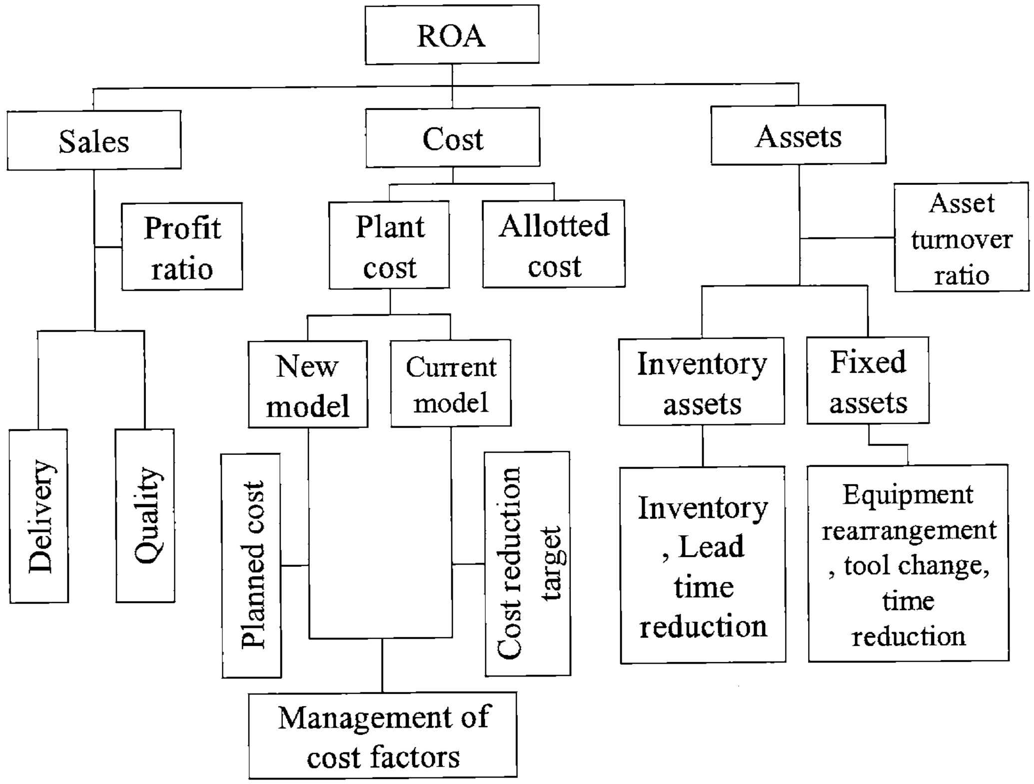


FIGURE 6-19. ROLES OF MANAGEMENT IN PLANT – VALUE MANAGEMENT BY ROA (ADAPTED FROM [TOYOTA 2001])

In addition to the decomposition, the view to the cost within Toyota is interesting. An engineer at Toyota confessed that each plant of Toyota has different costing systems and thus, the unit costs of a car in different plants are not comparable to each other. However, every plant strives to continuously improve its operation and thus overcome the cost target that is planned during the product development with the target costing process. At any rate, it is evident that Toyota has never lost money since the 1950s and this offers a complete review of the traditional manufacturing system design approach driven by traditional cost accounting practices. Some authors address this issue [Cochran et al. 2001b and 2001c], [Cochran et al. 2002], [Johnson 1992, 2001], [Johnson and Kaplan 1987], [Kaplan 1984], [Kaplan and Norton 1992, 1996].

In addition to Toyota's example, it is interesting to see the cost reduction campaign of a Toyota's subsidiary company, Aisin AW. This company tries to cut its cost by 30% in 5 years. Their first motto for this aggressive cost cut target is to maximize customer satisfaction by producing quality products, and delivering them faster than its competitors and on time. Some savings such as floor space saving was seen as a by-product of its efforts to minimize the time to the customers. Typical view of western counterparts on cost reduction that is represented by head count cut could not be found. The only cost items addressed in this cost-cutting activity was plant-level cost drivers such as energy saving and was suggested as a minor activity to follow.

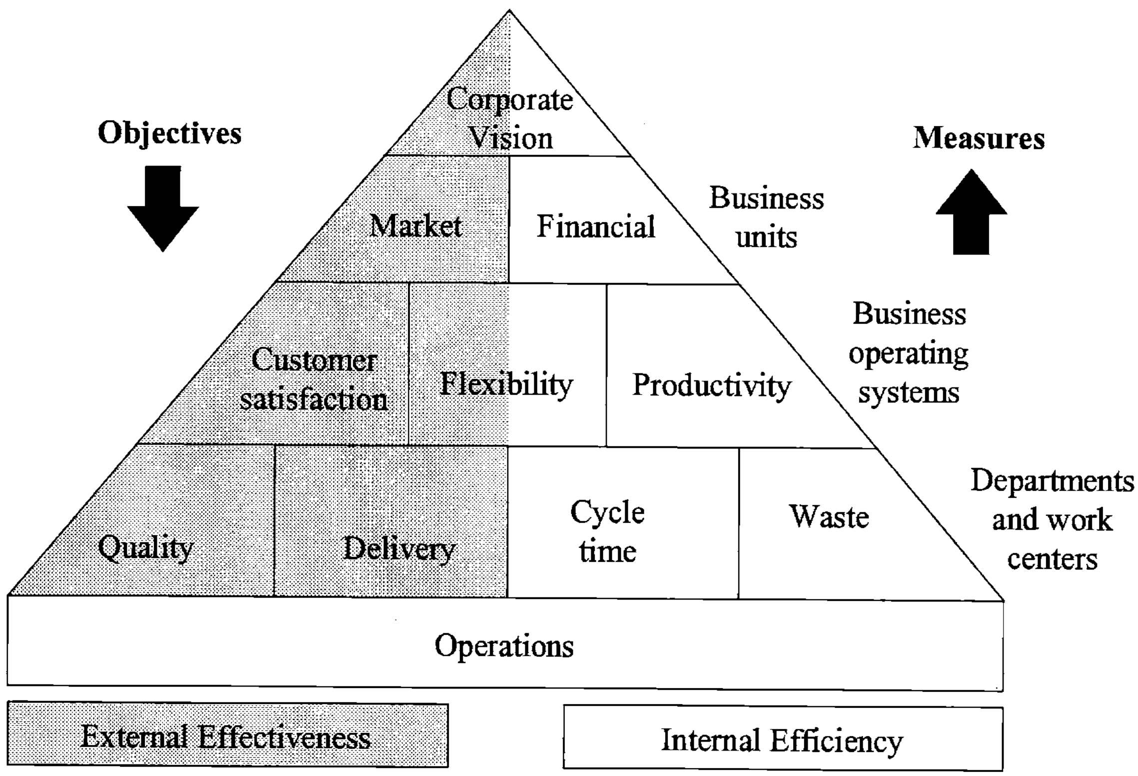


FIGURE 6-20. THE PERFORMANCE PYRAMID (ADAPTED FROM [MCNAIR ET AL. 1990])

In the academia, Ferdow and De Meyer [1990] propose a "sand cone model" for system improvement, which starts with quality, then reliability, and finally efficiency and costs, which is similar to the structure of the MSDD. Filippini et al. [1998] performed an analysis of 45 manufacturing companies in Italy and found that "compatibility between punctuality and economic performance has been found only in the presence of high values of quality consistency and delivery time." Linck [2001] proposes to use the MSDD to evaluate the state of manufacturing systems and presents interesting research results on the relationship between the conformance level to the MSDD and the traditional performance metrics. McNair et al. [1990] propose to use a 'performance pyramid' as is shown in Figure 6-20. They categorized the objectives of an enterprise and the performance measures into external effectiveness and internal efficiency and stressed the importance of quality, delivery, cycle time, and waste.

6.5 Application of the MSDD

The MSDD has successfully served as a platform to link the various disciplines of the enterprise system design to manufacturing system design (Figure 6-21). The linkage between the existing framework for each discipline and the MSDD can be easily found due to the structure of the MSDD that separates the objectives from the means.

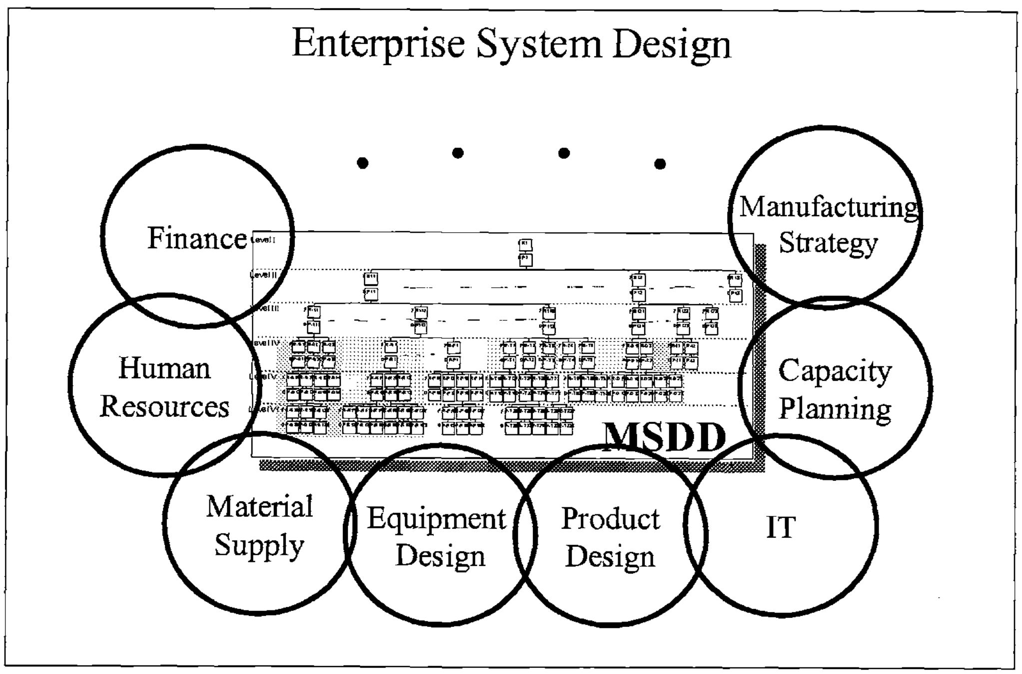


FIGURE 6-21. THE MSDD AND OTHER DISCIPLINES OF THE ENTERPRISE SYSTEM DESIGN

For example, Arinez [2000] developed an equipment design approach using the MSDD as a source to derive equipment design requirements. He proposed four design steps of equipment design: identification of the set of manufacturing system requirements that affect equipment design, transformation of the requirements into views for the various equipment designers with different interests, analysis of requirements, and decomposition of the requirements into equipment design parameters. Duda [2000] proposed a process for linking manufacturing strategy with the MSDD. The process aims to guide the designer from the statement of strategic objectives through trade-off analysis of design alternatives relative to the objectives, to the final evaluation of the relative strength of design alternatives. Cochran et al. [2000d] suggested a process that uses the MSDD for facility design. In this process, the MSDD is combined with a procedural system design approach proposed by Kettner et al. [1984]. The MSDD is used to provide the design objectives, which become the input in the design phases of the procedural approach.

The benefits of using the MSDD come from its clear separation of the objectives from the means and its clear identification of functional dependencies between the objectives and the means. This benefit is sought again in this thesis to link product design with manufacturing system design.

6.6 Top-Down Approaches vs. Bottom-Up Approaches

The MSDD is based on the Axiomatic Design methodology that is a top-down approach. Therefore, the MSDD holds the benefits and detriments of the top-down approach. Much of the discussion in this section is based on the systems engineering literature (i.e., [Blanchard and Fabrycky 1998]).

Design methodologies can be categorized into two groups: top-down approach and bottom-up approach. Top-down approach starts from general requirements for system performance, whereas bottom-up approach starts with a set of known design elements. In the top-down approach, the required system performance is analyzed to identify its functional characteristics and these functional elements to meet the functional requirements are sought. Design is completed by further decomposing the requirements into lower levels of abstraction and finding functional elements to satisfy the requirements. Finally, all functional elements are synthesized to verify their appropriateness. On the other hand, the bottom-up process uses a synthesis to create the system. However, it is unlikely that the functional need is met on the first attempt. Therefore, after measuring the product's performance and its deviation from the requirement, the system elements and their combination are altered for another solution.

Therefore, the design process is iterative and the number of design iterations greatly depends on designer's knowledge, creativity, and experience as well as the complexity of the products [Blanchard and Fabrycky 1998].

The benefits of the top-down approach are many-folds. First, the general application of the framework is possible since the beginning of the top-down approach involves the general requirements of the system. Second, all functional requirements are satisfied by the inherent virtue of design process. Furthermore, a small number of functional elements can represent a series of different physical implementations. However, the feasibility of physical realization is not assured with the top-down approach. Contrastingly, the bottom-up approach ensures the physical realization of design solutions, but the satisfaction of the functional requirements is not guaranteed.

For further discussion on the top-down and bottom-up design approach, please refer to [Blanchard and Fabrycky 1998].

6.7 Chapter Summary

In this chapter, the Manufacturing System Design Decomposition (MSDD) is presented and the rationale behind the decomposition is explained in detail. In addition, a brief introduction of the Axiomatic Design theory is provided since it constitutes a basis of the MSDD development.

The decomposition process of the MSDD starts from the high level business objective of increasing long term return on investment (ROI) and ends with six distinctive branches of quality, identifying and resolving problems, predictable output, delay reduction, operational cost reduction, and investment. Except the investment branch, other branches are further decomposed into specific objectives and corresponding means to achieve them. The decomposition process ends at the level that is specific enough to be applied to manufacturing system design process while keeping general applicability to repetitive, high-volume manufacturing systems.

In addition, empirical and theoretical evidences that support basic ideas of the MSDD are provided. With the help of the well-defined decomposition processes of the Axiomatic Design theory, the MSDD is the result of logical decomposition processes of a business objective based on the knowledge of world-class manufacturing system designs. Therefore, it is natural to see that many authors and practices have similar ideas with those of the MSDD.

7 A METHODOLOGY TO INTEGRATE PRODUCT DEVELOPMENT AND MANUFACTURING SYSTEM DESIGN

7.1 Introduction

The objective of this thesis is to develop a methodology that can be applied to see the effects of product development decisions on manufacturing systems. This methodology will serve for the integration of product development decisions with manufacturing system design decisions by providing a way to see the interactions.

The Oxford Dictionary [1992] defines a methodology as the 'study of systematic methods of scientific research,' used in a particular branch of activity. Tate [1999] distinguishes a methodology from a technique and a philosophy. According to him, strictly speaking, a methodology may lack the precision of a technique, but is a better guide to an action than a philosophy. Whereas a technique enlightens the user how to do something and a philosophy indicates what needs to be done, the methodology contains elements of principles related to both the how and the what. A methodology is, therefore, an explicit way of structuring one's thinking and actions, and showing what steps to take, how those steps are performed, and why those steps should be followed in the suggested order. A methodology may not offer solutions for specific problems, but it can provide a method of assessing the likelihood of success in order to allow an informed decision to be made [Tate 1999].

Therefore, the approach proposed in this thesis is going to be called as a methodology since it provides a way of structuring thinking and steps to enable educated decisions to be made.

7.2 Background Ideas

In this section, the background ideas of the proposed methodology are explained in detail. The methodology proposed in this thesis is provided in section 7.3. This section describes the ideas behind the proposed answers to the first three sub-problems presented in section 3.4.2. The three subproblems are:

1) How can we represent the logic of manufacturing system design?
2) How can we represent product development?
3) What decisions in product development (especially related to product/process design) affect manufacturing system design?

In addition to the background ideas used to find the proposed answers to the above sub-problems, the basic assumptions made and the scope of the proposed methodology are provided.

7.2.1 MSDD Development

The first sub-problem is how to represent manufacturing system design. Since the main objective of the research is to develop a methodology to capture the interactions between product development decisions and manufacturing system design, it is important to systematically represent manufacturing system design. The systematic representation of manufacturing system design enables a clear definition of the interface between product design and manufacturing system design. For this purpose, the manufacturing system design decomposition (MSDD) is applied. As is explained in Chapter 4, the MSDD is a systematic representation of manufacturing system design that clearly separates the objectives of manufacturing systems from the means to achieve the objectives. The development of the MSDD is explained in detail in Chapter 4.

The MSDD presents effectively the interrelationships between the different elements of a system design in different system design hierarchies by adopting the Axiomatic Design methodology. Some other models of manufacturing system design (see Figure 7-1, 7-2, and 7-3 for some examples of them) may be used instead of the MSDD, but the MSDD has several advantages over the other representations.

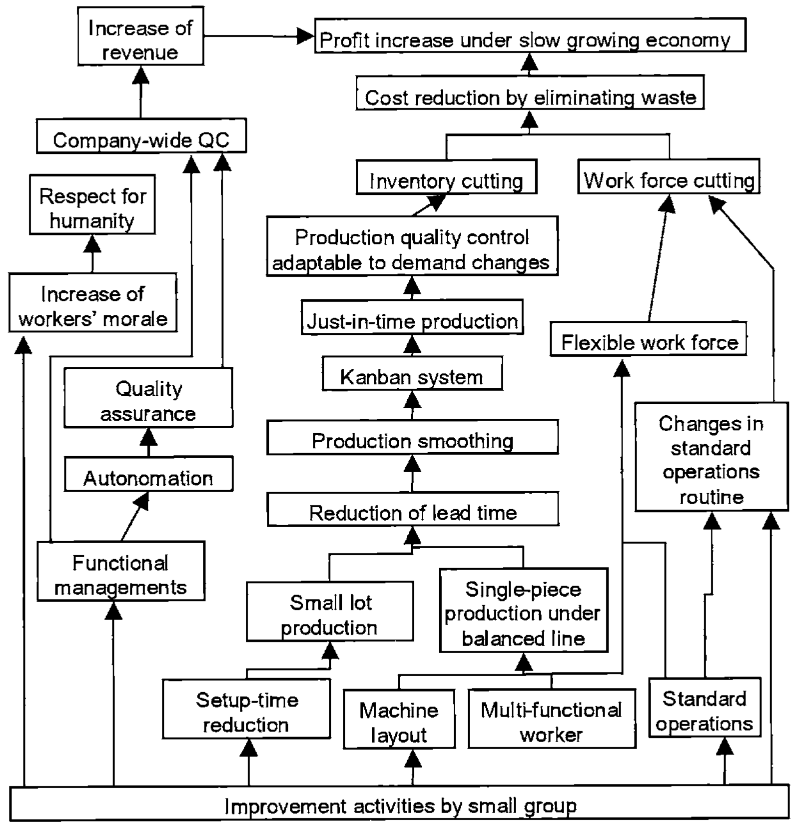


FIGURE 7-1. IMPLEMENTATION STEPS FOR TOYOTA PRODUCTION SYSTEM [MONDEN, 1998].

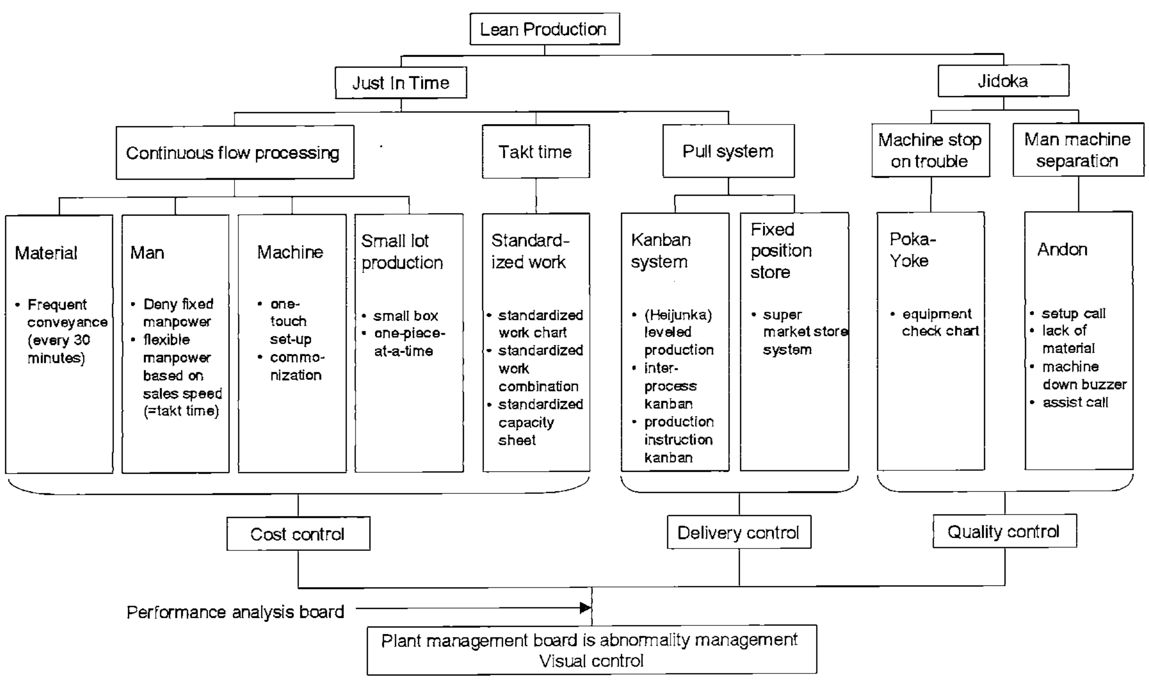


FIGURE 7-2. LEAN PRODUCTION FRAMEWORK [SUZUKI, 1999].

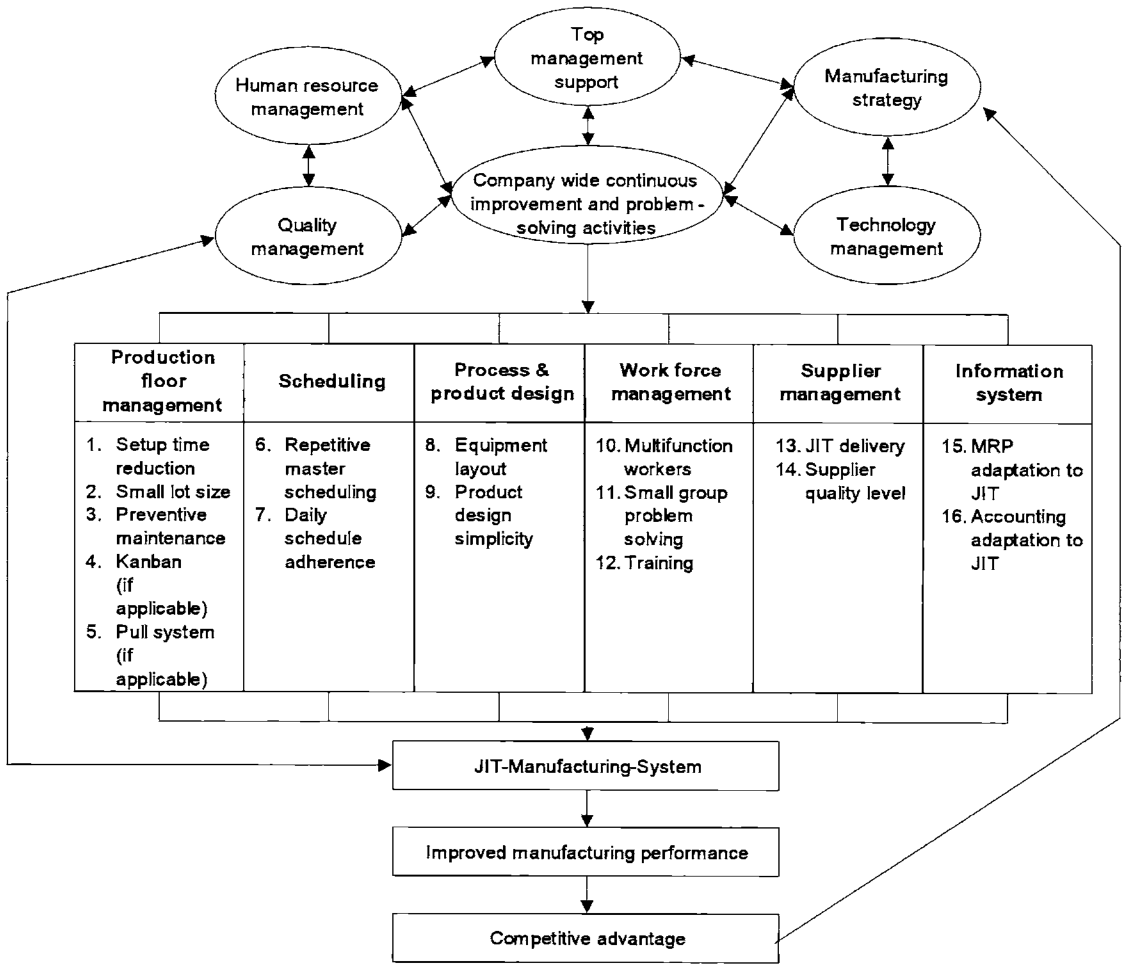


FIGURE 7-3. CORE JJUST-IN-TIME MANUFACTURING FRAMEWORK [SAKABIBARA ET AL., 1993].

First, as is previously discussed in Chapter 4, the MSDD provides a clear separation between the objectives and the means of achievement, which makes it easier to see how a product decision affects the achievement of the goals of a manufacturing system. In addition, the MSDD presents the 'decoupled' interrelationships between the system activities in a hierarchy. Even though the MSDD assumes an ideal case, these decoupled interrelationships among the system design elements can provide an ideal sequence of implementation among different system design elements (see Chapter 4 or [Suh 1990] for detailed discussion on decoupling and sequence of implementation).

Moreover, the MSDD is developed to be general enough to be applicable to repetitive and discrete part manufacturing systems in a wide range of industries. Therefore, a methodology that is developed around the MSDD is applicable in a wide range of industries of repetitive and discrete part manufacturing.

More importantly, the MSDD has been validated through the successful applications on equipment design [Arinez 2000], and performance measurement and manufacturing strategy [Duda 2000]. In addition, Linck [2001] attempts to validate several premises and propositions of the MSDD using a questionnaire approach based on the MSDD.

Considering these advantages of the MSDD over other representations, it seems to be appropriate to use the MSDD to represent the manufacturing system design. Therefore, the MSDD is adopted in this thesis in order to represent the manufacturing system design. Some arguments on the validity of the MSDD may be possible, but strictly proving the validity of the MSDD is out of scope of this thesis. This thesis is going to accept the MSDD as it is and assume that the MSDD is a valid representation of manufacturing system design. The main aim of the thesis is to develop a methodology to see the interactions between manufacturing system design and product development and a successful development of the methodology will indirectly contribute to the validation of the MSDD.

There is one thing, however, that should be kept in mind with the use of the MSDD. One basic assumption made with the adoption of the MSDD is that “lean” manufacturing is the most appropriate manufacturing system design that serves best to satisfy the requirements of contemporary customers. The MSDD has been developed keeping “lean” manufacturing principles in mind and thus, reflects the principles of “lean” manufacturing in many ways. Therefore, it may be argued that the proposed methodology may not be applicable to a manufacturing system that is not designed to achieve the FRs provided by the MSDD.

However, the MSDD starts by describing the general requirements for manufacturing systems and develops by decomposing the requirements into sub-level requirements while finding an adequate solution to each requirement. The general requirements in the higher levels (quality, delivery, operating cost, and investment) of the MSDD are believed to be generally applicable to many manufacturing systems. Therefore, even the enterprises with manufacturing systems designed with different FRs (i.e., mass manufacturing) should be able to get benefits from applying the proposed methodology as an ideal case. These enterprises may have to adopt the proposed methodology while trying to improve their manufacturing systems to follow the principles provided by the MSDD.

There are some cases that the MSDD may not be applicable and need to be modified. In the case that new FRs are requested from customers that add or modify the FRs stated in the MSDD, the MSDD itself may need to be modified to accommodate the changes in its FRs. In addition, the MSDD may need to be changed when new solutions (DPs) for the requirements (FRs) are found. However, within this thesis, the MSDD is accepted as it is since there is no evidence of new FRs or DPs that are generally accepted as replacing the current FRs and DPs of the MSDD.

7.2.2 Product/Process Design Representation

The second sub-problem is how to represent product development. In fact, product development refers to many activities beginning with recognizing market opportunities and ending with delivery of a product. Therefore, strictly speaking, the aim of the proposed methodology that will be described in section 7.3 is to provide a way to see the interactions between the activities of product design and process design, and manufacturing system design. Therefore, the scope of the proposed methodology excludes such areas of product development as marketing, customer relations, and distribution. The proposed methodology of this thesis focuses on the interactions between product/process design decisions and manufacturing system design. In addition, considering the main aim of the proposed methodology, it is important not to model the entire product/process design procedures but to find out the general elements of product/process design that significantly interacts with manufacturing systems.

Several models of product development are reviewed to see if they are appropriate to achieve the main objective of the research: to see the interactions between manufacturing systems and product/process design. Process oriented approaches are introduced in section 7.2.2.1 and decomposition based approaches are reviewed in section 7.2.2.2.

7.2.2.1 Process oriented approaches

Process oriented approaches model product development procedures. In general, they provide sequenced steps of product development and activities to be done at each step. For example, Ulrich and Eppinger [2000] model the product development process in six phases as is shown in Figure 7-4.

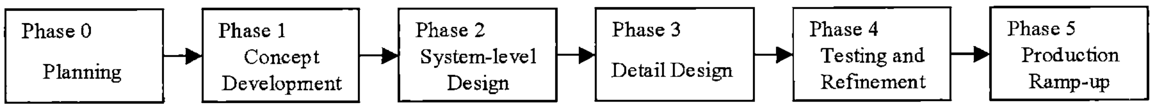


FIGURE 7-4. THE PRODUCT DEVELOPMENT PROCESS [ULRICH AND EPPINGER 2000]

Each phase comprises of a series of activities and feedback processes. For instance, Ulrich and Eppinger [2000] present the front-end activities comprising the concept development phase (see Figure 7-5).

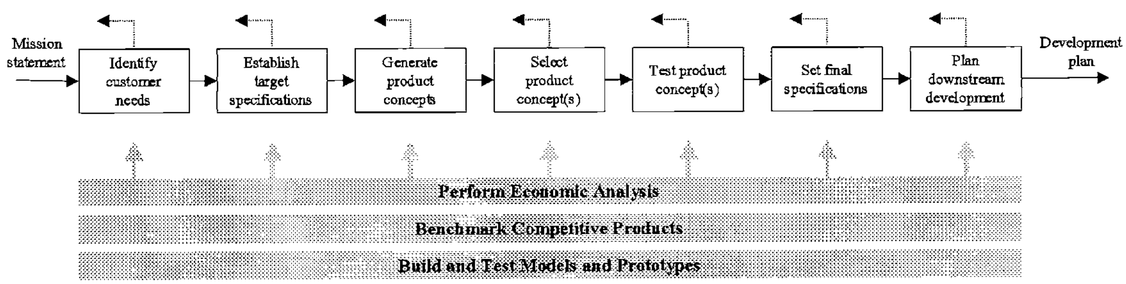


FIGURE 7-5. THE FRONT-END ACTIVITIES COMPRISING THE CONCEPT DEVELOPMENT PHASE [ULRICH AND EPPINGER 2000].

The process oriented approaches may differ from each other in terms of details provided in the description of product development steps or terminologies used. However, from the perspective that they propose the steps to take for product development and provide rationale behind the propositions, the process oriented approaches are very similar. It is evident when the procedures proposed by Phal and Beitz [1996] (Figure 7-6) after consulting VDI (Verein Deutscher Ingenieure) guidelines are compared to those of Ulrich and Eppinger [2000] (Figure 7-4 and 7-5). Except the terms used in a different way, the basic procedures proposed by both approaches are very similar.

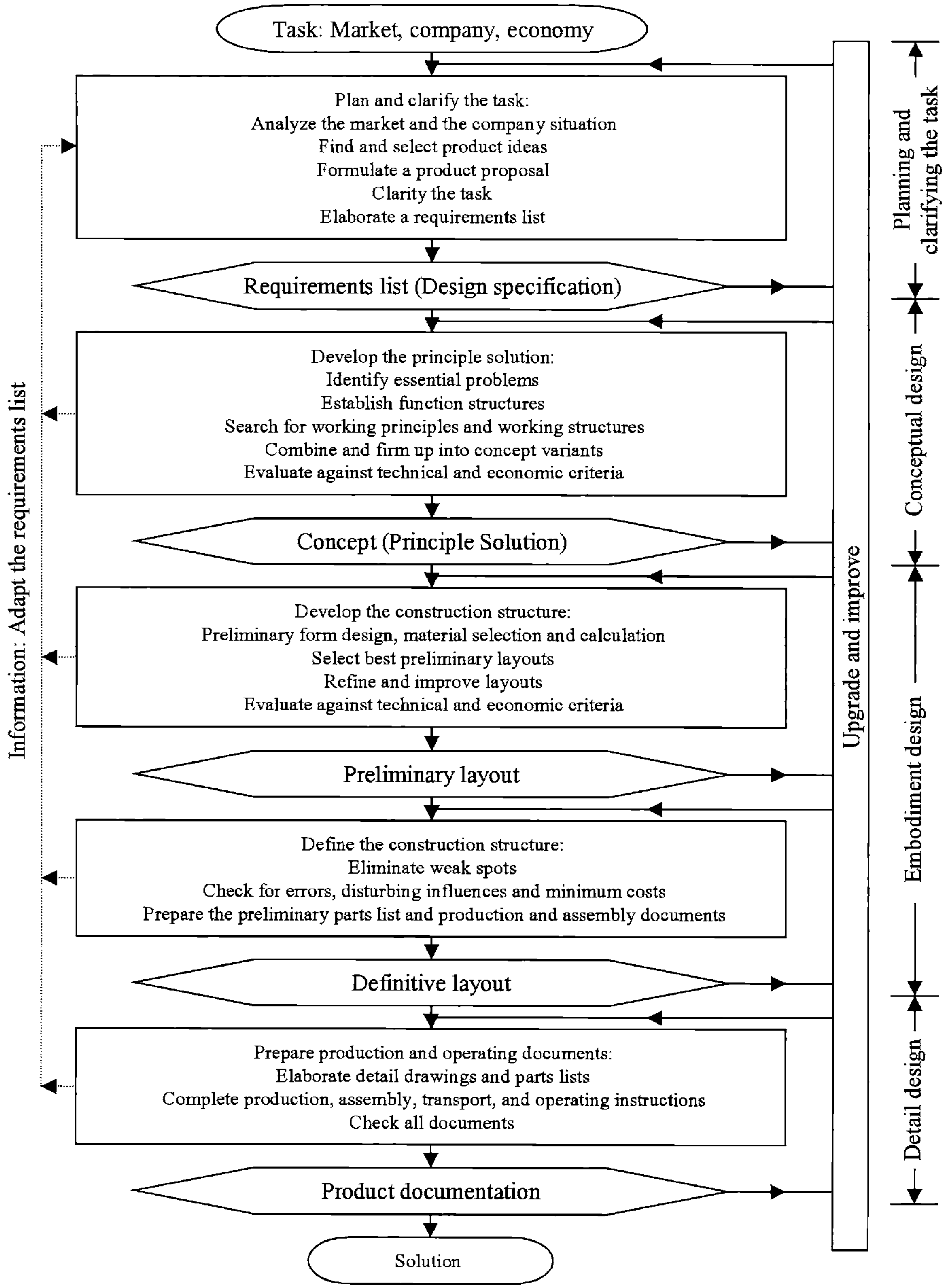


FIGURE 7-6. STEPS OF THE PLANNING AND DESIGN PROCESS (ADOPTED FROM PHAL AND BEITZ [1996])

These approaches, however, do not show what functional department should be involved with each step. In other words, organizational issues are excluded in the presentation of the product development procedures. Therefore, Ulrich and Eppinger [2000], and Wheelwright and Clark [1992], add organizational information to the procedural models. They are shown in Table 7-1 and 7-2 respectively. The diagrams shown in Table 7-1 and 7-2 include general activities to be taken by each functional department during each phase of product development.

TABLE 7-1. THE GENERIC PRODUCT DEVELOPMENT PROCESS (ADAPTED FROM [ULRICH AND EPPINGER 2000]).

Planning	Concept development	System-level design	Detail design	Testing and refinement	Production ramp-up
Marketing • Articulate market opportunity. • Define market segments.	• Collect customer needs. • Identify lead users. • Identify competitive products.	• Develop plan for product options and extended product family.	• Develop marketing plan.	• Develop promotion and launch materials. • Facilitate field testing.	• Place early production with key customers.
Design • Consider product platform and architecture. • Assess new technologies.	• Investigate feasibility of product concepts. • Develop industrial design concepts. • Build and test experimental prototypes.	• Generate alternative product architectures. • Define major sub-systems and interfaces. • Refine industrial design.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Reliability testing. • Life testing • Performance testing. • Obtain regulatory approvals. • Implement design changes.	• Evaluate early production output.
Manufacturing • Identify production constraints. • Set supply chain strategy.	• Estimate manufacturing cost. • Assess production feasibility.	• Identify suppliers for key components. • Perform make-buy analysis. • Define final assembly scheme.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Begin procurement of long-lead tooling.	• Facilitate supplier ramp-up. • Refine fabrication and assembly processes. • Train work force. • Refine quality assurance processes.	• Begin operation of entire production system.
Other functions					
• Research: Demonstrate available technologies. • Finance: Provide planning goals. • General Management: Allocate project resources.	• Finance: Facilitate economic analysis. • Legal: Investigate patent issues.	• Finance: Facilitate make-buy analysis. • Service: Identify service issues.		• Sales: Develop sales plan.	

TABLE 7-2. FUNCTIONAL ACTIVITIES UNDER CROSS-FUNCTIONAL INTEGRATION (ADAPTED FROM [WHEELWRIGHT AND CLARK 1992])

Functional activities	Phases of Development					
	Concept development	Product planning	Detailed design and development		Commercial preparation	Market introduction
			Phase I	Phase II		
Engineering	Propose new technologies; develop product ideas; build models; conduct simulations	Choose components and interact with suppliers; build early system prototypes; define product architecture	Do detailed design of product and interact with process; build full-scale prototypes; conduct prototype testing	Refine details of product design; participate in building second-phase prototypes	Evaluate and test pilot units; solve problems	Evaluate field experience with product
Marketing	Provide market-based input; propose and investigate product concepts	Define target customer's parameters; develop estimates of sales and margins; conduct early interaction with customers	Conduct customer tests of prototypes; participate in prototyping evaluation	Conduct second-phase customer tests; evaluate prototypes; plan marketing rollout; establish distribution plan	Prepare for market rollout; train sales force and field service personnel; prepare order entry/process system	Fill distribution channels; sell and promote; interact with key customers
Manufac-turing	Process and investigate process concepts	Develop cost estimates; define process architecture; conduct process simulation; validate suppliers	Do detailed design of process; design and develop tooling and equipment; participate in building full-scale prototypes	Test and try out tooling & equipment; build second-phase prototypes; install equipment and bring up new procedures	Build pilot units in commercial process; refine process based on pilot experience; train personnel and verify supply channel	Ramp up plant to volume targets; meet targets for quality, yield, and cost

As is previously explained, it is important to find the elements of product/process design that affect manufacturing systems. Therefore, among the described steps and activities of these approaches, those that are related to manufacturing systems are identified. The identified steps and activities are summarized in Table 7-3. As for the procedural approach, the procedures proposed by Phal and Beitz [1996] are used. Among the procedural approaches with organizational consideration, the sequenced activities proposed by Wheelwright and Clark [1992], and Ulrich and Eppinger [2000] are investigated. Investigating representative models should be enough since process oriented approaches propose more or less similar product development procedures as is discussed earlier.

TABLE 7-3. ACTIVITIES / STEPS OF PRODUCT / PROCESS DESIGN THAT MAY AFFECT MANUFACTURING SYSTEMS

	Phal and Beitz [1996]	Wheelwright and Clark [1992]	Ulrich and Eppinger [2000]
Planning	• Find and select product ideas		• Product platform and architecture • Identify production constraints • Set supply chain strategy
Conceptual design	• Evaluate the concept against technical criteria	• Investigate process concepts	• Assess production feasibility
System level design	• Develop the construction structure • Material selection • Prepare preliminary parts list and production and assembly documents	• Choose components and interact with suppliers • Define product architectures • Define process architecture • Validate suppliers	• Generate alternative product architectures • Define major sub-systems and interfaces. • Identify suppliers for key components • Make-buy analysis • Define final assembly scheme
Detail design	• Elaborate detail drawings and parts lists • Complete production, assembly, transport, and operating instructions	• Detailed design of process • Design and develop tooling and equipment	• Choose materials • Assign tolerances • Define piece part production processes • Design tooling

7.2.2.2 Decomposition oriented approaches

Stimulated by the successful application of the MSDD in manufacturing system design, several attempts have been made to approach product development in the same way. These approaches are characterized by the development of a decomposition of product development and thus, can be called as decomposition oriented approaches. Decomposition oriented approaches aim to develop a MSDD for product development so that the benefits that the MSDD provides in manufacturing system design can be achieved in product development. Researchers such as Bocanegra [2001], Lenz and Cochran [2000], and Dobbs [2001] propose Product Development Design Decomposition (PD^3), Product Development System Design Decomposition (PDSDD), and Aerospace Manufacturing System Design Decomposition (AMSDD).

The PD^3 was developed to provide a standard way to develop products throughout an enterprise, emphasizing the importance of communication between product design and manufacturing [Bocanegra 2001] (see Figure 7-7 and Appendix B). Since the PD^3 developed for an aerospace company, it contains FRs and DPs specific to the need of aerospace industry. For example, to avoid risk associated with misunderstanding baseline requirements (FR-U11), the contract is studied and understood (DP-U11). The contract with the government is a typical starting point in the development of military aircraft.

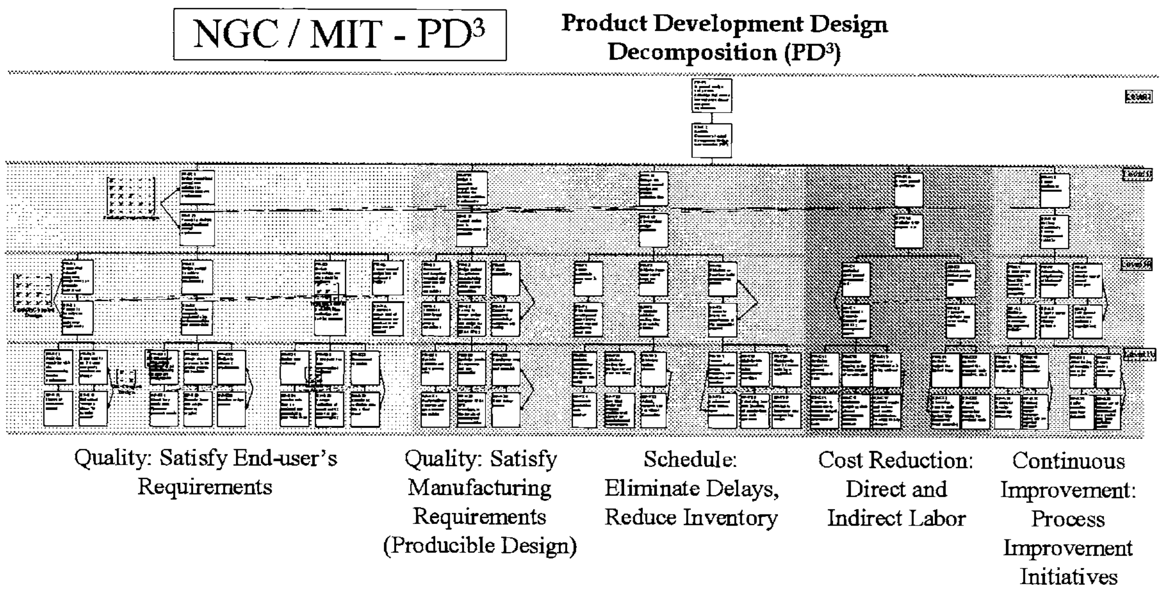


FIGURE 7-7. PRODUCT DEVELOPMENT DESIGN DECOMPOSITION (PD^3) [BOCANEGRA 2001]

The PD^3 has five high-level functional requirements (FRs). They are:

FR011: Design a functional product that satisfies the external customer requirement,

FR012: Design a producible product that satisfies the internal customer requirements,

FR013: Reduce the overall product design and process definition time,

FR014: Ensure product is profitable, and

FR015: Ensure continuous improvement.

These FRs of the PD^3 use an analogy to the FRs of the MSDD. For example, FR011 and FR012 are considered as 'quality' branches that address the issues of satisfying internal (manufacturing) and external (government) customer requirements. FR013 is considered as 'schedule' branch, which is about eliminating delays and reducing inventory. Then, "cost reduction by efficiently utilizing direct and indirect labor" (FR014) and "continuous improvement" (FR015) follow.

In the context of the aim of this thesis, it is noteworthy that the PD^3 has a branch of satisfying internal customer requirements, which are manufacturing requirements. In this branch, Bocanegra decomposes FR013 into three sub-FRs of:

FR-E1: Understand and document manufacturing processes and process capabilities,

FR-E2: Design product for optimized manufacturing processes and within process capabilities, and

FR-E3: Validate producibility.

The corresponding solutions (DPs) for these requirements are:

DP-E1: Process to identify and document process capabilities,

DP-E2: Process to ensure design for assembly and design for manufacturing (DFA/DFM), and

DP-E3: Compile and document producibility validation and testing.

Then, FR-E2 and DP-E2 are further decomposed into lower levels to elaborate the elements of existing DFM/DFA approaches. In addition to these FR-DP pairs, some other DPs in quality branch of satisfying end-user's requirements affect the FRs in this manufacturable product design branch. Table 7-4 lists the FR-DP pairs that are linked to manufacturing system design issues.

The producible product design branch, however, has a limited scope to overlook manufacturing system issues, while the traditional DFMA knowledge is extensively reflected. For example, it does not address the impact of product design on setup changeover, which is an important issue in many manufacturing systems. In addition, the decomposition of the producible product design branch is not collectively exhaustive so that there are some factors that are not considered in the decomposition. For example, product architecture design is not addressed even though it can affect the manufacturability of a product design. Furthermore, a very complex nature of dependencies between detailed product design, material selection, and process selection is not clearly addressed in detail but simplified.

TABLE 7-4. A LIST OF THE FR-DP PAIRS IN THE PD3 THAT AFFECT MANUFACTURING SYSTEM DESIGN.

	FR	DP
U21	Statement of work allocated to sub-teams according to their core competencies	Closed loop requirement flow-down process/matrix
U22	Assure needed resources in the design process are available	Organize team and supply tools as required
U23	Design to allocated requirements	Detailed design process
U31	Design data validated	Receive data from as-designed and producibility plan validations
U32	Part(s) and/or sub-assembly(ies) validated	Perform validation of actual part(s) and/or sub-assembly(ies)
E1	Understand and document manufacturing processes and process capabilities	Process to identify and document process capabilities
E21	Optimize assembly and sub-assembly plan	Apply optimum assembly and sub-assembly capabilities
E22	Optimize details for assembly and sub-assemblies	Integrate DFA/DFM techniques to the details of assembly and sub-assemblies
E23	Specify the best components and materials	Make or buy process
E3	Validate producibility	Compile and document producibility validation and testing
T31	Improve communication among customer, team members, and suppliers	Environment that fosters open communication
K1	Ensure useful knowledge is identified, captured, and organized accurately	Northrop-Grumman's knowledge management initiative
K2	Allow sharing, adoption, and utilization of knowledge	Easy to access and user-friendly database

The PDSDD is developed by Lenz and Cochran [2000] and focuses on the product development system design (see Figure 7-8 and Appendix C). Starting from the highest level FR-A, "define and design a manufacturable product," the PDSDD focuses on the integration of product development activities. The PDSDD aims to facilitate the general design process of a product development system (or product development organization) and elaborate environment-neutral design issues [Lenz 1999]. The PDSDD is comprised of four major branches: total product quality, development lead time, development operating cost, and development investment. This structure is exactly same as that of the MSDD since the PDSDD is developed using the analogy with the MSDD. For example, in the PDSDD, information flows between functional parties of product development are viewed as material flows between machines of a manufacturing system.

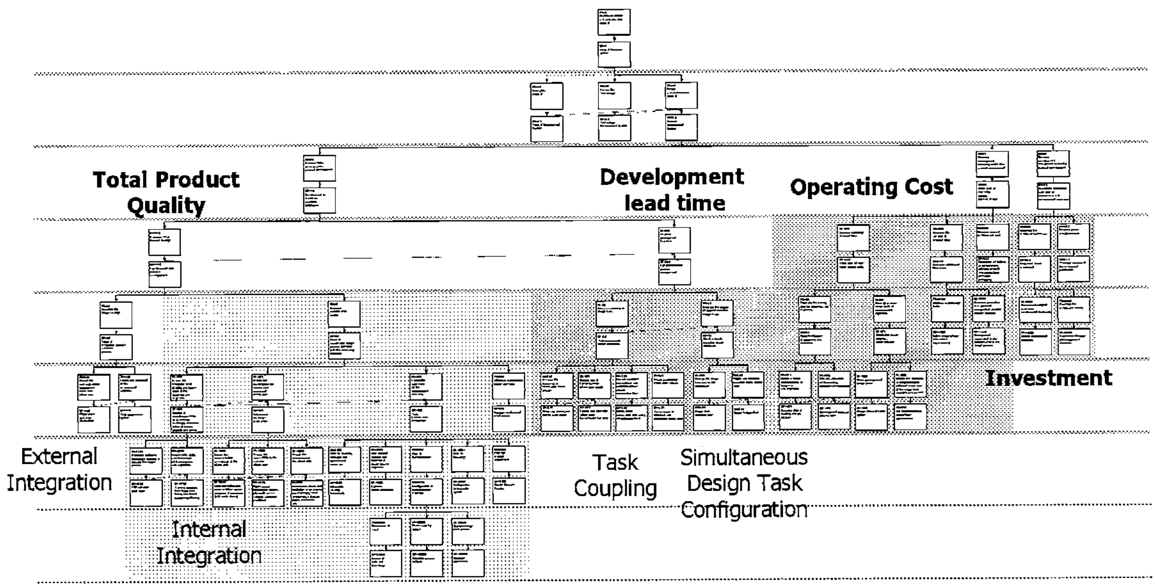


FIGURE 7-8. PRODUCT DEVELOPMENT SYSTEM DESIGN DECOMPOSITION [LENZ AND COCHRAN 2000]

In the total quality branch of the PDSDD, FR111 (maximize total product quality) is satisfied by DP111 (highly coordinated process arrangement). The term, 'coordinated,' characterizes the extent of the alignment and adjustment of organizational activities. Lenz and Cochran [2000] claim that in product development, quality is obtained when all discrete design processes incorporate the restrictions that limit their scope. Therefore, from their perspective, quality can be assured by 'coordinating' the product development processes (or activities). Lenz and Cochran further distinguish external integration from internal integration. External integration refers to the alignment of the internal design process with external requirements and restrictions. Internal integration indicates the integration within the product development system. For example, product design meets the constraints of the manufacturing system. To ensure the internal integration, Lenz and Cochran [2000] stress information flow coordination, engineers' knowledge, and the alignment of development activities. The integration through information flow coordination is important, but it does not provide what kind of impact product design endows on manufacturing systems. In other words, the content of the information flows that need to be coordinated is not discussed in the PDSDD while the coordination of information flows is suggested as a solution for the internal integration. The content of the information flow is provided by the engineers' knowledge and documentation of former projects (FR-I11) instead of a systematic framework.

Product development lead time is minimized (FR112) by highly overlapping product development processes (DP112) through uncoupling coupled tasks (FR-L1) and encouraging simultaneous execution of product development activities (FR-L2). Product development operating cost is minimized (FR12) by efficiently using direct (FR/DP121) and indirect labor (FR/DP122). Investment efficiency (FR13) is guaranteed by flexible (FR-DP1311) and highly utilized development resources (FR-DP1312).

As discussed previously, the PDSDD is strong at presenting the coordination of the product development activities but is weak to reveal what interactions exist between product development decisions and manufacturing systems. A list of the FR-DP pairs that affect manufacturing system design is shown in Table 7-5.

TABLE 7-5. A LIST OF THE FR-DP PAIRS IN THE PDSDD THAT AFFECT MANUFACTURING SYSTEM DESIGN.

	FR	DP
E11	Ensure the exchange of the coordination dependent information	Information exchange mechanism
I111	Install the skills and knowledge required to execute the design process	Well selected work force
I112	Improve the skills and knowledge of the designers and engineers	Training program, knowledge data bases, functional expertise gathering
I121	Ensure the documentation and storage of the information	Work-flow integrated documentation system and general databases (CAX-applications)
I122	Ensure the accessibility to the required information	Open-access information system, physically and/or virtually collocated workforce
I123	Ensure the distribution of the information	Standardized information distribution mechanisms.
I135	Align by mutual adjustment	Design decision process
L13	Ensure upstream-downstream and downstream-upstream information flow	Bi-directional information flow setup (feedback system)
D11	Enable a broad applicableness of designers and engineers	Cross functional training and job rotation
D22	Provide the designers and engineers with sufficient information of the design task objective and content	Continuously updated product plan specifications

The AMSDD extends the MSDD into the product design area. The AMSDD adds an additional branch of product design to the MSDD, while some of the MSDD branches are modified to be applicable in aerospace industry, which is characterized by a small total production volume rather than repetitive mass production. The schematic view of the AMSDD is provided in Figure 7-9 and the AMSDD itself is presented in Appendix D.

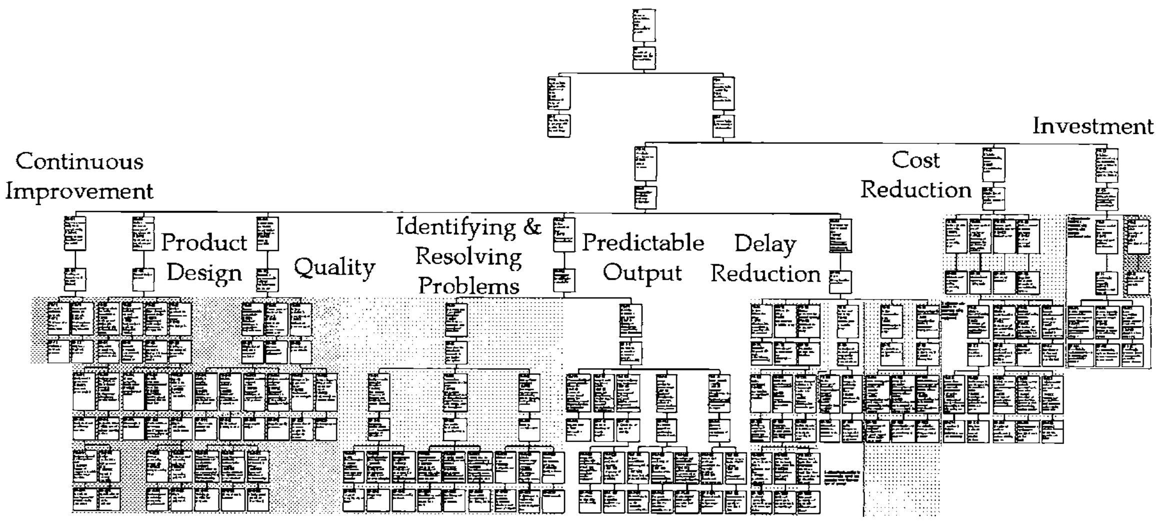


FIGURE 7-9. A SCHEMATIC VIEW OF THE AMSDD [DOBBS 2001]

The product design branch of the AMSDD discusses product design issues that affect manufacturing system design while avoiding the decomposition of whole product design, which is out of the scope of the AMSDD research [Dobbs 2001]. A list of the FR-DP pairs that interact with manufacturing system design is provided in Table 7-6. In the product design branch, FR-D1 (design products that can be manufactured) is satisfied by DP-D1 (integrated product and manufacturing system design), and then further decomposed into FR-D11 (design stable processes) and FR-D12 (design products for defect-free fabrication and assembly). These two sublevel FRs are satisfied by DP-D11 (equipment and part feature selection) and DP-D12 (product designs facilitate use of mistake proofing devices), respectively. Further decomposition of this branch is available in Appendix C. In addition, FR-D4 (design products the customer can afford) branch also describes some popular ways of decreasing manufacturing burdens by designing standardized parts, using commodity raw materials and off-the-shelf parts, and using simple processes. However, the product design branch of the AMSDD shows weaknesses such as not providing rich content of the interactions between manufacturing system design and product design. This branch shows only nine leaf FR-DP pairs and does not provide further insights on the manufacturing-product design interactions than existing approaches such as using commodity parts and design standardization.

TABLE 7-6. A LIST OF THE FR-DP PAIRS IN THE PRODUCT DESIGN BRANCH OF THE AMSDD THAT AFFECT MANUFACTURING SYSTEM DESIGN.

	FR	DP
D111	Design equipment for high process yield	Selection / development of manufacturing processes
D112	Design products for high process yield	Specification of tolerances that can be achieved
D12	Design products for defect-free fabrication and assembly	Product designs facilitate use of mistake proofing devices
D3	Accommodate future changes in product design	Standard method to incorporate new features into design
D41	Reduce processing requirements	Standardized part designs
D42	Specify affordable components and materials	Preferential use of 'off the shelf' parts and commodity raw materials
D431	Reduce processing complexity	Parts designed to minimize processing requirements
D432	Reduce cost of processing equipment	Simple processing equipment

In this section, three decomposition approaches to represent product development are reviewed. It is noteworthy that all three approaches stress the importance of designing producible or manufacturable products while failing to propose a method to see the interactions between product design and manufacturing system design. Adopting the insights provided by existing approaches such as design standardization to design a manufacturable product can be a good starting point. However, those insights usually see a facet of the interactions between manufacturing system design and product design. Therefore, in order to capture the manufacturing-product development interactions from a system perspective, a new methodology is necessary.

7.2.2.3 Representation of product development decisions

As is previously claimed, considering the main aim of the proposed methodology, it is important not to model the entire product/process design procedures but to find out the general elements of product/process design that significantly interacts with manufacturing systems.

One of the reasons to take this approach is practical difficulty to model the product design and process design. For example, product design and process design to physically realize the product design are very case-specific. Different product and process designs are prepared for different products. Therefore, in order to make the methodology generally applicable, general elements of product and process design need to be extracted. In other words, instead of trying to find out the impact of the decision of the wire diameter of a clip on clip manufacturing systems, it is more beneficial to think about the impact of detail design on manufacturing systems in order to make the proposed method be generally applicable to wide variety of products.

Before trying to figure out what elements of product/process design significantly affect manufacturing systems, it should be first considered when manufacturing issues arise during product design. As is defined in Chapter 3, product design itself is nothing but a planning of a product. Product design itself is not physical but conceptual. Therefore, a product design should be physically realized. When the physical realization does matter, manufacturing issues arise and thus, manufacturing system issues arise. However, it is difficult to clearly separate the product design phase and the physical realization phase since many aspects of product design in various levels of details are related to its physical realization. For example, product architecture determines the physical structure of a product, which is closely related to manufacturing systems. Detailed design also affects manufacturability of a product, which is directly related to manufacturing systems. Some of the researchers in product design theory area already addressed this issue. For example, in his Axiomatic Design, Suh [1990] claims that the design should be done by the zigzagging between three design domains of functional, physical, and process. Phal and Beitz [1994] describes "embodiment phase" of product design process as is presented in Figure 7-6. Both approaches reveal that a product cannot be designed in detail unless high level physical realization planning (e.g., material selection, principle process selection) is not made.

Having in mind that manufacturing system issues arise because of physical realization of product design, a thorough review is given to the elements of product/process design that affect manufacturing systems, which are presented in Table 7-3, 7-4, 7-5, and 7-6. The can be categorized into six different groups: 1) product variety (PV), 2) product architecture (PA), 3) purchasing decision (P), 4) material selection (MS), 5) process selection (PS), and 6) detailed design (DD). The summary of the categorization of those elements is presented in Table 7-7.

TABLE 7-7. THE CATEGORIZATION OF PRODUCT/PROCESS DESIGN ACTIVITIES THAT AFFECT MANUFACTURING SYSTEMS.

	Phal and Beitz	Wheelwright and Clark	Ulrich and Eppinger	PD^3	PDSDD	AMSDD
PV	• product ideas		• product platform			• D41, D42
PA	• develop the construction structure • prepare preliminary part list	• define product architecture • choose components	• product architecture • generate alternative product architecture • define major sub-systems and interfaces			• D3, D41, D42
P		• interact with suppliers • validate suppliers	• supply chain strategy • identify suppliers for key components • make-buy analysis	• E23		
MS	• material selection		• choose materials			• D42
PS	• prepare production & assembly documents	• define process architecture • investigate process concepts • design & develop tooling & equipment	• final assembly scheme • define piece part production processes • design tooling	• E1, E21, E22		• D111, D431, D432
DD	• detail drawings		• assign tolerances	• U23, U31		• D112, D12, D431

In the categorization presented in Table 7-7, the elements address the issues of organization, knowledge management, and communication are excluded since they are not directly related to product/process design. All elements of the PDSDD are about the free exchange of information through enhanced communication and thus, are excluded from Table 7-7. In addition, the elements that address the issue of validation of product design in general are excluded. They do not provide any useful information how to validate product designs. Furthermore, the elements that describe the manufacturing system design such as equipment design, part transportation, and operating instruction documentation are excluded. The scope of the research is limited to product/process design phases during product development.

7.2.3 How to See the Interactions

The interactions between manufacturing system design and six categories of product/process design can be captured by reviewing each category against the FRs and DPs of the MSDD. For example, the product variety decisions can be reviewed from the perspectives of each FR-Q111 and DP-Q111 of the MSDD. FR-Q111 states to "ensure operator has knowledge of required tasks" and this is achieved by DP-Q111 "training program." Product variety decisions can affect the achievement of FR-Q111 by changing the amount of knowledge of required tasks for operators. Therefore, when a product variety decision is made, its on required operator knowledge should be reviewed and considered for a better manufacturing system design. This reviewing process can be repeated to the other FRs and DPs of the MSDD so that a complete map of the interactions of each category with the FRs and DPs of the MSDD can be developed.

The reason why both the FRs and DPs of the MSDD are considered in the reviewing process is that the DPs stated in the MSDD are believed to be a reasonable way to satisfy the FRs. Therefore, it is believed to be beneficial to check if product/process design decisions are appropriate from the suggested DPs point of view. In addition, the decomposition itself cannot be completed without specifying the DPs and thus, it is necessary to include DPs in the reviewing process.

The results of the reviewing process for the six categories of product/process design are presented in the next section. In the reviewing process, all leaf FRs and DPs of the MSDD are primarily considered. However, since the MSDD assumes given product design and process design, high level FRs and DPs are considered whenever necessary to reflect product/process design issues.

7.2.3.1 Product variety

Product variety significantly affects manufacturing systems in various ways. It is directly related to the required flexibility of the manufacturing system, which is closely linked to operating costs and investment. The FRs and DPs of the MSDD that can be affected by product variety decisions are shown in Figure 7-10 as black boxes.

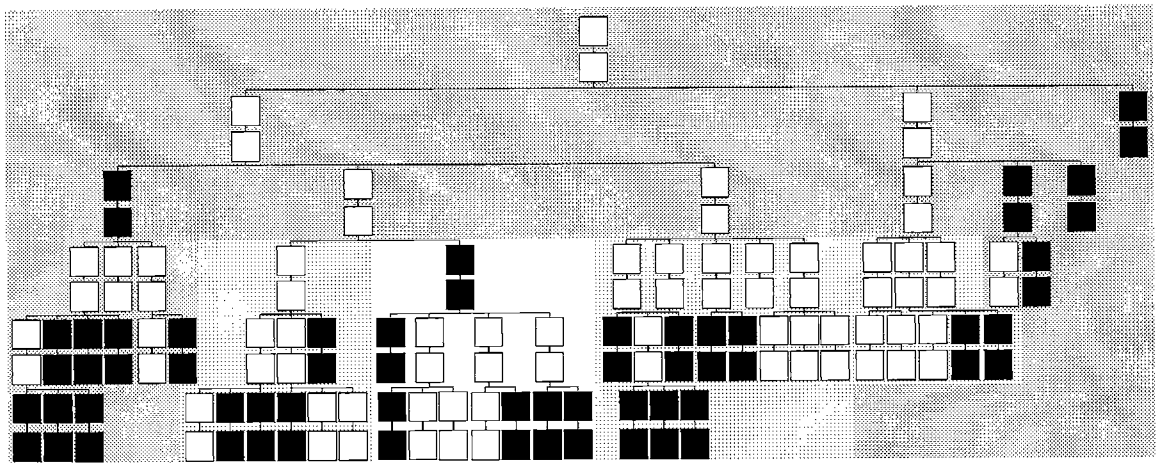


FIGURE 7-10. THE FRS AND DPS OF THE MSDD THAT CAN BE AFFECTED BY A PRODUCT VARIETY DECISION

As is indicated in Figure 7-10, product variety decisions heavily affect quality, identifying and resolving problems, and delay reduction branches. Predictable output and operating cost branches are also affected by product variety decisions along with the investment branch. Detailed explanations of the impact of product variety decisions on the FRs and DPs of the MSDD are provided in the following sections.

7.2.3.1.1 Quality Branch

In the quality branch of the MSDD, product variety decisions are related to seven FR-DP pairs out of nine leaf FR-DP pairs and one higher level FR-DP pair. The list of the FR-DP pairs that are affected by product variety decisions is provided in Table 7-8.

TABLE 7-8. LIST OF THE FR-DP PAIRS IN THE QUALITY BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT VARIETY DECISIONS.

	FR	DP
Q111	Ensure that operator has knowledge of required tasks	Training program
Q112	Ensure that operator consistently performs tasks correctly	Standard work method
Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
Q12	Eliminate machine assignable causes	Failure mode and effects analysis
Q13	Eliminate method assignable causes	Process plan design
Q14	Eliminate material assignable causes	Supplier quality program
Q32	Reduce impact of input noise on process output	Robust process design
111	Manufacture products to target design specifications	Production processes with minimal variation from the target

A product variety decision can affect the achievement of FR-Q111 by changing the required tasks for operators. For example, a wider product variety may increase the amount of operator knowledge required to perform his/her tasks by increasing required tasks. In a similar way, FR-Q112 and DP-Q112 may be affected by a product variety decision. Increased level of product variety may require changes in the standard work method in use or deteriorate consistent operator performance by confusing them with increased work tasks. FR-Q113 and DP-Q113 can be also affected by a product variety decision. Increased product variety can increase operator human errors that should not be transferred to defects. The mistake proof devices used in the manufacturing system may need to be modified according to the given product variety while the level of product variety in a production line may need to be adjusted to avoid too many mistakes from the operators.

Increased product variety may also require a higher level of flexibility from the existing equipment (e.g., machine, fixture, tools). Otherwise, the equipment would not be able to produce parts according to the design specification, which can be interpreted as machine assignable causes of quality problems (FR-Q12). In the same way, increased product variety may require a higher level of flexibility from the production method in use. A careful study on the capability of the applied production method should be conducted to understand the possible limitation in the capability of the production method. In addition, the quality of incoming materials should be good enough to satisfy various processing requirements caused by product variety in order to eliminate material assignable causes (FR-Q4). Likewise, it is important to make different processes robust to input noises for all types of products within a product family (FR-Q32).

FR-111 describes that products should be manufactured to target design specifications. Similar levels of tolerances can be given to the products within a product family in order to avoid the possible manufacturing complexity associated.

The summary of the interactions described in this section is recorded in the second round questionnaire that will be explained in Chapter 9. Even though the questionnaire is developed to evaluate the existing interfaces between product/process design and manufacturing system design, it can also serve as a quick reference on the forms of interactions.

7.2.3.1.2 Identifying and Resolving Problems Branch

In the identifying and resolving problems branch of the MSDD, product variety decisions are related to four FR-DP pairs out of seven leaf FR-DP pairs. The list of the FR-DP pairs that are affected by product variety decisions is provided in Table 7-9.

FR-R112 and DP-R112 state to identify where disruptions occur through simplified material flow paths. Since product variety decisions can significantly alter the material flow paths in a manufacturing system, this FR-DP pair is affected by product variety decisions. Simple material flow paths should be maintained for quick problem identification and resolution in manufacturing systems and thus, the product variety decision should be made after considering the capacity, capability, and material flow paths of a selected production site. In addition, product variety may affect the form of disruptions at sub-systems (FR-R113). Possible disruptions that can be caused by increased product variety may be studied to keep the capability of quick response to the problems.

TABLE 7-9. LIST OF THE FR-DP PAIRS IN IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT VARIETY DECISIONS.

	FR	DP
R112	Identify disruptions where they occur	Simplified material flow paths
R113	Identify what the disruption is	Feedback of sub-system state
R121	Identify correct support resources	Specified support resources for each failure mode
R13	Solve problems immediately	Standard method to identify and eliminate root cause

FR-R121 indicates to identify correct support resources by specified support resources for each failure mode (DP-R121). Increased product variety may require additional support personnel to support the failures caused by product variety and it is necessary to specify support personnel for product variety related problems.

FR-R13 is to solve problems immediately and DP-R13 states to achieve it through standard method to identify and eliminate root causes. In this case, it may need to be studied if the standard method is applicable to the given product variety. Some modifications on the level of product variety or the standard method in use may be made based on the study.

7.2.3.1.3 Predictable Output Branch

In the predictable output branch of the MSDD, product variety decisions are related to five FR-DP pairs out of eight leaf FR-DP pairs and one highest FR-DP pair. The list of the FR-DP pairs that are affected by product variety decisions is provided in Table 7-10.

TABLE 7-10. LIST OF THE FR-DP PAIRS IN THE PREDICTABLE OUTPUT BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT VARIETY DECISIONS.

	FR	DP
P11	Ensure availability of relevant production information	Capable and reliable information system
P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
P132	Service equipment regularly	Regular preventative maintenance program
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
P142	Ensure proper timing of part arrivals	Parts moved to downstream operations at pace of customer demand
P1	Minimize production disruptions	Predictable production resources (people, equipment, information)

FR-P11 and DP-P11 address the issue of production information management. More production information may need to be managed to produce more variety of products, which requires a more capable and reliable information system. For example, e-kanban may be more appropriate to deal with high product variety than conventional paper kanban. Therefore, the existing information system should be reviewed in terms of its capability to deal with the proposed level of product variety during product development.

Sometimes, operators may find it difficult to properly handle the proposed product variety. This can lead to the increased variation of each task completion time (FR-P121), which should be avoided. In addition, increased product variety may require various processing capability to the individual equipment. In this case, the preventative maintenance program should be modified to accommodate the changes (FR-P132).

FR-P141 states to ensure the availability of parts to the material handlers by maintaining standard work in process (SWIP) between sub-systems (DP-P141). Product variety decisions significantly affect the level of SWIP in the manufacturing systems. SWIP is necessary to prevent part shortages but should be minimized since it increases manufacturing throughput time as well as costs. Product variety strategies such as modular design and standardized parts sharing may be considered to minimize the level of SWIP within a manufacturing system. In addition, product variety affects part transportation. To ensure proper timing of part arrivals (FR-P142), the consequence of product variety decisions on transportation planning should be thoroughly studied.

Sometimes, the efforts to reduce product variety lead to reduced production disruptions by reducing the sources of disruptions. For example, if the designs of different parts were standardized to reduce product variety in a stamping process, it would eliminate the need for die changeover, which takes out the need for die changeover activity and die transportation activity. These activities can be sources of production disruptions.

7.2.3.1.4 Delay Reduction Branch

In the delay reduction branch of the MSDD, product variety decisions are related to seven FR-DP pairs out of twelve leaf FR-DP pairs. The list of the FR-DP pairs that are affected by product variety decisions is provided in Table 7-11.

TABLE 7-11. LIST OF THE FR-DP PAIRS IN THE DELAY REDUCTION BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT VARIETY DECISIONS.

	FR	DP
T21	Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range
T221	Ensure that automatic cycle time ≤ minimum takt time	Design of appropriate automatic work content at each station
T222	Ensure that manual cycle time ≤ minimum takt time	Design of appropriate operator work content / loops
T223	Ensure level cycle time mix	Stagger production of parts with different cycle times
T23	Ensure that part arrival rate is equal to service rate ($r_a = r_s$)	Arrival of parts at downstream operations according to pace of customer demand
T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment

The delay reduction branch starts from defining takt time (FR-T21) by defining or grouping customers (DP-T21). Product variety decisions may influence the customer demand volume and thus, affect the takt time of a production line. Product variety plays an important role in reducing delays in a manufacturing system. The automatic cycle time of the different types of parts should be ensured to be less than the minimum takt time (FR-T221). The same rule applies to manual cycle time to process the parts (FR-T222). Leveling cycle time mix may help to respond to unexpected variations and be applied to the case that the automatic cycle time is longer than the takt time. However, if different types of products are produced at the same station, their cycle times should not be very different to maximize the efficiency.

Balancing different production groups (e.g., cell, department) to downstream operations in order to have part arrival rate equal to service rate (FR-T23) can be difficult in the case that each production group needs to manage various products. Therefore, the balancing should be carefully coordinated according to the product variety strategy implemented (e.g., modular design, part sharing, delaying differentiation points).

Product variety is also closely related to reducing run size delay. More careful and complex handling of production mix information may be required for increased product variety (FR-T31). In addition, setup changeover capability is heavily influenced by the product variety (FR-T32). Therefore, deep consideration of changeover requirement should be made when product variety decisions are made. For example, a family of products can be designed to minimize the setup changeover requirement. The mix capability of a production line that will produce new products should be considered to check if it is adequate for planned product variety under the selected variety strategy such as modular design and part sharing.

7.2.3.1.5 Operating Cost Branch

In the operating cost branch of the MSDD, product variety decisions are related to four FR-DP pairs out of nine leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by product variety decisions is provided in Table 7-12.

Product variety may require many types of tools, which can make it difficult to standardize tools used at each station and locate them in designated places (FR-D22). On the other hand, it stresses the importance of the standardization of the tools and their locations. Serious consideration needs to be given to the tools in use in case of increased product variety. In a similar way, product variety may increase the kinds of standard work tasks performed at each station. In this case, it may be difficult to assure ergonomic interface designs between the operator, machine, and fixture (DP-D23).

TABLE 7-12. LIST OF THE FR-DP PAIRS IN THE OPERATING COST BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT VARIETY DECISIONS.

	FR	DP
D22	Minimize wasted motion in operators' work preparation	Standard tools/equipment located at each station (5S)
D23	Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine, and fixture
I2	Eliminate information disruptions	Seamless information flow (visual factory)
122	Reduce waste in indirect labor	Reduction of indirect labor tasks
123	Minimize facilities cost	Reduction of consumed floor space

Product variety also affects the information flows within a manufacturing system by increasing the content of information that needs to be transferred (DP-I2). Seamless information flow through visual factory may not be achieved with high product variety. In addition, higher product variety usually requires more indirect labor to coordinate complicated work tasks such as scheduling, tool management, and SWIP management (FR-122). Therefore, the consequence of product variety decisions on indirect labor requirements should be carefully reviewed when product variety decisions are made. Furthermore, the facilities cost that may be increased by product variety should be also considered (FR-123). The results of high product variety such as more tools in use and higher level of SWIP can lead to the consumption of more floor space.

7.2.3.1.6 Investment Branch

Product variety may be provided with increased costs associated with the equipment since it requires flexibility to the equipment. Minimization of investment should be sought but all other requirements described previously should be met first. After resolving all other conflicts, a rational investment decision can be made since the stability of manufacturing systems is kept.

7.2.3.2 Product architecture

Product architecture is closely related to how product variety is provided to the customers. For example, modular design to minimize the complexity associated with the product variety is a result of product architecture design. Therefore, product architecture can affect manufacturing systems by affecting product variety strategy. On the other hand, product architecture itself significantly interacts manufacturing systems in various ways. It is directly related to the structure or layout of manufacturing systems. The FRs and DPs of the MSDD that can be affected by product architecture decisions are shown in Figure 7-11 as black boxes.

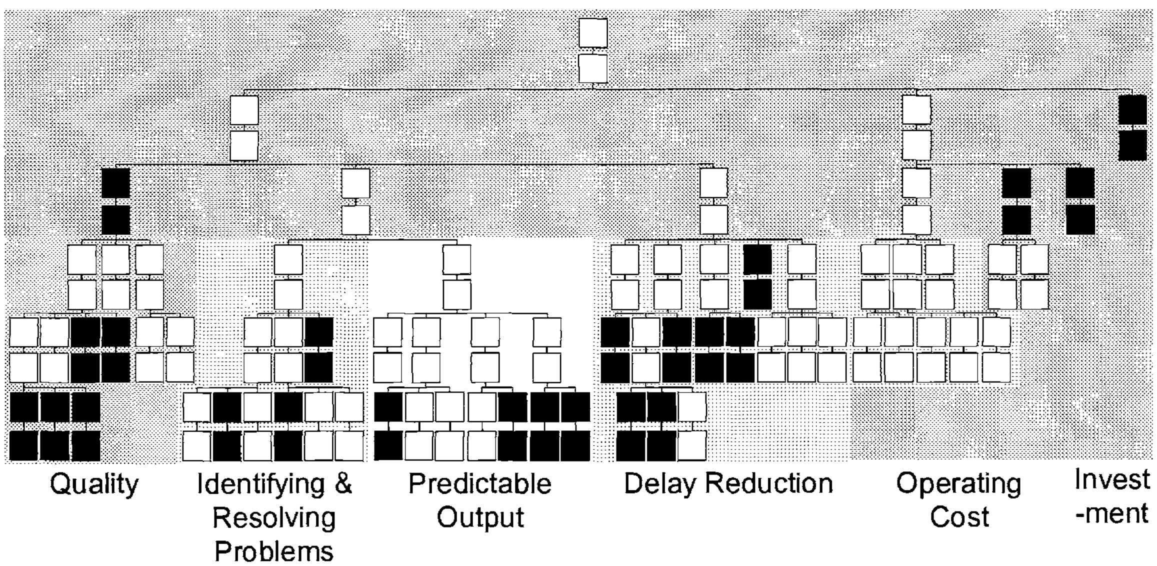


FIGURE 7-11. THE FRS AND DPS OF THE MSDD THAT CAN BE AFFECTED BY A PRODUCT ARCHITECTURE DECISION

As is indicated in Figure 7-11, product variety decisions heavily affect quality and delay reduction branches. Identifying and resolving problems, and predictable output branches are also affected by product architecture decisions along with the investment branch while the impact on operating costs is minimal. Detailed explanation of the impact of product architecture decisions on the FRs and DPs of the MSDD is provided in the following sections. The definition of product architecture used in this thesis is the mapping of functional elements on physical elements as is given in Chapter 3.

7.2.3.2.1 Quality Branch

In the quality branch of the MSDD, product architecture decisions are related to five FR-DP pairs out of nine leaf FR-DP pairs and one highest level FR-DP pair. The list of the FR-DP pairs that are affected by product architecture decisions is provided in Table 7-13.

A product layout design or a bill of materials that is a result of product architecture design influences operator's work tasks. First, often it defines the required tasks for operators and thus, it decides their knowledge requirement (FR-Q111). An inappropriate product layout design may cause inconsistent operator performance in terms of quality (FR-Q112) and thus, the standard work methods in use need to be reconsidered (DP-Q112). In addition, product architecture should be designed to support product variety strategy so that it can contribute to minimize the product variety exposed to operators. This may decrease operator human errors caused by product variety (FR-Q113).

TABLE 7-13. LIST OF THE FR-DP PAIRS IN THE QUALITY BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT ARCHITECTURE DECISIONS.

	FR	DP
Q111	Ensure that operator has knowledge of required tasks	Training program
Q112	Ensure that operator consistently performs tasks correctly	Standard work method
Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
Q13	Eliminate method assignable causes	Process plan design
Q14	Eliminate material assignable causes	Supplier quality program
111	Manufacture products to target design specifications	Production processes with minimal variation from the target

In some cases, the product architecture may not conform to the production method in use (FR-Q13). For example, inappropriate part division may lead to a bad design for casting by requiring extra joining processes. In addition, the materials used to realize the product design may not be adequate with a certain product architecture design (FR-Q14). The material conformance between adjacent parts should be assured in terms of the chemical characteristics as well as mechanical characteristics, for example.

Products should be designed in a way that they work properly when products are manufactured to target design specifications. Product architecture designs are closely related to the propagation of tolerances and thus, inappropriate product architecture may lead to internal failure of product design itself (FR-111). In addition, product architecture designs may lead to a reduced number of assembly processes that are subject to quality control, which may ease the quality control and improve the quality.

7.2.3.2.2 Identifying and Resolving Problems Branch

In the identifying and resolving problems branch of the MSDD, product architecture decisions are related to three FR-DP pairs out of seven leaf FR-DP pairs. The list of the FR-DP pairs that are affected by product architecture decisions is provided in Table 7-14.

TABLE 7-14. LIST OF THE FR-DP PAIRS IN IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT ARCHITECTURE DECISIONS.

	FR	DP
R112	Identify disruptions where they occur	Simplified material flow paths
R121	Identify correct support resources	Specified support resources for each failure mode
R13	Solve problems immediately	Standard method to identify and eliminate root cause

Product architecture decisions are closely linked to material flow paths since they decide the physical division of a product into its components. Therefore, product architecture decisions can affect material flow paths and thus, they should be made after considering their impact on material flow paths (FR-R112).

In addition, specific support resources should be allocated to the failures related to product architecture decisions (DP-R121) and product architecture may be designed in a way that the disruptions related to the design of a component can be solved without affecting other components, which may enhance the speed of problem solving (FR-R13).

7.2.3.2.3 Predictable Output Branch

In the predictable output branch of the MSDD, product architecture decisions are related to four FR-DP pairs out of eight leaf FR-DP pairs. The list of the FR-DP pairs that are affected by product architecture decisions is provided in Table 7-15.

A product architecture design may affect the assembly of a product since it decides the physical structure of a product to be assembled. Depending on the structures that product architecture designs provide, the task completion time of the assembly operators may vary due to the assembly difficulties (FR-P121). In a similar way, maintenance requirements of the equipment in use may be changed depending on the product architecture designs (FR-P132).

TABLE 7-15. LIST OF THE FR-DP PAIRS IN THE PREDICTABLE OUTPUT BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT ARCHITECTURE DECISIONS.

	FR	DP
P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
P132	Service equipment regularly	Regular preventative maintenance program
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
P142	Ensure proper timing of part arrivals	Parts moved to downstream operations at pace of customer demand

Product architecture design can influence FR-P141 indirectly through supporting the product variety strategies such as modular design and part sharing. Part transportation methods, routes, and schedules are subject to changes according to the product architecture designs and thus, they need to be carefully planned to ensure the part supply at the proper timing (FR-P142).

7.2.3.2.4 Delay Reduction Branch

In the delay reduction branch of the MSDD, product architecture decisions are related to seven FR-DP pairs out of twelve leaf FR-DP pairs. The list of the FR-DP pairs that are affected by product architecture decisions is provided in Table 7-16.

The bill of material is the final result of product architecture design decisions and indicates how many components need to be made to build a final product. Therefore, the bill of material is closely related to takt time calculation since takt time is calculated by dividing the available time with customer demand volume (FR-T21). Customer demand volume can be divided into the demand for components, which decide the takt time of the sub production groups (e.g., cells for sub-components, production departments for components).

TABLE 7-16. LIST OF THE FR-DP PAIRS IN THE DELAY REDUCTION BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT ARCHITECTURE DECISIONS.

	FR	DP
T21	Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range
T221	Ensure that automatic cycle time ≤ minimum takt time	Design of appropriate automatic work content at each station
T222	Ensure that manual cycle time ≤ minimum takt time	Design of appropriate operator work content / loops
T23	Ensure that part arrival rate is equal to service rate ($r_a = r_s$)	Arrival of parts at downstream operations according to pace of customer demand
T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment
T4	Reduce transportation delay	Material flow oriented layout design

Product architecture design is about the physical division of a product. Therefore, product architecture design modification may be considered in cases when the automatic cycle time or manual cycle time at a production station is longer than minimum takt time (FR-T221, FR-T222). In addition, as is discussed in the previous section, product architecture affects the material flows within a manufacturing system. When the material flows within a plant are decided, the balancing between production groups to ensure part arrival rate equal to service rate should be reflected in product architecture design (FR-T23). Reducing transportation delay can be also considered at the same time (FR-T4).

Furthermore, product architectures can be designed to support the product variety strategy to minimize the impact of product variety exposed to manufacturing systems, so that the product mix information within a manufacturing system can be reduced (FR-T31). This may lead to the reduced setup changeover requirements since the level of product variety itself is reduced at each station (FR-T32).

7.2.3.2.5 Operating Cost Branch

In the operating cost branch of the MSDD, product architecture decisions are related to one FR-DP pairs out of nine leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by product architecture decisions is provided in Table 7-17.

TABLE 7-17. LIST OF THE FR-DP PAIRS IN THE OPERATING COST BRANCH OF THE MSDD THAT ARE AFFECTED BY PRODUCT ARCHITECTURE DECISIONS.

	FR	DP
122	Reduce waste in indirect labor	Reduction of indirect labor tasks
123	Minimize facilities cost	Reduction of consumed floor space

Labor requirements are linked to the product structure decisions (FR-122). For example, if a product is divided into more physical chunks, more direct labors to assemble them and more indirect labors to manage the chunks as well as direct labors may be necessary. To the contrary, the fine segmentation of a product may lead to easier fabrication which leads to less indirect labor to assure quality, for instance. Therefore, instead of blindly pursuing the famous DFMA rule to minimize the number of parts, indirect labor requirements according to different product architecture design options should be reviewed when product architecture is designed along with their benefits and losses. In a similar way, product architecture decisions affect the consumed floor space (DP-123).

7.2.3.2.6 Investment Branch

The investment requirements of different product architecture design options may be considered as a decision criterion during the product architecture design decision process.

7.2.3.3 Purchasing

Purchasing decisions are made when make or buy decisions are made. If the products are decided to be produced in house, the other five categories such as product variety are applied. However, if the products are decided to be outsourced, some special considerations should be given to the decision in order to keep the stability of the manufacturing system. The FRs and DPs of the MSDD that can be affected by purchasing decisions are presented in Figure 7-12 as black boxes.

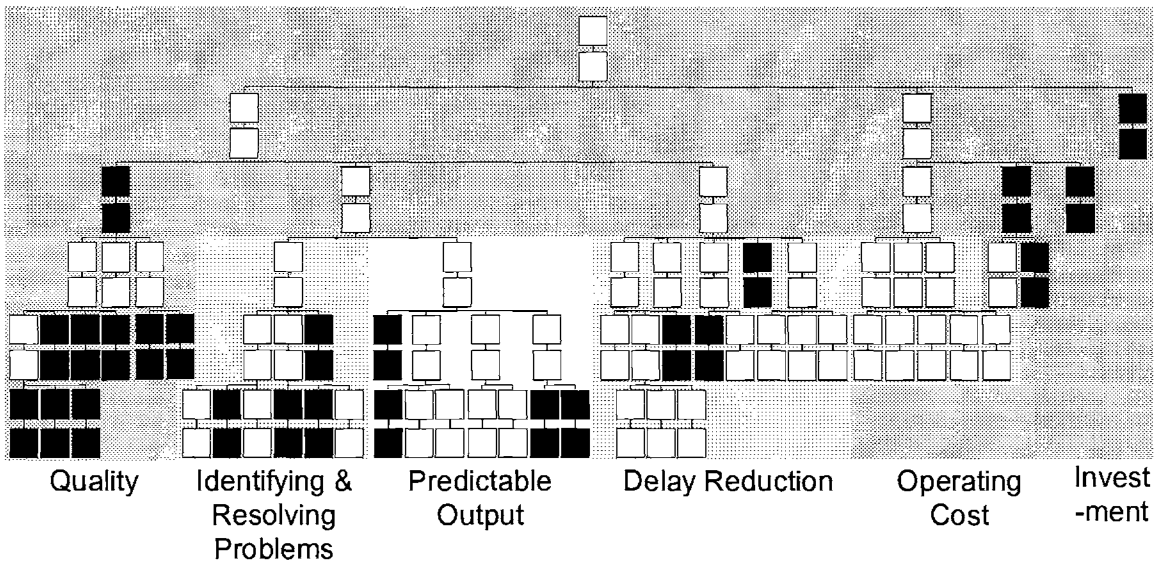


FIGURE 7-12. THE FRS AND DPS OF THE MSDD THAT CAN BE AFFECTED BY A PURCHASING DECISION

As is shown in Figure 7-12, purchasing decisions significantly affect quality, and identifying and resolving problems. Predictable output, delay reduction, and operating cost branches are also affected by purchasing decisions along with the investment branch.

The general problems with the purchased parts are that they are produced by suppliers and thus, the necessary information to assemble the purchased parts may not be available in house. In addition, the supply of the purchased parts should be aligned with in-house productions while minimizing the labor requirements to manage the supplied parts.

Detailed explanation of the impact of purchasing decisions on the FRs and DPs of the MSDD are provided in the following sections.

7.2.3.3.1 Quality Branch

In the quality branch of the MSDD, purchasing decisions are related to eight FR-DP pairs out of nine leaf FR-DP pairs and one highest level FR-DP pair. The list of the FR-DP pairs that are affected by purchasing decisions is provided in Table 7-18.

Assembly operators need to be well trained on how to assemble the purchased parts. Other operators that deal with the purchased parts should be also trained on the characteristics of the purchased parts that require their special attention (FR-Q111). Standard assembly methods need to be prepared for purchased parts (FR-Q112). In black box purchasing cases [Clark and Fujimoto 1991], incorporation of poka-yoke features into the purchased parts may be asked to the part suppliers for easy and defect-free assembly (FR-Q113). Of course, close collaboration between OEM companies and part suppliers is prerequisite for this.

TABLE 7-18. LIST OF THE FR-DP PAIRS IN THE QUALITY BRANCH OF THE MSDD THAT ARE AFFECTED BY PURCHASING DECISIONS.

	FR	DP
Q111	Ensure that operator has knowledge of required tasks	Training program
Q112	Ensure that operator consistently performs tasks correctly	Standard work method
Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
Q12	Eliminate machine assignable causes	Failure mode and effects analysis
Q13	Eliminate method assignable causes	Process plan design
Q14	Eliminate material assignable causes	Supplier quality program
Q31	Reduce noise in process inputs	Conversion of common causes into assignable causes
Q32	Reduce impact of input noise on process output	Robust process design
111	Manufacture products to target design specifications	Production processes with minimal variation from the target

After human related quality issues are solved, other sources of assignable causes should be reviewed. The suitability of purchased parts to existing equipment (FR-Q12) needs to be checked as well as the conformance to the assembly methods in use (FR-Q13). To eliminate material assignable causes (FR-Q14), a new supplier quality program needs to be prepared whenever new purchasing is considered. Through the supplier program, incoming part quality should be guaranteed so that no additional work force is assigned to inspect the incoming purchased parts.

Regarding the noise effect, purchased parts can be a source of noise in process inputs (FR-Q31) and thus, are subject to thorough investigations. To reduce the noise effect, the assembly processes of purchased parts may be designed to be robust to the variation of purchased parts (FR-Q32).

Overall, target design specifications of purchased parts need to be set through discussion with part suppliers (FR-111). In addition, it should be considered that purchasing may eliminate the need for quality assurance of fabrication of sub-assembly parts in house but slow feedback from the suppliers on quality problems may deteriorate the parts quality and require additional workforce to fix the problems.

7.2.3.3.2 Identifying and Resolving Problems Branch

In the identifying and resolving problems branch of the MSDD, purchasing decisions are related to four FR-DP pairs out of seven leaf FR-DP pairs. The list of the FR-DP pairs that are affected by purchasing decisions is provided in Table 7-19.

TABLE 7-19. LIST OF THE FR-DP PAIRS IN IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD THAT ARE AFFECTED BY PURCHASING DECISIONS.

	FR	DP
R112	Identify disruptions where they occur	Simplified material flow paths
R121	Identify correct support resources	Specified support resources for each failure mode
R122	Minimize delay in contacting correct support resources	Rapid support contact procedure
R13	Solve problems immediately	Standard method to identify and eliminate root cause

Purchasing of parts eliminates the need for constructing production lines for the purchased parts. Therefore purchasing may contribute to simplified material flow paths (DP-R112), which serve to identify disruptions where they occur (FR-R112).

As is discussed before, communication problems can be critical to identify and resolve production disruptions in the purchasing case since the parts are produced in suppliers' plants. To identify correct support resources (FR-R121), specified support personnel need to be assigned in both OEM company and supplier companies for each failure mode. To minimize delay in contacting correct support resources (FR-R122), the communication channels with the part suppliers should be well established to ensure quick exchange of information.

To solve problems related to purchased parts immediately (FR-R13), close collaboration with part suppliers is necessary. Standard procedures to solve the disruption problems associated with purchased parts may be prepared in advance and part suppliers may be evaluated based on their ability to immediately respond to and solve the disruption problems.

7.2.3.3.3 Predictable Output Branch

In the predictable output branch of the MSDD, purchasing decisions are related to four FR-DP pairs out of eight leaf FR-DP pairs. The list of the FR-DP pairs that are affected by purchasing decisions is provided in Table 7-20.

TABLE 7-20. LIST OF THE FR-DP PAIRS IN THE PREDICTABLE OUTPUT BRANCH OF THE MSDD THAT ARE AFFECTED BY PURCHASING DECISIONS.

	FR	DP
P11	Ensure availability of relevant production information	Capable and reliable information system
P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
P142	Ensure proper timing of part arrivals	Parts moved to downstream operations at pace of customer demand

Production information of the OEM company is important for the part suppliers to establish their own production schedules and supply parts in a just-in-time basis. Therefore, sharing of relevant production information with part suppliers through a capable and reliable information system is necessary. Production information sharing with part suppliers should be planned in advance during product development in order to avoid production disruptions (FR-P11).

To reduce variability of task completion time (FR-P121), task completion time variation related to the assembly of purchased parts is studied and the result is reflected in both purchasing decision and work method design.

To avoid production disruptions caused by unavailability of materials when they are necessary, the availability of materials to material handlers and their proper transportation are important. The proper level of standard work in process (SWIP) for purchased parts needs to be implemented to avoid unavailability of purchased parts (FR-P141) and the proper level can be decided considering various factors such as transportation distance from the suppliers. Delivery of purchased parts from the storage area to the point of use according to pace of customer demand is necessary to ensure proper timing of purchased parts arrivals (FR-P142).

7.2.3.3.4 Delay Reduction Branch

In the delay reduction branch of the MSDD, purchasing decisions are related to three FR-DP pairs out of twelve leaf FR-DP pairs. The list of the FR-DP pairs that are affected by purchasing decisions is provided in Table 7-21.

TABLE 7-21. LIST OF THE FR-DP PAIRS IN THE DELAY REDUCTION BRANCH OF THE MSDD THAT ARE AFFECTED BY PURCHASING DECISIONS.

	FR	DP
T23	Ensure that part arrival rate is equal to service rate ($r_a = r_s$)	Arrival of parts at downstream operations according to pace of customer demand
T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer
T4	Reduce transportation delay	Material flow oriented layout design

To satisfy FR-T23, the arrival rate of purchased parts to the point of use should be considered. The part arrival rate is fine as long as it is determined by the pace of customer demand. However, the amount of delivery per each shipment from the suppliers is determined considering other factors such as transportation distance and shipping cost.

The sharing of production mix information with part suppliers is important to satisfy FR-T31. For a sequenced delivery of parts from the suppliers in a just-in-time base, the sharing of production mix information with the suppliers is essential.

Transportation delay (FR-T4) may be reduced by direct delivery of purchased parts to the point of use by the part suppliers. Part supply paths should be aligned with material flow oriented layout design of the OEM manufacturing system.

7.2.3.3.5 Operating Cost Branch

In the operating cost branch of the MSDD, purchasing decisions are related to two FR-DP pairs out of nine leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by purchasing decisions is provided in Table 7-22.

TABLE 7-22. LIST OF THE FR-DP PAIRS IN THE OPERATING COST BRANCH OF THE MSDD THAT ARE AFFECTED BY PURCHASING DECISIONS.

	FR	DP
I2	Eliminate information disruptions	Seamless information flow (visual factory)
122	Reduce waste in indirect labor	Reduction of indirect labor tasks
123	Minimize facilities cost	Reduction of consumed floor space

To eliminate information disruption (FR-I2) between the OEM company and the part suppliers, the information flows to and from the part suppliers should be carefully reviewed so that sources of information disruption can be identified and eliminated. This work should be done when purchasing decisions are made to prevent future manufacturing problems. Some information technology (IT) tools may be considered to reduce the indirect labor associated with the information management but the efforts to clearly specify the information flows and simplify them should be made first.

There can be various types of indirect labors associated with purchasing (FR-122). To reduce the wastes in indirect labor, the impact of purchasing decisions on the indirect labors should be identified first. For example, it should be studied how a purchasing decision affects the work content of the purchasing department. A through study on the impact of new purchasing decisions on the capacity and capability of the purchasing functional group will prevent the capacity problems of the purchasing department, which may call for more indirect labors to correct the problems (or to do fire-fighting).

Facility costs associated with part purchasing may be reduced by minimizing the number of purchased parts stored as SWIP (FR-123). However, when the number of purchased parts stored as SWIP is minimized, the requirements from other MSDD branches should be met first.

7.2.3.3.6 Investment Branch

When selecting the part suppliers, it is important to evaluate the capability of the suppliers in various aspects of manufacturing systems as is discussed so far in this section. If only supply cost is considered for supplier selection, the cost saved now will be smaller than the benefits that might be gained by considering other factors concurrently. Suppliers need to interact with OEM companies in many ways as described in this section and the close interaction between two groups will lead to enhanced quality, improved delivery performance, and reduced operating costs in a long run.

7.2.3.4 Material selection

Material selection is an important issue during product development since it affects many aspects of manufacturing systems. Material selection is closely linked to the manufacturing quality. In addition, the selected material works as a constraint when the production process is decided and detailed design is made. Therefore, the material should be selected while considering both production process selection and detailed design simultaneously. The FRs and DPs of the MSDD that can be affected by material selection are presented in Figure 7-13 as black boxes.

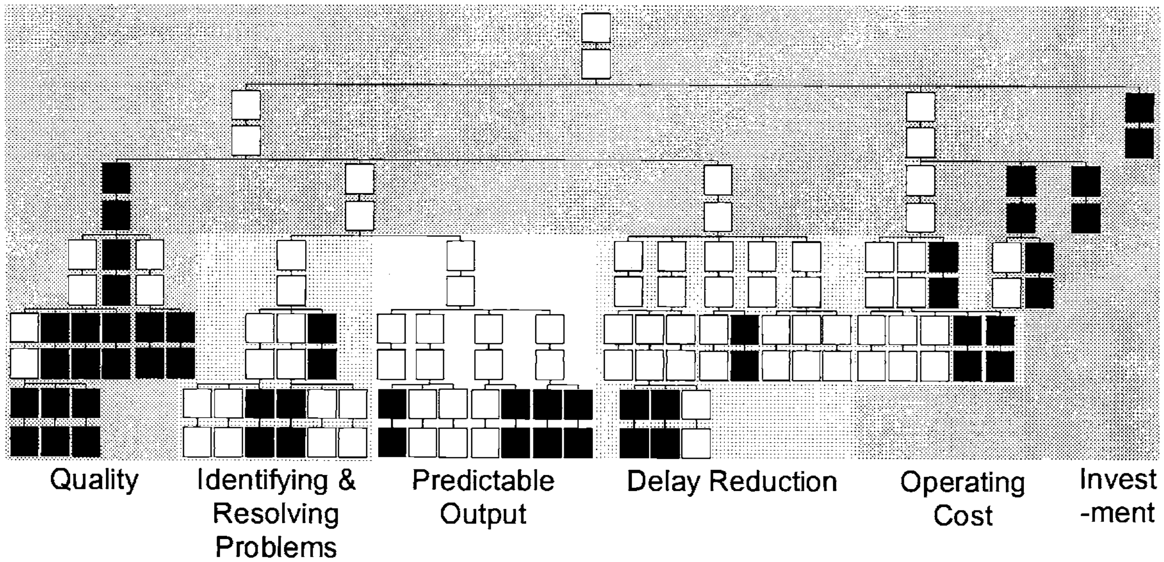


FIGURE 7-13. THE FRS AND DPS OF THE MSDD THAT CAN BE AFFECTED BY MATERIAL SELECTION

As is shown in Figure 7-13, material selection significantly affects quality and operating cost. Identifying and resolving problems, predictable output, and delay reduction branches are also affected by material selection. Detailed explanation of the impact of material selection on the FRs and DPs of the MSDD are provided in the following sections.

7.2.3.4.1 Quality Branch

In the quality branch of the MSDD, material selection is related to all nine leaf FR-DP pairs and one highest level FR-DP pair. The list of the FR-DP pairs that are affected by material selection is provided in Table 7-23.

Material selection is one of the critical decisions for manufacturing quality. With regard to the human related causes of quality problems, new material may call for a different set of required tasks for the operators (FR-Q111) and the established standard work methods are affected by the introduction of new material (DP-Q112). In addition, new material may require mistake-proof features (FR-Q113) when, for example, there is a direction in the material that significantly affects its property (e.g., grain of wood). Therefore, improper consideration of material properties may lead to a big problem in quality by operators' human errors.

Material selection also affects other sources of quality problems. The existing equipment may not be appropriate to process the selected material (FR-Q12). In this case, failure mode and effects analysis (FMEA) data may be reviewed to investigate the effect of materials on the failure of existing equipment if the data are available. In addition to the equipment related problems, the production methods in use may not match with the selected material (FR-Q13) or the quality of incoming materials may not be good enough for processing (FR-Q14). In the latter case, new supplier quality program is necessary to control the quality of incoming materials. The collaboration with material suppliers may enable stable supply of quality materials.

TABLE 7-23. LIST OF THE FR-DP PAIRS IN THE QUALITY BRANCH OF THE MSDD THAT ARE AFFECTED BY MATERIAL SELECTION.

	FR	DP
Q111	Ensure that operator has knowledge of required tasks	Training program
Q112	Ensure that operator consistently performs tasks correctly	Standard work method
Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
Q12	Eliminate machine assignable causes	Failure mode and effects analysis
Q13	Eliminate method assignable causes	Process plan design
Q14	Eliminate material assignable causes	Supplier quality program
Q2	Center process mean on the target	Process parameter adjustment
Q31	Reduce noise in process inputs	Conversion of common causes into assignable causes
Q32	Reduce impact of input noise on process output	Robust process design
111	Manufacture products to target design specifications	Production processes with minimal variation from the target

To center process mean on the target (FR-Q2), it is necessary to thoroughly study material properties and its interactions with process parameters during the material selection process. Then, the noise factor can be treated. To reduce impact input noise on process output (FR-Q31), incoming materials need to be checked if any sources of noise can come from the selected incoming materials. In addition, the production process for the selected material should be designed to be robust to the material property variation (DP-Q32).

Overall, meaningful tolerance levels (FR111) according to the material types should be well understood and reflected in the material selection (e.g., achievable tolerance of wooden product is different from that of aluminum alloy).

7.2.3.4.2 Identifying and Resolving Problems Branch

In the identifying and resolving problems branch of the MSDD, material selection is related to three FR-DP pairs out of seven leaf FR-DP pairs. The list of the FR-DP pairs that are affected by material selection is provided in Table 7-24.

TABLE 7-24. LIST OF THE FR-DP PAIRS IN IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD THAT ARE AFFECTED BY MATERIAL SELECTION.

	FR	DP
R113	Identify what the disruption is	Feedback of sub-system state
R121	Identify correct support resources	Specified support resources for each failure mode
R13	Solve problems immediately	Standard method to identify and eliminate root cause

Material selection may affect FR-R113 by adding new kind of disruptions that can happen with new materials. Possible disruption states due to the introduction of new materials (e.g., new material can damage tools in certain conditions) may be studied and reflected in the feedback system in order to satisfy the FR-R113.

With regard to FR-R121, specific support resources should be assigned to the failure modes related to the materials in both material suppliers and the OEM company. In addition, standard procedures to solve the production disruptions associated with new materials may need to be prepared in advance (FR-R13).

7.2.3.4.3 *Predictable Output Branch*

In the predictable output branch of the MSDD, material selection is related to four FR-DP pairs out of eight leaf FR-DP pairs. The list of the FR-DP pairs that are affected by material selection is provided in Table 7-25.

TABLE 7-25. LIST OF THE FR-DP PAIRS IN THE PREDICTABLE OUTPUT BRANCH OF THE MSDD THAT ARE AFFECTED BY MATERIAL SELECTION.

	FR	DP
P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
P132	Service equipment regularly	Regular preventative maintenance program
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
P142	Ensure proper timing of part arrivals	Parts moved to downstream operations at pace of customer demand

The introduction of new materials may affect the variability of task completion time of the workers and thus, the standard work methods may be modified accordingly to minimize the variation of work completion time (FR-P121). In addition, new materials may work differently to the equipment in use and change the maintenance requirements. Therefore, the preventative maintenance program may be subject to modification depending on the type of materials used (DP-P132).

Reliable and timely supply of new materials is important. Before selecting the material, the material should be reviewed if it can be supplied reliably (FR-P141) and timely (FR-P142). Selecting commodity materials may help to minimize these problems.

7.2.3.4.4 *Delay Reduction Branch*

In the delay reduction branch of the MSDD, material selection is related to three FR-DP pairs out of twelve leaf FR-DP pairs. The list of the FR-DP pairs that are affected by material selection is provided in Table 7-26.

In case that a new material is used with the existing process, to ensure the FR-T221, the new material should be checked if it affects automatic cycle time of the existing process and it should be assured that the automatic cycle time with new material is shorter than minimum takt time. Otherwise, alternative materials need to be studied to keep automatic cycle time under minimum takt time. Material properties can lead to different processing time to achieve a certain level of quality. For example, drilling a hole on an aluminum block is different from doing the same work on a steel block.

The same principle applies to the case of FR-T222. The consequence of new material on the cycle time of existing manual operation in use needs to be thoroughly studied and should be assured that the manual cycle time with new material is shorter than minimum takt time.

The introduction of new materials on the shop floor may affect the requirements for the changeover. For example, the introduction of different materials at the same machine may require complete cleaning of the machine to minimize the contamination of the next product. In addition, new material that helps quick changeover is continuously sought to support production (e.g., new painting material that support changeover between colors).

TABLE 7-26. LIST OF THE FR-DP PAIRS IN THE DELAY REDUCTION BRANCH OF THE MSDD THAT ARE AFFECTED BY MATERIAL SELECTION.

	FR	DP
T221	Ensure that automatic cycle time ≤ minimum takt time	Design of appropriate automatic work content at each station
T222	Ensure that manual cycle time ≤ minimum takt time	Design of appropriate operator work content / loops
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment

7.2.3.4.5 Operating Cost Branch

In the operating cost branch of the MSDD, material selection is related to five FR-DP pairs out of nine leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by material selection is provided in Table 7-27.

The introduction of a new material often requires special tools to handle the process. The tool requirement of the new material needs to be studied and the standardization should be pursued, so that the tools can be shared in other processes. Tool management and location should also be planned so that the operators do not need to waste their precious time finding tools (FR-D22). For the same purpose, the impact of the new material on the ergonomic design of interfaces between machine, fixture, and people may be studied (FR-D23). Especially in the case that the selected material is not a commodity material, it is important to check above-mentioned characteristics of the material.

TABLE 7-27. LIST OF THE FR-DP PAIRS IN THE OPERATING COST BRANCH OF THE MSDD THAT ARE AFFECTED BY MATERIAL SELECTION.

	FR	DP
D22	Minimize wasted motion in operators' work preparation	Standard tools/equipment located at each station (5S)
D23	Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine, and fixture
D3	Eliminate operators' waiting on other operators	Balanced work-loops
I2	Eliminate information disruptions	Seamless information flow (visual factory)
122	Reduce waste in indirect labor	Reduction of indirect labor tasks
123	Minimize facilities cost	Reduction of consumed floor space

A new material may affect the design of operators' work tasks or the information requirement. It needs to be clarified that the new material does not negatively affect the existing operator work loops (FR-D3). In addition, the additional information requirements due to the introduction of the new material should be identified and incorporated into the visual information system to eliminate information disruptions (FR-I2).

The consequence of the use of new material on indirect labor requirement should be reviewed and considered during material selection process (FR-122). A special material may require additional indirect labor to inspect, store, and process it. Furthermore, it needs to be checked if the use of a new material requires additional storage space and if there is space available for the new material in the selected production site (FR-123).

7.2.3.4.6 Investment Branch

Any investment decision regarding the introduction of a new material is subject to thorough financial analysis after resolving the conflicts with the previous FR-DP pairs.

7.2.3.5 Process selection

Process selection is a very important issue during product development with regard to manufacturability since it directly and widely affects manufacturing systems. In other words, selected processes define almost every aspect of manufacturing systems such as the equipment to be used, the assembly sequence to be used, and the cycle time to be achieved. Especially, process selection is closely linked to manufacturing quality, since the quality of a product is a result of production processes. In addition, the selected process works as a constraint when the detailed design is made. The detailed design should be made to support the selected processes.

The FRs and DPs of the MSDD that can be affected by process selection are presented in Figure 7-14.

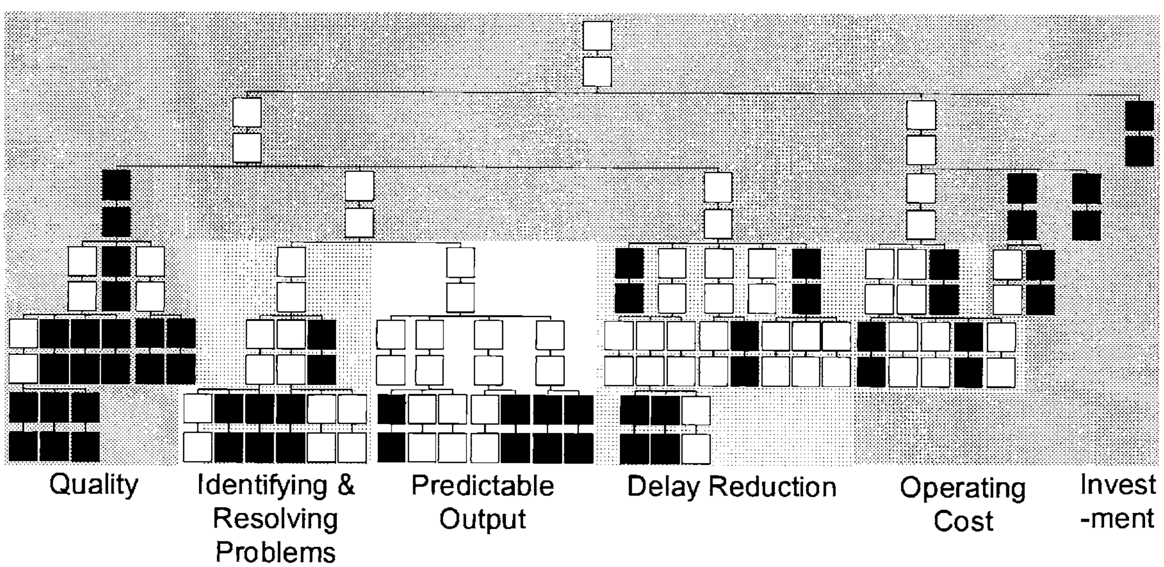


FIGURE 7-14. THE FRS AND DPS OF THE MSDD THAT CAN BE AFFECTED BY PROCESS SELECTION

As is shown in Figure 7-14, process selection significantly affects quality, identifying and resolving problems, reducing delays, and operating cost. Especially, all nine leaf FR-DP pairs in the quality branch of the MSDD are related to process selection. This is expected natural since the quality branch of the MSDD is made up of FRs and DPs related to the control of the manufacturing processes. Predictable output and investment branches are also affected by process selection. Detailed explanation of the impact of process selection on the FRs and DPs of the MSDD are provided in the following sections.

7.2.3.5.1 Quality Branch

In the quality branch of the MSDD, process selection is related to all nine leaf FR-DP pairs and one highest level FR-DP pair. The list of the FR-DP pairs that are affected by process selection is provided in Table 7-28.

TABLE 7-28. LIST OF THE FR-DP PAIRS IN THE QUALITY BRANCH OF THE MSDD THAT ARE AFFECTED BY PROCESS SELECTION.

	FR	DP
Q111	Ensure that operator has knowledge of required tasks	Training program
Q112	Ensure that operator consistently performs tasks correctly	Standard work method
Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
Q12	Eliminate machine assignable causes	Failure mode and effects analysis
Q13	Eliminate method assignable causes	Process plan design
Q14	Eliminate material assignable causes	Supplier quality program
Q2	Center process mean on the target	Process parameter adjustment
Q31	Reduce noise in process inputs	Conversion of common causes into assignable causes
Q32	Reduce impact of input noise on process output	Robust process design
111	Manufacture products to target design specifications	Production processes with minimal variation from the target

A new process often requires new tasks from operators. Operators should be well aware of new tasks from the new process and it is beneficial for operators to be familiar with a new process since it may reduce possible sources of variation. Therefore, first, operators' capabilities and knowledge on the new process need to be reviewed and considered when a major decision on process design is made. Then newly required operators' knowledge for the new process should be identified and the planning of the operator training program should follow (FR-Q111). In addition, the new process calls for new standard work methods to be used to ensure the operators consistently perform tasks correctly (FR-Q112).

To satisfy FR-Q113, typical operators' human mistakes with the new process should be identified first. The sources of the human mistakes may be eliminated through changing the proposed process or implementing mistake-proof devices that are appropriate with the new process.

Other assignable causes of quality problems should be also studied. The suitability of the existing or selected equipment should be reviewed, and possible machine assignable causes need to be identified and eliminated (FR-Q12). The capability of the process may need to be checked against the given product design and tolerances (FR-Q13), and the adaptability of the selected process to the selected material should be checked (FR-Q14).

In order to center process mean on the target (FR-Q2), it is essential to understand the impacts of process parameters on the process output mean. In addition, the characteristics of the equipment used for the new process may need to be studied through the close collaboration with equipment vendors. In a similar way, the noise in process input may be eliminated or compensated through a careful study of the effect of the noise on the output quality of the new process (FR-Q31) and based on the gained knowledge, the robust design of the process may be achieved (FR-Q32).

Choosing different processes may lead to a reduced number of production processes. For example, near-net shape processes such as casting can greatly reduce the number of production processes that are subject to quality control, which may contribute to quality improvement (FR-111). The sensitivity of the process outputs on each process parameter may be analyzed and used to control the variation of the process outputs.

7.2.3.5.2 *Identifying and Resolving Problems Branch*

In the identifying and resolving problems branch of the MSDD, process selection is related to four FR-DP pairs out of seven leaf FR-DP pairs. The list of the FR-DP pairs that are affected by process selection is provided in Table 7-29.

Such processes as stamping and casting greatly affect the material flows within a plant due to the associated huge investment or very short cycle time. Therefore, to identify disruptions where they occur (FR-R112) through simplified material flow paths (DP-R112), the impact of a new process on the material flow paths within a selected production site should be thoroughly studied so that the simplest material flow paths can be maintained.

In addition, different processes may lead to different types of disruptions on the shop floor. For example, a casting process may show different types of disruptions from a machining process. Possible disruption states due to the new process need to be studied and reflected in the feedback system (DP-R113). Specific support personnel in manufacturing, production engineering, and produce design groups can be assigned to the disruptions related to the new process (DP-R121).

The root causes of the production disruption due to the new process should be eliminated by the standard procedures and thus, the standard procedures should be defined and prepared in advance (FR-R13).

TABLE 7-29. LIST OF THE FR-DP PAIRS IN IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD THAT ARE AFFECTED BY PROCESS SELECTION.

	FR	DP
R112	Identify disruptions where they occur	Simplified material flow paths
R113	Identify what the disruption is	Feedback of sub-system state
R121	Identify correct support resources	Specified support resources for each failure mode
R13	Solve problems immediately	Standard method to identify and eliminate root cause

7.2.3.5.3 *Predictable Output Branch*

In the predictable output branch of the MSDD, process selection is related to four FR-DP pairs out of eight leaf FR-DP pairs. The list of the FR-DP pairs that are affected by process selection is provided in Table 7-30.

The introduction of a new process may lead to variable task completion time. To reduce the variation of task completion time, standard work methods for the new process need to be developed (FR-P121). In addition, different production processes may call for different maintenance requirements for the equipment (FR-P132). Therefore, the consequence of the selected process on existing preventative maintenance programs should be reviewed and appropriate changes should be made accordingly.

TABLE 7-30. LIST OF THE FR-DP PAIRS IN THE PREDICTABLE OUTPUT BRANCH OF THE MSDD THAT ARE AFFECTED BY PROCESS SELECTION.

	FR	DP
P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
P132	Service equipment regularly	Regular preventative maintenance program
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
P142	Ensure proper timing of part arrivals	Parts moved to downstream operations at pace of customer demand

The proper level of standard work in process (SWIP) should be planned for the selected process to ensure the parts availability after the selected process (FR-P141) and the planning of the transportation of the parts to and from the selected process is necessary to ensure proper timing of part arrivals (FR-P142).

7.2.3.5.4 *Delay Reduction Branch*

In the delay reduction branch of the MSDD, process selection is related to four FR-DP pairs out of twelve leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by process selection is provided in Table 7-31.

When defining the lot size (or transfer batch size), it is necessary to consider the characteristics of the selected process to decide the adequate lot size. For example, casting of small parts may be done in a batch due to the required cooling time, mold costs, or necessary investment on the casting equipment. Even in this case, it should be reminded that single piece flow is the best way to reduce lot delay (FR-T1) and thus, the minimization of the transfer batch size should be sought.

Estimated automatic cycle time of a new process should be shorter than the minimum takt time (FR-T221). Otherwise, alternative processes may be considered to keep automatic cycle time under minimum takt time. Duplication of the process may be another solution but should be avoided if possible since it complicates the material flows and information flows. In addition, production processes should be allocated to each machine in a way that the total cycle time is less than minimum takt time. Otherwise, some of the processes are allocated to another machine. The same rule applies to the manual cycle time (FR-T222).

TABLE 7-31. LIST OF THE FR-DP PAIRS IN THE DELAY REDUCTION BRANCH OF THE MSDD THAT ARE AFFECTED BY PROCESS SELECTION.

	FR	DP
T1	Reduce lot delay	Reduction of transfer batch size (single-piece flow)
T221	Ensure that automatic cycle time ≤ minimum takt time	Design of appropriate automatic work content at each station
T222	Ensure that manual cycle time ≤ minimum takt time	Design of appropriate operator work content / loops
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment
T5	Reduce systematic operational delays	Subsystem design to avoid production interruptions.

The changeover capability of the selected process needs to be considered (FR-T32). The changeover capability of a process depends on the equipment used and the characteristics of the process. A thorough review on the changeover capability is necessary to produce in sufficiently small run sizes. This issue becomes more important in case of high product variety.

Systematic operational delay is caused by the interruption among production resources with supportive resources (FR-T5). The consequence of the selected process on systematic interruptions should be studied. For example, a new process may be considered to eliminate the need for supportive activities. Using laser trimming instead of stamping will eliminate the need for stamping die transportation activity, which is a support activity.

7.2.3.5.5 Operating Cost Branch

In the operating cost branch of the MSDD, process selection is related to five FR-DP pairs out of nine leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by process selection is provided in Table 7-27.

TABLE 7-32. LIST OF THE FR-DP PAIRS IN THE OPERATING COST BRANCH OF THE MSDD THAT ARE AFFECTED BY PROCESS SELECTION.

	FR	DP
D11	Reduce time operators spend on non-value added tasks at each station	Machines and stations designed to run autonomously
D22	Minimize wasted motion in operators' work preparation	Standard tools/equipment located at each station (5S)
D3	Eliminate operators' waiting on other operators	Balanced work loops
I2	Eliminate information disruptions	Seamless information flow (visual factory)
122	Reduce waste in indirect labor	Reduction of indirect labor tasks
123	Minimize facilities cost	Reduction of consumed floor space

Efficient use of operators is possible by reducing the time operators spend on non-value added tasks at each station (FR-D11). This is possible through the design of machines and stations that run automatically and detect problems by themselves. Therefore, it is necessary to study technical feasibility of automating the selected process. Another way to maximize the operator utilization is to minimize wasted motion in work preparation (FR-D22). Tools necessary for the selected process should be identified and their standardization and storage need to be planned considering various factors such as the frequency of changeover and operators' walking distance.

The introduction of a new process on the shop floor may affect the operators' work loops, which may lead to unbalanced operators work loops. The impact of the new process on existing operators work loops should be thoroughly studied to avoid this conflict (FR-D3). The new process may also affect the information flows. The effect of the new process on the information flows should be reviewed in order to minimize information disruptions. Eliminating the need for information flows is a good way to eliminate the information disruptions. For example, laser cutting substituting stamping eliminates the need for die changeover information flow (FR-I2).

In addition, the introduction of a new process can affect indirect labor requirement in various ways (FR-122). For example, laser cutting substituting stamping eliminates the need for indirect labors that transport and maintain dies used in stamping, while increases the need for maintenance resources for laser technology. The effect of new processes on floor space consumption also needs to be reviewed (FR-123).

7.2.3.5.6 Investment Branch

The introduction of a new process on the shop floor is usually accompanied by the new equipment for the new process. Therefore, investment efficiency evaluation is inevitable. Various financial analyses may be conducted including net present value analysis (NPV) of the savings and the necessary investment with the introduction of the new process. However, financial analyses should not lead the process selection decisions. They should be used as the final decision criterion to choose one among many options that resolve the conflicts addressed in the previous sections.

7.2.3.6 Detailed design

Detailed design decisions are closely linked to other categories of product/process decisions with regard to manufacturability. Detailed designs are made to support the decisions made in upstream such as product variety, product architecture, materials, and processes. For example, detailed design should support the selected process (e.g., casting) with special features (e.g., draft angles) in order to facilitate manufacturing. Therefore, detailed design affects the manufacturability of a product design indirectly. On the other hand, detailed design directly affects the manufacturability by deciding the final geometry and tolerance of a product design. In this section, the term, detailed design, is used to generally indicate the activity to finalize the details of a product design.

The FRs and DPs of the MSDD that can be affected by detailed design decisions are presented in Figure 7-15 as black boxes.

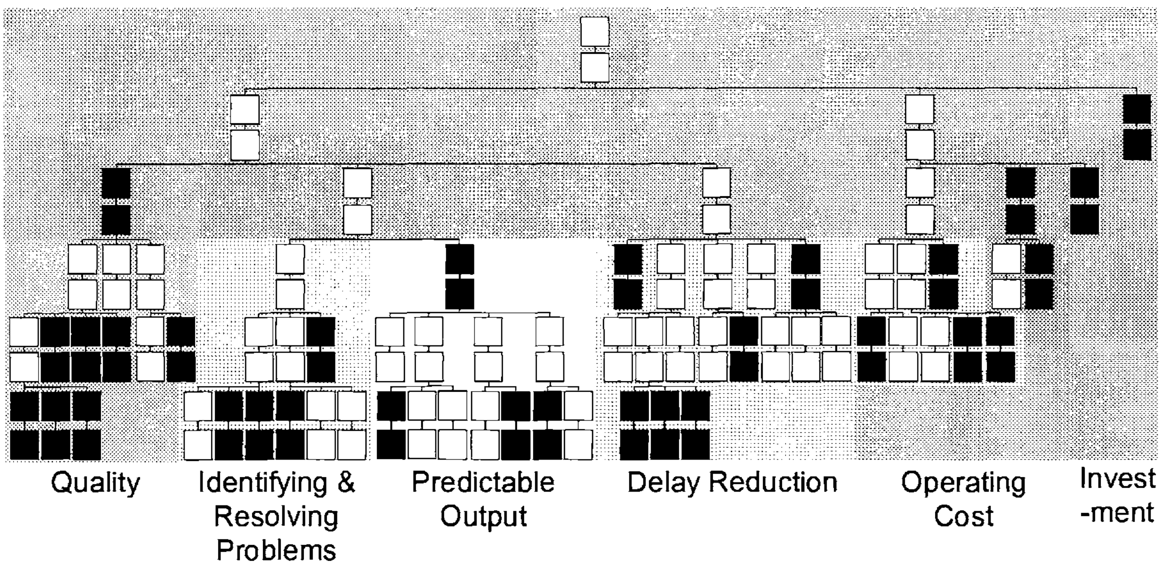


FIGURE 7-15. THE FRS AND DPS OF THE MSDD THAT CAN BE AFFECTED BY DETAILED DESIGN

As is shown in Figure 7-15, detailed design decisions significantly affect quality, identifying and resolving problems, reducing delays, and operating cost. Predictable output and investment branches are also affected by detailed design decisions. Detailed explanation of the impact of detailed design decisions on the FRs and DPs of the MSDD are provided in the following sections.

7.2.3.6.1 Quality Branch

In the quality branch of the MSDD, detailed design decisions are related to seven leaf FR-DP pairs and one highest level FR-DP pair. The list of the FR-DP pairs that are affected by detailed design decisions is provided in Table 7-33.

Regarding the operator assignable causes of quality problems, detailed design decisions may negatively affect the efforts to eliminate quality problems in several ways. First detailed design decisions can shape the tasks that are supposed to be performed by the operators (FR-Q111). The degree of the influence may not be as significant as that of product architecture design, for example, but detailed design can certainly affect the required tasks. Therefore, the consequence of detailed design decisions on the operators' work tasks should be reviewed. Operators need to be trained on the required tasks set by detailed design decisions. Another way that detailed design decisions influence the operator assignable quality problems is by affecting the standard work methods. Changes in detailed design may require corresponding changes in the existing standard work methods and thus, disturb the achievement of FR-Q112. The consequence of detailed design decisions on standard work methods needs to be reviewed. Some design changes may be made accordingly if necessary. Furthermore, detailed design decisions can interrupt the satisfaction of FR-Q113. Detailed design of a product is closely related to the mistakes made by the operators and thus, can be used to eliminate the mistakes. For example, if detailed design of a product supports easy and obvious assembly (e.g., it is easy to locate a part in the right position and direction during the assembly), the operator human mistakes can be greatly reduced during the assembly.

TABLE 7-33. LIST OF THE FR-DP PAIRS IN THE QUALITY BRANCH OF THE MSDD THAT ARE AFFECTED BY DETAILED DESIGN DECISIONS.

	FR	DP
Q111	Ensure that operator has knowledge of required tasks	Training program
Q112	Ensure that operator consistently performs tasks correctly	Standard work method
Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
Q12	Eliminate machine assignable causes	Failure mode and effects analysis
Q13	Eliminate method assignable causes	Process plan design
Q14	Eliminate material assignable causes	Supplier quality program
Q32	Reduce impact of input noise on process output	Robust process design
111	Manufacture products to target design specifications	Production processes with minimal variation from the target

FR-Q12 is linked to the issue of equipment reusability. If new detailed design decisions bring too many machine assignable quality problems, a new machine may need to be implemented. In addition, if the existing machines are not capable of processing the given detailed design, it can be another reason for investing in new machines. Therefore, the consequence of the detailed design on the reusability of existing equipment needs to be reviewed and design changes should be made accordingly to maximize the reuse of existing equipment. It is often economical to change product designs instead of manufacturing equipment.

Detailed design decisions also interact with production methods (FR-Q13). The capability of the existing production methods against the given detailed design can be a problem while the supportability of the detailed design to the given production methods may cause some troubles. The decision will vary depending on where to place the priority. Typically, detailed design changes are made according to the selected production method since detailed design is easier to change, compared to the change of production methods. In a similar way, detailed design affect the achievement of FR-Q14. Therefore, it may need to be checked if detailed design decisions are appropriate with the current quality level of incoming materials, for example.

Products may be designed to be robust to the variation of process output caused by input noise (FR-Q32) by setting tolerances generously (FR-111). Tolerances need to be optimized between engineering requirements and manufacturing requirements. It is necessary to consider both aspects. As one way to consider the manufacturing side in tolerance decision, process capability of the existing production line may be reviewed by product designers so that the current process capability can be reflected in design specifications in order to avoid further investment on improving the process capability.

7.2.3.6.2 Identifying and Resolving Problems Branch

In the identifying and resolving problems branch of the MSDD, detailed design decisions are related to four FR-DP pairs out of seven leaf FR-DP pairs. The list of the FR-DP pairs that are affected by detailed design decisions is provided in Table 7-34.

Detailed design decisions may affect the material flow paths within the manufacturing system (DP-R112). For example, as is presented in Chapter 2, angled fluid channels of an ABS housing may require dedicated machines, which changes the material flow paths. Product designers need to understand the consequences of detailed design on the material flow paths. In addition, there may be some disruptions caused by detailed design decisions, which should be reflected in the feedback system (FR-R113).

FR-R121 indicates to identify correct support resources. Particular support resources to each failure mode related to detailed design can be specified for this purpose. Support resources should be specified in manufacturing, production engineering, and product design groups so that they can solve the problems together. These support resources may solve the disruption problems associated with detailed design with the standard procedures prepared in advance (FR-R13).

TABLE 7-34. LIST OF THE FR-DP PAIRS IN IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD THAT ARE AFFECTED BY DETAILED DESIGN DECISIONS.

	FR	DP
R112	Identify disruptions where they occur	Simplified material flow paths
R113	Identify what the disruption is	Feedback of sub-system state
R121	Identify correct support resources	Specified support resources for each failure mode
R13	Solve problems immediately	Standard method to identify and eliminate root cause

7.2.3.6.3 *Predictable Output Branch*

In the predictable output branch of the MSDD, detailed design decisions are related to three FR-DP pairs out of eight leaf FR-DP pairs and one highest level FR-DP pair. The list of the FR-DP pairs that are affected by detailed design decisions is provided in Table 7-35.

Detailed design decisions can be made in a way to reduce the variations in the task completion time (FR-P121). For example, parts can be designed to be easily maneuverable to reduce the variation of handling time. The new detailed design decisions made to satisfy FR-P121 may interact with the machine, which brings new maintenance requirements. Therefore, the existing preventative maintenance programs should be reviewed and modified to accommodate the new requirements (DP-P132).

The MSDD indicates to satisfy FR-P141 by standard work in process between sub-systems (DP-P141). Detailed design can support the satisfaction of FR-P141 by enabling part sharing through the use of common components within a product family

TABLE 7-35. LIST OF THE FR-DP PAIRS IN THE PREDICTABLE OUTPUT BRANCH OF THE MSDD THAT ARE AFFECTED BY DETAILED DESIGN DECISIONS.

	FR	DP
P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
P132	Service equipment regularly	Regular preventative maintenance program
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
P1	Minimize production disruptions	Predictable production resources (people, equipment, information)

During the detailed design phase of product development, detailed design decisions should be made in a way to minimize the production disruptions (FR-P1). Frequent design change suggestions from manufacturing may greatly facilitate this.

7.2.3.6.4 Delay Reduction Branch

In the delay reduction branch of the MSDD, detailed design decisions are related to five FR-DP pairs out of twelve leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by detailed design decisions is provided in Table 7-36.

TABLE 7-36. LIST OF THE FR-DP PAIRS IN THE DELAY REDUCTION BRANCH OF THE MSDD THAT ARE AFFECTED BY DETAILED DESIGN DECISIONS.

	FR	DP
T1	Reduce lot delay	Reduction of transfer batch size (single-piece flow)
T221	Ensure that automatic cycle time ≤ minimum takt time	Design of appropriate automatic work content at each station
T222	Ensure that manual cycle time ≤ minimum takt time	Design of appropriate operator work content / loops
T223	Ensure level cycle time mix	Stagger production of parts with different cycle times
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment
T5	Reduce systematic operational delays	Subsystem design to avoid production interruptions

Once the production process is decided and thus, the lot size is decided, detailed designs should be made to support the selected lot size (FR-T1). For example, if four parts are produced by the casting process at one cycle, detailed designs should be made to fit for the given lot size.

Minor changes in detailed design that do not interact with other design decisions may be sought to satisfy the sub-FRs of FR-T22. Detailed design changes may be sought to keep automatic (FR-T221) and manual cycle time (FR-T222) under the minimum takt time. If different types of products are to be produced at the same station/machine, detail designs may be modified to make their cycle times similar (FR-T223). Furthermore, product design engineers may be able to facilitate setup changeover by changing detailed design (FR-T32). For instance, standardizing the location of holes of various products may lead to the elimination of the stamping die changeover. This effort may result in the elimination of the need for supporting activities (FR-T5). Standardizing the hole locations eliminates the need for die changeover, which also gets rid of the need for die transportation activity. Since less supporting activities are applied, the chance for a production disruption caused by the supporting activities is lowered.

7.2.3.6.5 Operating Cost Branch

In the operating cost branch of the MSDD, detailed design decisions are related to six FR-DP pairs out of nine leaf FR-DP pairs and one high level FR-DP pair. The list of the FR-DP pairs that are affected by detailed design decisions is provided in Table 7-37.

FR-D11 states to reduce time operators spend on non-value added tasks at each station. DP-D11 indicates to satisfy this FR by autonomously running machines. Autonomous running means the simple and reliable automation with problem detection capability or mistake proof capability. Product designers need to consider the issues related to the automation of the production processes and reflect them into detailed design to facilitate autonomous run of the equipment. In addition, the tool requirements caused by the detailed design decisions should also be studied. Standardization of the tools should be sought along with efficient tool retrieval and storage (FR-D22).

Detailed design decisions may negatively affect the interface design between man, machine, and fixture. The impact of detailed designs on the ergonomic design of the interfaces needs to be analyzed and detailed designs that support the ergonomic interfaces should be sought (FR-D23).

TABLE 7-37. LIST OF THE FR-DP PAIRS IN THE OPERATING COST BRANCH OF THE MSDD THAT ARE AFFECTED BY DETAILED DESIGN DECISIONS.

	FR	DP
D11	Reduce time operators spend on non-value added tasks at each station	Machines and stations designed to run autonomously
D22	Minimize wasted motion in operators' work preparation	Standard tools/equipment located at each station (5S)
D23	Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine, and fixture
D3	Eliminate operators waiting on other operators	Balanced work-loops
I2	Eliminate information disruptions	Seamless information flow (visual factory)
122	Reduce waste in indirect labor	Reduction of indirect labor tasks
123	Minimize facilities cost	Reduction of consumed floor space

There are several other manufacturability issues associated with detailed design decisions. The balancing of the operators work loops should be maintained with the selected detail design. If not, minor modification on detailed design may be sought to regain the balance (FR-D3). The effect of new detailed design on information flow also needs to be studied. A wise detailed design may eliminate the need for the information flows and thus, reduces information disruptions. Standardizing the location of the holes of a part in stamping process, for example, eliminates the need for the information flow for die changeover (FR-I2). Overall, the consequence of detailed design decisions on indirect labor requirement should be studied and reflected in detailed design (FR-122).

Detailed design may be able to contribute to reduce the floor space consumption. It is often done in an indirect way. For example, by supporting product variety strategies such as component sharing, detailed design can reduce the consumed floor space (DP-123).

7.2.3.6.6 Investment Branch

Detailed design decisions are sometimes significantly related to the investment issues. As is stated in Chapter 2, the angled fluid channels of the ABS housing lead to the additional investment on fixtures and the dedication of the machines to a certain product type.

However, detailed design often indirectly affects the investment decisions by supporting other categories of product/process design to minimize the total costs. For example, detailed design should support the delaying of differentiation points as late as possible, which can decrease the level of product variety exposed to the production. Decreased product variety requires less equipment flexibility and this may lead to smaller investment requirements.

7.2.4 The Relationship Between Six Categories of Design Decisions and the FRs of the MSDD

In the previous sections, the FR-DP pairs that are affected by each category of design decisions are investigated. It is considered how a design decision may affect the FRs and DPs of the MSDD. By reversing the order, however, some insights on the relationship between the achievement of the FRs of the MSDD and the design decisions may be obtained. In this way, when a FR of the MSDD is not satisfied well in a manufacturing system, its root cause can be traced back to the design of the products that are produced in the manufacturing system. In this section, it is reviewed what categories of design decisions affect a FR-DP pair of the MSDD. The relationship between the FRs of the MSDD and the design categories are presented in Table 7-38. As shown in Table 7-38, the quality branch of the MSDD is most significantly affected by design decisions. Therefore, it is no wonder to see that existing literature such as DFMA focuses on quality issues.

A detailed study on the individual FR-DP pairs that are affected by each of the six design decision categories reveals that some FR-DP pairs are affected by the most of the six design decision categories. Table 7-39 shows the FR-DP pairs that are affected by more than five categories of design decisions out of six categories.

TABLE 7-38. THE RELATIONSHIP BETWEEN SIX CATEGORIES OF DESIGN DECISIONS AND THE FRS OF THE MSDD

						Product Variety	Product Architecture	Purchasing	Material Selection	Process Selection	Detailed Design
FR1	FR11	FR111				V	V	V	V	V	V
			FR-Q1								
				FR-Q11							
					FR-Q111	V	V	V	V	V	V
					FR-Q112	V	V	V	V	V	V
					FR-Q113	V	V	V	V	V	V
				FR-Q12		V		V	V	V	V
				FR-Q13		V	V	V	V	V	V
				FR-Q14		V	V	V	V	V	V
			FR-Q2						V	V	
			FR-Q3								
				FR-Q31				V	V	V	
				FR-Q32		V		V	V	V	V
		FR112									
			FR-R1								
				FR-R11							
					FR-R111						
					FR-R112	V	V	V		V	V
					FR-R113	V			V	V	V
				FR-R12							
					FR-R121	V	V	V	V	V	V
					FR-R122			V			
					FR-R123						
				FR-R13		V	V	V	V	V	V
			FR-P1			V					
				FR-P11		V		V			
				FR-P12							
					FR-P121	V	V	V	V	V	V
					FR-P122						
					FR-P123						
				FR-P13							
					FR-P131						
					FR-P132	V	V		V	V	V
				FR-P14							
					FR-P141	V	V	V	V	V	V
					FR-P142	V	V	V	V	V	
		FR113									
			FR-T1							V	V
			FR-T2								
				FR-T21		V	V				
				FR-T22							
					FR-T221	V	V		V	V	V
					FR-T222	V	V		V	V	V
					FR-T223	V					V
				FR-T23		V	V	V			
			FR-T3								
				FR-T31		V	V	V			
				FR-T32		V	V		V	V	V
			FR-T4				V	V			
			FR-T5							V	V
				FR-T51							
				FR-T52							
				FR-T53							
	FR12	FR121									
			FR-D1								
				FR-D11						V	V
				FR-D12							
			FR-D2								
				FR-D21							
				FR-D22		V			V	V	V
				FR-D23		V			V		V
			FR-D3						V	V	V
		FR122				V	V	V	V	V	V
			FR-I1								
			FR-I2			V		V	V	V	V
		FR123				V	V	V	V	V	V
	FR13					V	V	V	V	V	V

TABLE 7-39. THE FR-DP PAIRS OF THE MSDD AFFECTED BY FIVE OR MORE CATEGORIES OF DESIGN DECISIONS OUT OF SIX CATEGORIES.

Branch	FR/DP	FR	DP
Quality	111	Manufacture products to target design specifications	Production processes with minimal variation from the target.
	Q111	Ensure that operator has knowledge of required tasks	Training program
	Q112	Ensure that operator consistently performs tasks correctly	Standard work methods
	Q113	Ensure that operator human errors do not translate to defects	Mistake proof operations (poka-yoke)
	Q12	Eliminate machine assignable causes	Failure mode and effects analysis
	Q13	Eliminate method assignable causes	Process plan design
	Q14	Eliminate material assignable causes	Supplier quality program
	Q32	Reduce impact of input noise on process output	Robust process design
Identifying and resolving problems	R112	Identify disruptions where they occur	Simplified material flow paths
	R121	Identify correct support resources	Specified support resources for each failure mode
	R13	Solve problems immediately	Standard method to identify and eliminate root cause
Predictable output	P121	Reduce variability of task completion time	Standard work methods to provide repeatable processing time
	P132	Service equipment regularly	Regular preventative maintenance program
	P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems
	P142	Ensure proper timing of part arrivals	Parts moved to downstream operation at pace of customer demand
Delay reduction	T221	Ensure that automatic cycle time is less than minimum takt time	Design of appropriate automatic work content at each station
	T222	Ensure that manual cycle time is less than minimum takt time	Design of appropriate operator work content/loops
	T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment
Operating cost	122	Reduce waste in indirect labor	Reduction of indirect labor tasks
	I2	Eliminate information disruptions	Seamless information flow (visual factory)
	123	Minimize facility cost	Reduction of consumed floor space
Investment	13	Minimize investment over production system lifecycle	Investment based on a long term strategy

From the result of Table 7-38, it is revealed that the FRs and DPs listed in Table 7-39 are greatly linked to the product design decisions. Therefore, when a FR listed in Table 7-39 is not achieved satisfactorily in a manufacturing plant, product design decisions may need to be reviewed as a probable source of problems.

The proportions of the FRs presented in Table 7-39 to the total FRs and total leaf FRs are shown in Figure 7-16.

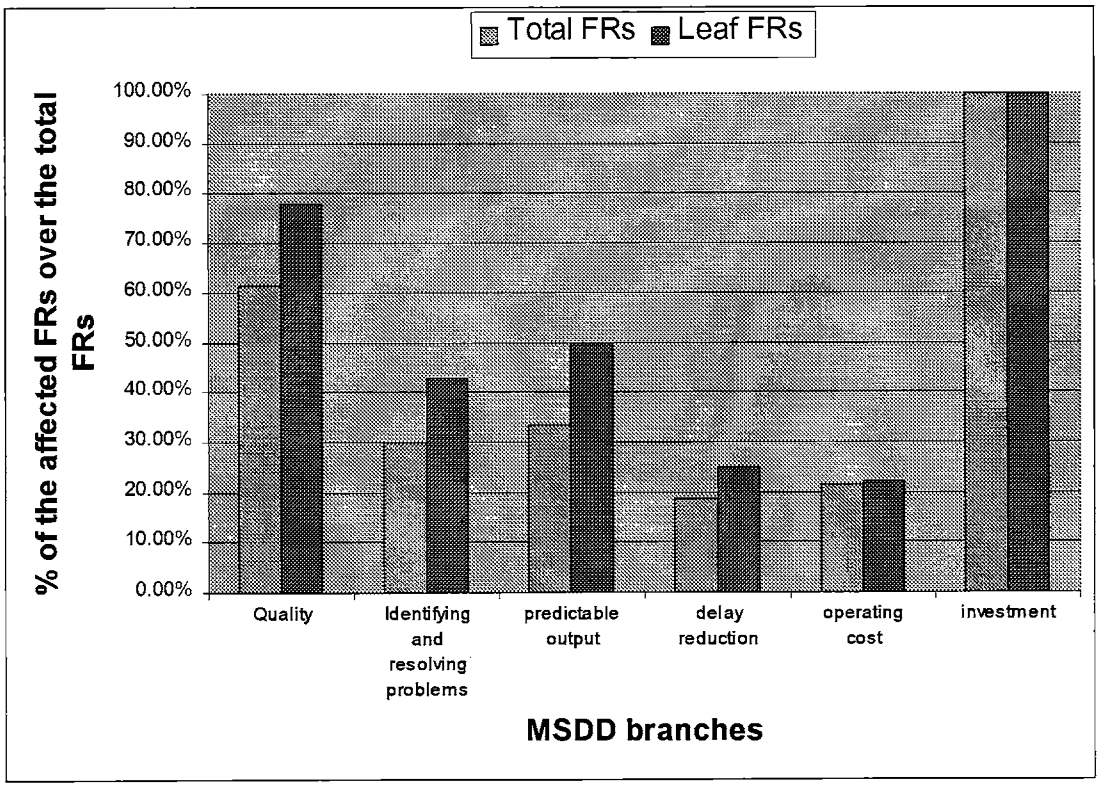


FIGURE 7-16. PROPORTIONS OF THE FRS THAT ARE AFFECTED BY FIVE OR MORE DESIGN DECISION CATEGORIES TO THE TOTAL FRS AND LEAF FRS OF THE MSDD

Figure 7-16 shows the proportions of the FRs that are affected by more than five design decision categories to the total FRs and total leaf FRs of the MSDD. The left columns show the proportion to the total FRs and the right columns present the proportion to the total leaf FRs of the MSDD. As is shown in Figure 7-16, the quality branch of the MSDD is the most significantly affected branch. About 80% of the leaf FRs in the quality branch are affected by more than five categories of the design decisions. Therefore, it is important to consider product design related causes when a quality problem is identified.

Then, the predictable output branch and the identifying and resolving problems branch follow the quality branch. The investment branch has the proportion of 100% since the MSDD does not further decompose the FR13. There is only one FR in the investment branch and every design decision is more or less related to investment regardless of the category the design decision belongs to.

Figure 7-17 shows the proportion of the FRs in each branch of the MSDD that are affected any of the six design decision categories. It is observed that all FRs of the quality branch are affected by design decisions in any category. Figure 7-17 also reveals that more than 50% of the FRs in any branch of the MSDD are affected by product design decisions. Therefore, it is important to carefully consider product design decisions for better achievement of the FRs in the MSDD.

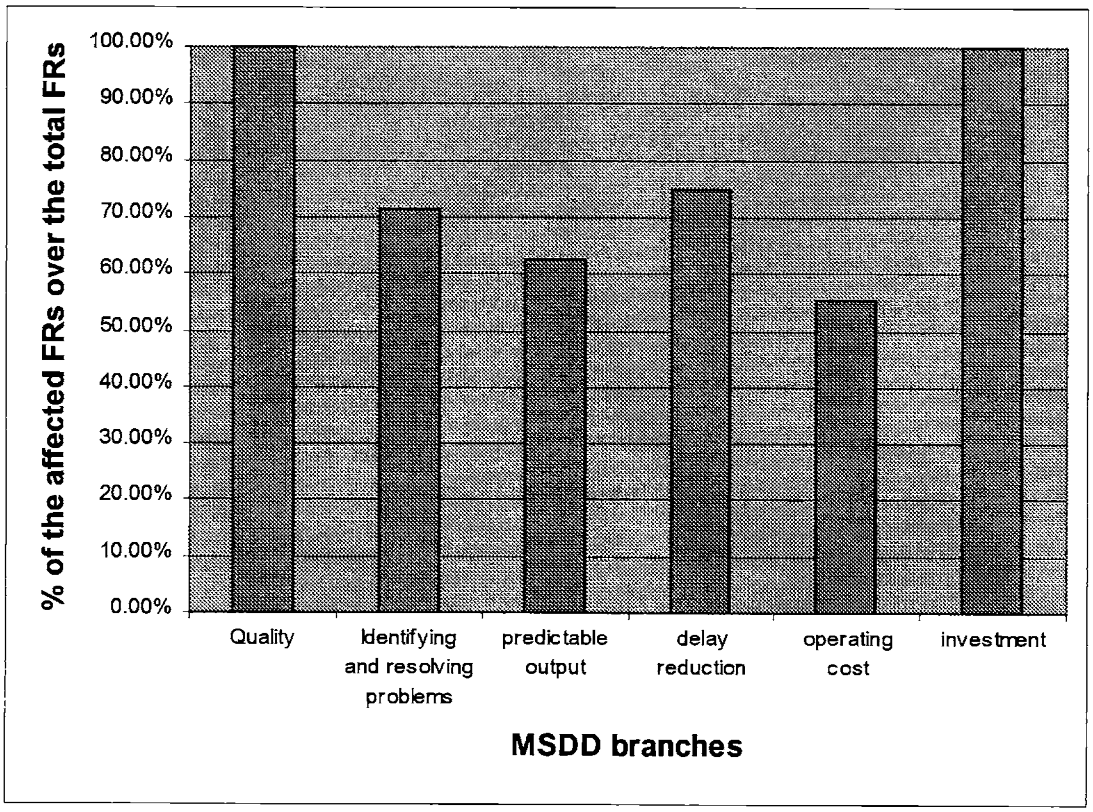


FIGURE 7-17. THE PROPORTION OF THE FRS THAT ARE AFFECTED BY AT LEAST ONE DESIGN DECISION CATEGORY OVER THE TOTAL LEAF FRS.

7.3 Manufacturability Evaluation Process

The manufacturability evaluation process proposed in this section attempts to see how a product/process design decision affects the achievement of the FRs and DPs of the MSDD in order to understand the impact of the design decision on manufacturing systems. Based on the understanding, the manufacturability of a product is ensured through resolving conflicts between product/process design and manufacturing system design if there is any. A major assumption with this approach is that the MSDD reflects the core characteristics of manufacturing system design. This assumption is supported by successful applications of the MSDD in various disciplines. As is discussed in the Chapter 4, several researchers address the use of the MSDD in various disciplines. For example, Arinez [2000] discusses the use of the MSDD for equipment design. Duda [2000] presents the use of the MSDD to link strategy, performance measurement, and manufacturing system design. Especially, Linck [2001] addresses the issue of validating the MSDD. He uses a questionnaire approach to validate the usefulness of the MSDD by applying the questionnaire to several different industry cases. He claims that the MSDD effectively reflects the elements of lean manufacturing and is useful to assess the level of 'leanness' of a plant.

Manufacturability should not be seen from the perspective of cost reduction or investment reduction, only. It is true that a product design with perfect manufacturability will eventually reduce the cost or investment associated with the introduction of the product design to a manufacturing system. However, manufacturability problems should not be approached purely from the financial viewpoint since this approach may lead to the decisions that deteriorate the performance of a manufacturing system. Instead, it should be approached to assure the stability of a manufacturing system against the introduction of new products. The financial advantage should be a result of keeping the stability of the manufacturing system, not a goal by itself. In addition, from the viewpoint that manufacturability is to keep the stability of a manufacturing system, the scope of traditional DFMA (Design for Manufacturing and Assembly) approaches is too narrow, focusing on quality issues. They need to be expanded to cover manufacturing system issues, which is one of the aims of the proposed evaluation process described in the next section.

7.3.1 Steps of the Manufacturability Evaluation Process

The manufacturability evaluation process begins with a product/process design decision to be reviewed. With this design decision, the level of abstraction or detail to study is decided (step 1). This is to decide the details of the design decision to study since there can be design decisions in various levels of product/process design from a product range decision to a hole-diameter decision. Then, it is decided to which category of the proposed six categories of product/process design the design decision belongs (step 2). The category decision enables the understanding of the general interactions between the category and manufacturing systems by reviewing the proposed interactions as discussed in section 7.2.3 (step 3). Based on the understanding of the general interactions, the case specific interaction can be studied by reviewing the design decision against each FR and DP of the MSDD (step 4). The reviewing process will reveal if there is any conflict between the design decision and the achievement of the FRs of the MSDD by the proposed DPs (step 5). If there is no conflict, the manufacturability of the design decision is confirmed. If there is any conflict, however, the conflict should be resolved by product design modification, manufacturing system design modification, or both (step 6). In case that product/process design modification is made, the new design decision is reviewed again from the step 4. If only manufacturing system design modification is made, the manufacturability of the design decision is confirmed with the modified manufacturing system design (step 7). The flow diagram of the manufacturability evaluation process is given in Figure 7-18.

In the following sections from 7.3.1.1 to 7.3.1.7, each of the steps is explained in detail.

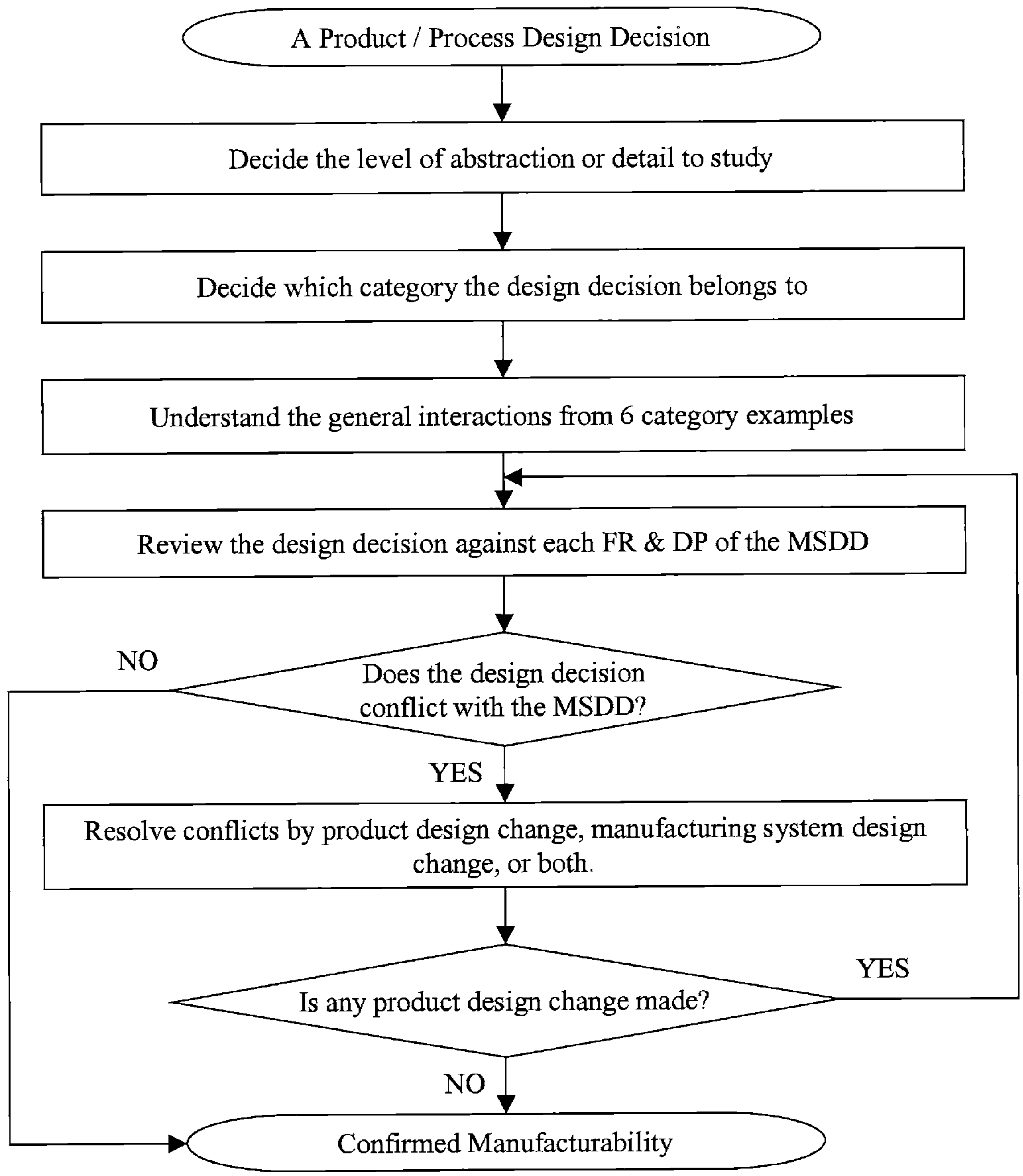


FIGURE 7-18. MANUFACTURABILITY EVALUATION PROCESS

7.3.1.1 Step 1: Decide the level of abstraction or detail to study

The first step of the manufacturability evaluation process is to decide the level of abstraction or detail to study with the design decision in mind. The level of detail of both the design decision and the manufacturing system design are important. As for the details of the design decision, there can be design decisions in various levels of product/process design from a product range decision to a detailed design decision such as a hole-diameter decision. If the design decision in consideration is in too much detail, it might be difficult to see its impact on manufacturing systems or the manufacturability issues are too trivial for a thorough study using the proposed evaluation process.

In addition, the level of detail of manufacturing system design should be also considered. The decomposition of the MSDD is done down to the level that can be generally applied to various industry. Therefore, if further analysis of manufacturability is necessary in a specific manufacturing system, the MSDD may need to be further decomposed to reflect the specific manufacturing system in further details.

Considering these issues, the details of the manufacturability study should be considered at the first step.

7.3.1.2 Step 2: Decide which category the design decision belongs to

The proposed manufacturability evaluation process presents six categories of product/process design that significantly affect manufacturing systems. They are 1) product variety decision, 2) product architecture design, 3) purchasing decision, 4) material selection, 5) process selection, and 6) detailed design. After deciding the level of detail to study, it is considered which category the design decision in mind belongs to. This step is necessary to use the general interactions between each category and manufacturing systems presented in section 7.2.3. If the design decision in consideration belongs to multiple categories, the general interactions of all applied categories may be reviewed.

7.3.1.3 Step 3: Understand the general interactions from six category examples

The interactions of each category of product/process design with manufacturing system design are described in section 7.2.3. These general interactions may be understood first before reviewing the specific design decision in mind against the FRs and DPs of the MSDD. This understanding also provides the general idea of how the specific design decision may affect the FRs and DPs of the MSDD. This step is important since it may be difficult to see the impact of a very detailed design decision on manufacturing systems. For example, the interactions between the cap diameter decision of juice bottles and the FRs and DPs of the MSDD may be difficult to be captured. In this case, the general interactions between detailed design and the FRs and DPs of the MSDD can be reviewed and used as a guideline.

As is discussed before, however, the general interactions presented in section 7.2.3 only reflect the existing knowledge on the interactions between manufacturing systems and product/process design. If new knowledge is gained in the interactions or new insights on manufacturing systems are found, they are subject to modification to reflect the changes in the existing knowledge.

7.3.1.4 Step 4: Review the design decision against each FR and DP of the MSDD

The interactions between manufacturing system design and six categories of product/process design are captured by reviewing each category against the FRs and DPs of the MSDD. The same process is repeated to review how the specific design decision affects manufacturing system design. Specific interactions may be found during this process while general interactions are considered during the reviewing process. In some cases, some of the FRs and DPs affected by the category that the design decision belongs to may not be affected by the specific design decision.

Through this reviewing process, the manufacturability issues can be systematically identified and thus, resolved accordingly.

7.3.1.5 Step 5: Does the design decision conflict with the MSDD?

After the reviewing process, it should be decided if there is any conflict with the design decision in mind and the achievement of the FRs by the proposed DPs of the MSDD. The reason why both FRs and DPs are considered is explained in section 7.2.3.

The conflicts between the design decision and the satisfaction of FRs by DPs in the MSDD indicate the cases when the design decision makes it more difficult to satisfy the FRs or fails to be compatible with the given DPs. For example, more product variety makes it more difficult to satisfy the FR-Q111 (ensure that operator has knowledge of required tasks). Therefore, there is a conflict with the increased product variety decision and manufacturing systems. Another example is FR-R112 (identify disruptions where they occur) and DP-R112 (simplified material flow paths). FR-R112 is satisfied by DP-R112 and a product architecture design can affect DP-R112 and thus, FR-R112. Therefore, any product architecture design that complicates material flow paths has a conflict with the MSDD. These conflicts should be resolved in the step 6.

7.3.1.6 Step 6: Resolve conflicts by product design change, manufacturing system design change, or both

After identifying the existence of the conflicts, those conflicts should be resolved. There are fundamentally two ways to resolve the conflicts: change the design decision or modify manufacturing system design. Since the manufacturability evaluation process will be conducted during product development, it will be better to find alternative product designs that will not make any conflicts with manufacturing systems. However, sometimes it is necessary to prepare manufacturing system design changes to eliminate the conflicts. The later case happens because the product design decision is a function of many factors such as product development drivers, customer satisfaction, engineering functionality satisfaction, manufacturability, and after-sale service. In other words, there are a lot of factors that affect product design other than manufacturability issues. A design decision should be made after considering all of these factors and thus, sometimes, manufacturing system design modification is required instead of product design change.

For example, Ulrich and Eppinger [2000] categorize five different product development drivers: generic market pull, technology push, platform products, process intensive, and customized. The characteristics of each type of the product development drivers and the examples are summarized in Table 7-40. Among these types of product development drivers, process intensive product development may prefer product design changes, compared to production process changes. In this case, it is most important to design a product that can be produced with existing equipment and processes. On the other hand, the technology push type focuses more on applying the developed technologies and thus, manufacturing system design modification is preferred to design decision changes.

Otherwise, a new manufacturing system is often constructed for this type of products. As for the rest categories of generic – market pull, platform products, and customized, either product/process design changes or manufacturing system design changes can be made according to the specific situation.

TABLE 7-40. SUMMARY OF VARIANTS OF GENERIC DEVELOPMENT PROCESS (ADAPTED FROM ULRICH AND EPPINGER [2000]).

	Generic - Market Pull	Technology Push	Platform Products	Process Intensive	Customized
Description	The firm begins with a market opportunity, then finds appropriate technologies to meet customer needs.	The firm begins with a new technology, then finds an appropriate market.	The firm assumes that the new product will be built around an established technological sub-system	Characteristics of the products are highly constrained by the production process.	New products are slight variations of existing configurations
Distinctions with respect to generic process		Planning phase involves matching technology and market. Concept development assumes a given technology	Concept development assumes a technology platform.	Both process and product must be developed together from the very beginning, or an existing production process must be specified from the beginning.	Similarity of projects allows for a highly structured development process.
Examples	Most sporting goods, furniture, tools.	Gore-tex rainwear, Tyvek envelopes	Consumer electronics, computers, printers.	Snack foods, cereal, chemicals, semiconductors.	Switches, motors, batteries, containers.

When product design decisions have conflicts with the FRs of the MSDD that are related to equipment design, new equipment may be necessary. In this case, the new equipment should be designed in a way that the FRs of the MSDD linked to equipment design, are reflected in the equipment design. Arinez [2000] describes an equipment design approach using the MSDD.

The requirement for new equipment itself is a factor that affects the form of conflict resolution, since new equipment is usually associated with large investment, which is an important factor to decide whether product/process design changes or manufacturing system design does. Therefore, it is natural to pursue the reuse of the existing equipment by modifying product/process designs when there is no significant difference in the rest of the factors that affect product/process design decisions.

7.3.1.7 Step 7: Is any product design change made?

After resolving the conflicts through the design decision changes with or without manufacturing system design modification, the new design decision should be reviewed again from the step 4 to re-confirm manufacturability of the proposed design decision. When only manufacturing system design modification is made, the manufacturability of the design decision is confirmed with the modified manufacturing system design.

7.3.2 Benefits of the Manufacturability Evaluation Process

The proposed manufacturability evaluation process has several advantages over the traditional DFMA approach. First, the proposed methodology shows how a design decision affects the achievement of the objectives of the manufacturing system. This is possible since the MSDD is used in the proposed methodology. The MSDD separates the objectives (FRs) from the means (DPs) to achieve them. This advantage can be used when the DFMA practices are rationalized. The proposed methodology can present which FRs and DPs of the MSDD are affected by the DFMA practices. Instead of claiming that cost reduction is the only benefit of the DFMA practices, product engineers can show how their DFMA practices will prevent manufacturing problems and even contribute to the achievement of the objectives of manufacturing systems. The financial benefit is the ultimate goal of the DFMA practices but it is the result of better achieving the objectives of manufacturing systems.

Second, the proposed methodology enables product engineers to view the impact of their design decision on manufacturing systems in a holistic way. Using the proposed method, it can be known which areas of the manufacturing system design are affected by the design decision: quality, time variation reduction, lead time reduction, operating cost reduction, or investment. With this approach, product engineers are able to consider other objectives of manufacturing in addition to the traditional quality requirement, which will prevent manufacturing system problems caused by blind pursuit of the traditional DFMA guidelines. The benefits and losses of the application of the DFMA rules can be shown with the proposed method.

Third, the proposed methodology can show the manufacturability of a design decision without relying on accumulated experience. This advantage is important since the analysis of the first round questionnaire shows that many companies have approached the manufacturability problems with knowledge management tools. Accumulated experience is important and useful but accumulated experience can be more effectively categorized and utilized with the manufacturability evaluation process. In addition, the proposed method can be applied to a completely new case, which cannot be supported by accumulated experience.

Fourth, it allows room for strategic decisions. The proposed methodology shows which FRs and DPs are affected by a design decision with some examples. However, it does not force that the design should always be changed. Instead, it shows what conflicts need to be resolved. Therefore, according to the other factors in consideration, various solutions can be developed to eliminate the conflicts between a design decision and manufacturing system design. The goal is to remove the conflicts, not to change the design decision.

Finally, the proposed methodology can be used as a base for an evaluation tool. The analysis of the first round questionnaire shows that different companies implement different approaches to the manufacturability problems. However, it is difficult to compare the effectiveness of different approaches. The proposed methodology suggests one way to compare those different approaches. They can be compared by the scope they cover relative to the MSDD. This comparison using the proposed methodology is discussed in more details in Chapter 9.

7.4 Chapter Summary

In this chapter, the manufacturability evaluation process is presented. The manufacturability evaluation process is developed by resolving the research subproblems provided in Chapter 1. First, the MSDD is developed to represent the requirements and the corresponding solutions of manufacturing system design. Then, six categories of product design decisions are recognized. The six categories include product variety, product architecture, purchasing, material selection, process selection, and detailed design. The possible interactions between these six categories of product design decisions and manufacturing system design are investigated using the MSDD. If the FRs and DPs of the MSDD are affected by a certain product design decision in a negative way, the conflicts should be resolved by either modifying the product design decision or changing the manufacturing system design. Finally, the steps of the manufacturability evaluation process are presented in detail along with a flow diagram shown in Figure 7-18.

The benefits of the proposed manufacturability evaluation process include:

- The proposed methodology shows how a design decision affects the achievement of the objectives of the manufacturing system. This is possible since the MSDD is used in the proposed methodology, which clearly separates the objectives (FRs) from the means (DPs) to achieve them.
- The proposed methodology enables product engineers to view the impact of their design decision on manufacturing systems in a holistic way. With the proposed approach, product engineers are able to consider other objectives of manufacturing (e.g., delay reduction, predictable output, etc.) in addition to the traditional quality requirement.
- The proposed methodology can show the manufacturability of a design decision without relying on accumulated experience.
- The proposed methodology allows room for strategic decisions by showing what conflicts need to be resolved.
- The proposed methodology can be used as a base for an evaluation tool.

8 APPLICATION EXAMPLES OF THE MANUFACTURABILITY EVALUATION PROCESS

In this chapter, a couple of industry case examples are presented to show how the proposed manufacturability evaluation process can be applied to the real industry problems. Along with the detailed description on the steps of the application, several issues associated with the actual application of the proposed method are discussed. The first example is about a manufacturing improvement project in an automotive supplier plant and the second example is the extended discussion of the plant C case in Chapter 2. In addition to the industry case examples, it is reviewed how existing DFM approaches can be viewed using the proposed framework.

8.1 Plant X Case

In this section, a manufacturing improvement project related to product/process design is reviewed from the manufacturability perspective. It is shown what manufacturability issues should have been considered during the improvement project. The proposed manufacturability evaluation process is used to check the manufacturability of the product/process design changes made for the manufacturing improvement.

8.1.1 Plant and Product Background

Plant X is one of the plants of a first tier supplier company in the automotive industry. Plant X produces meters used in the instrument panel located in the dash board. The schematic view of the product is shown in Figure 8-1.

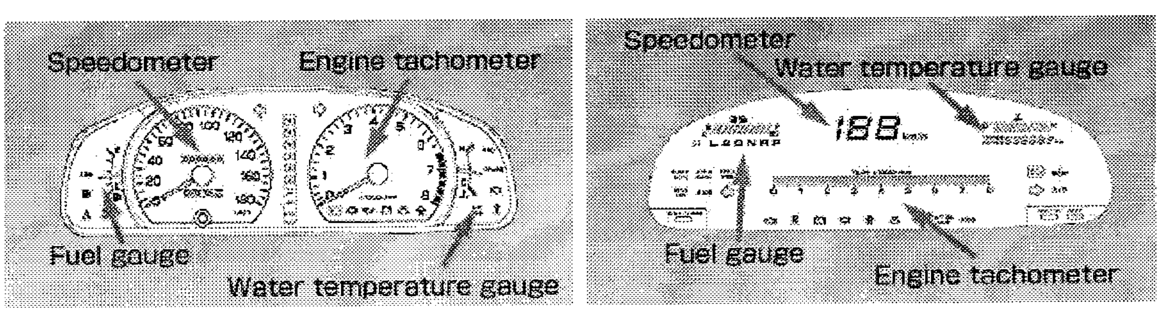


FIGURE 8-1. INSTRUMENT PANEL METERS (LEFT: ANALOG TYPE, RIGHT: DIGITAL TYPE)

Plant X started its first operation in 1974 and it is a huge plant with the floor space of 49 acres. The total plant area is up to about 90 acres. About 2,700 people work in plant X to manufacture meters, portable cellular phones, displays, and sensors for air-conditioning, etc. As for the meter production, about 300,000 analog meters are produced per month along with about 370,000 self-lighting meters. Therefore, each month, about 670,000 units of the meters need to be produced in this plant. The more interesting part is that the number of the types of the final meter assembly is up to 1,600. According to the interview with a production engineer of this plant, the average number of products produced per type is only about 10 units per day. Among 1,600 types of products, about 81 types have large production volumes that are about 1,800 units per day.

With the meter production of about 670,000 units per month, the mother company of the plant X takes about 40 % of the domestic market and 15 % of worldwide market.

8.1.2 The Improvement Project

The fabrication of the meter plates is comprised of three major production processes:

1) screen printing
2) stamping (dedicated dies are used)
3) external shape inspection

In the screen printing process, the numbers, scales, and symbols that are typically seen in the instrument panel are printed. In the stamping process the holes for further assembly are made and the outlines of the meter plates are trimmed. Then, the external shape of the meter plates is inspected with both operators' visual check and more complex automated visual check using an optical technology.

In the stamping process, stamping dies are used to make holes and trim outlines. It is a complicated process given that the product variety requires about 160 die changeovers made per day. In addition, new dies are necessary whenever a new meter plate design is introduced. Developing new dies requires significant financial and time investment. The production preparation time is about 20 days.

Two improvements have been made to simplify the stamping process while maintaining flexibility required. First, the positions of holes in the meter plates are standardized to minimize the number of die changeover time. Second, laser cutting technology is implemented for outline cutting, which substitutes traditional stamping processes. With these new methods, the number of die changeovers per day is decreased from 160 to zero and the production preparation time is decreased from 20 days to 1 day.

In the next section, manufacturability issues that exist in this improvement project are presented using the proposed manufacturability evaluation process.

8.1.3 Application of the Manufacturability Evaluation Process

The first step of the manufacturability evaluation process is to decide the level of abstraction or details of the analysis on the design decision in mind. The design decisions subject to the evaluation processes in this case are the standardization of the hole location and the process changes from stamping to laser cutting. These two decisions will be checked against the FRs and DPs of the MSDD. Further detailed analysis is avoided since this analysis is to examine the general applicability of the proposed approach. Plant specific analysis is not necessary for this purpose and therefore, further decomposition of the MSDD is not required.

The second step of the manufacturability evaluation process is to decide which categories the design decisions under consideration belong to. The proposed manufacturability evaluation processes have six categories of product/process design that significantly affect manufacturing systems. They are 1) product variety decision, 2) product architecture design, 3) purchasing decision, 4) material selection, 5) process selection, and 6) detailed design. In the Plant X case, standardization of hole locations belongs to the product variety and detailed design categories among the six proposed categories while the process change decision belongs to the process selection category. In the third step, general interactions between the three categories and manufacturing system design are then reviewed as are presented in section 7.2.3.

The fourth step is to review the design decisions against the FRs and DPs of the MSDD, considering the general interactions of the relevant categories presented in section 7.2.3.

The result of the reviewing process is presented in Figures 8-2, 8-3, and 8-4. The gray colored blocks indicate the FRs and DPs of the MSDD that are relevant to the category but not significantly related to the design decisions. The black colored blocks point out the FRs and DPs that are positively affected by the design decisions in consideration. The dashed blocks indicate the FR-DP pairs that require further consideration before implementing the design decisions. After identifying the FR-DP pairs that are affected by the design decisions, any conflicts between the design decisions and the satisfaction of the FRs should be identified and resolved. After the manufacturability evaluation process, it can be said that the manufacturability of the design decisions is confirmed.

8.1.3.1 Standardization of hole locations

The standardization of hole locations works to reduce the effective product variety to the stamping process. Since hole locations on different products are the same, there is no conflict coming from the increased product variety and most of the FRs and DPs that are related to product variety are positively affected. For example, FR-T32 (produce in sufficiently small run sizes) can be satisfied even without DP-T32 (design quick changeover for material handling and equipment) since now there is only one type of product from the stamping process point of view. The ideal run size of one can be achieved. However, there are a couple of FRs on which the reduced product variety may act negatively. FR-Q12 states to 'eliminate machine assignable causes.' Reduced product variety results in more frequent use of the same die, which causes faster die wear, which can cause quality problems. Furthermore, FR-P132 indicates to 'service equipment regularly' and this FR is satisfied by the DP-P132, 'regular preventative maintenance program.' The existing preventative maintenance program should be modified to reflect the increased die wear rate in order to avoid disruptions caused by die failure.

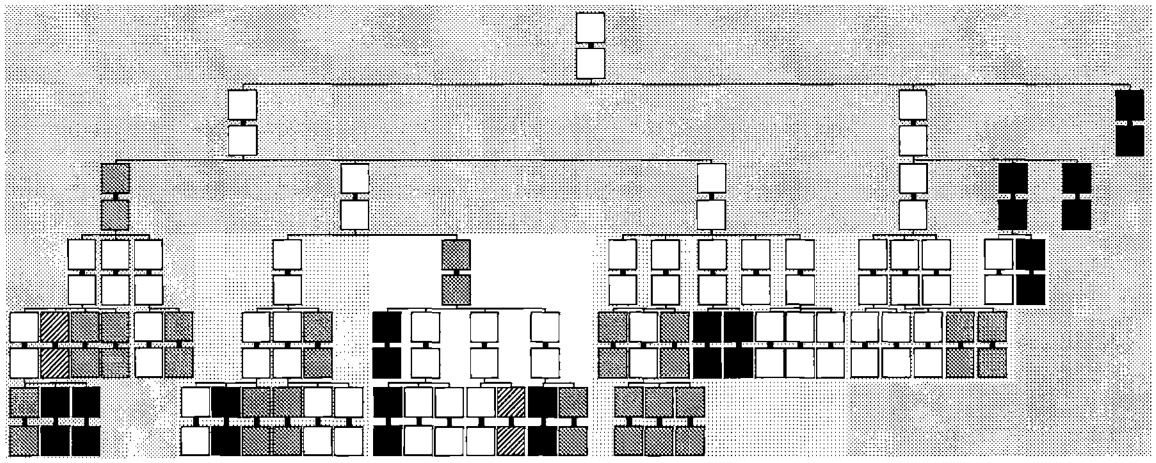


FIGURE 8-2. THE IMPACT OF STANDARDIZING HOLE LOCATIONS ON THE FRS AND DPS OF THE MSDD FROM THE PRODUCT VARIETY PERSPECTIVE.

From the detailed design point of view, the quality issue is most significant. First, there should be no quality problem after standardizing the hole locations. Many things should be checked for quality assurance purposes but since the same stamping process is used to make holes, the number of issues that are subject to strict scrutiny is greatly reduced. For example, using the same stamping process may result in little change in the knowledge required of operators on their tasks (FR-Q111). It would be enough for the operators to know that the locations of holes are standardized and they no longer need to make die changeovers. In a similar way, existing standard work methods may be used with slight modification (DP-Q112) along with existing mistake-proof devices (DP-Q113). More consideration on mistake-proof devices may be given since now only one design is processed and thus, it may be easier to develop more comprehensive mistake-proof devices.

Other sources of quality problems include machine (FR-Q12), method (FR-Q13), and material (FR-Q14). Machine assignable causes of quality problems may not be significant in this case since the same stamping machine can be used as long as the new design does not require any additional capability from the machine (e.g., more force requirement). The same failure modes and effects analysis (FMEA) data may be utilized to eliminate machine assignable causes.

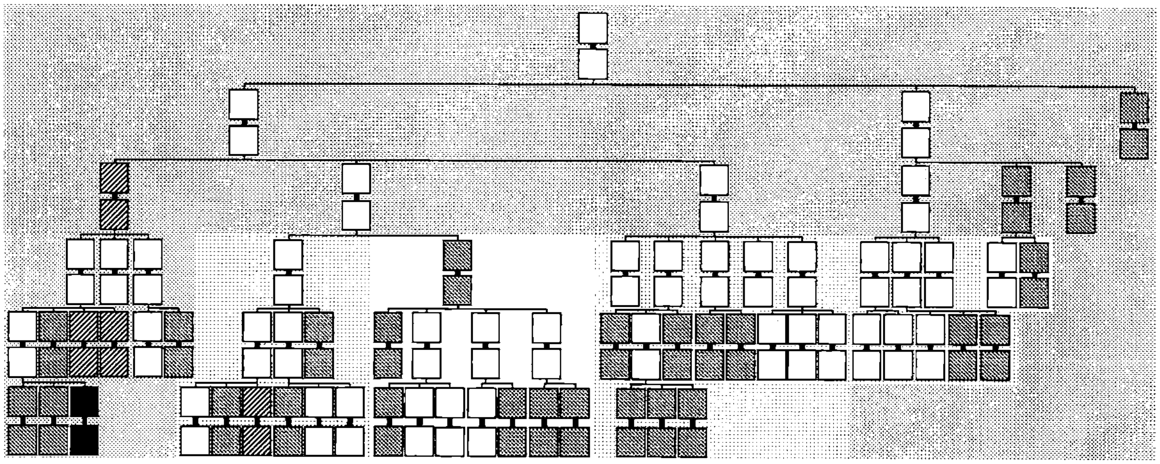


FIGURE 8-3. THE IMPACT OF STANDARDIZING HOLE LOCATIONS ON THE FRS AND DPS OF THE MSDD FROM THE DETAILED DESIGN PERSPECTIVE.

Some attention, however, needs to be paid to method assignable causes of quality problems. For example, the standardized hole locations need to be appropriate to the stamping process. The location of the holes should have a certain margin from the edge to avoid the fracture of the meter plate. However, it would not be an unsolvable issue since the plant has prior experience with the stamping process and meter plate design. In addition, new hole locations should not affect quality due to the incoming material quality.

The new design specification may affect manufacturing quality the most. If the designed tolerance of hole locations or hole sizes is not in the same order as the previous design, the existing process may need to be modified, requiring a complete manufacturability review on the sources of quality problems. However, in the case presented, the same machine and process can be used, which indicates that no significant changes are made in terms of design tolerances.

In the identifying and resolving problems branch, the standardization of hole locations does not seriously affect the FRs and DPs from a detailed design perspective. Different patterns of production disruptions, however, are likely to happen. Disruptions caused by die wear may increase while disruptions caused by maintenance and transportation of different dies to the stamping machines are eliminated. Therefore, slight modification of the existing feedback system is necessary. Less supportive resources may be required due to decreased product variety while the minor design change caused by the standardization of hole locations may not significantly change the characteristics of the process. In a similar way, the existing standard method to identify and eliminate root causes can be used to solve disruption problems immediately.

In the predictable output branch, the standardization of the hole locations affects the FRs and DPs in a similar way as it does in the identifying and resolving problems branch. The reduced product variety due to the new design may diminish the variability of the task completion time since now the operators need to manage only one pattern of the hole location. Furthermore, standard work methods can be simplified. The new design itself does not change the existing standard method in use. Similar pattern can be found with the equipment maintenance (FR-P132) and parts availability (FR-P141). From the detailed design perspective, the standardization of the hole locations does not significantly affect the maintenance of the equipment or the standard work in process. Production disruptions may be reduced by eliminating the need for die transportation and die changeover. This is possible by the detailed design that supports the product variety strategy of standardization.

In the delay reduction and the operating cost branches, the impact of the standardization from the detailed design perspective is insignificant since the same process with the same equipment is used. However, many benefits are achieved from the product variety perspective. For example, the elimination of the die changeover reduces the indirect labor associated with the maintenance, storage, and transportation of the dies as well as the indirect labor related to the information management to signal die changeover. In addition, the storage area for dies is eliminated and the time that operators spend on non-value added tasks (die changeover) is reduced. As for the investment branch, not a big investment is involved with the standardization of the hole locations.

So far, the impact of the standardization of hole locations on manufacturing system design is reviewed and it is found that most of the benefits come from the reduced variety. On the other hand, several conflicts with the manufacturing system design are identified. It is shown that even the reduction of product variety may cause some problems in the stamping process and there are several issues to be considered from the proposed manufacturability viewpoint with the design of the new hole locations that looks quite simple and trivial.

8.1.3.2 Process change from stamping to laser cutting

The impact of process change on the manufacturing system is significant since manufacturing systems are comprised of a series of production processes. Figure 8-4 presents the FRs and DPs that are affected by the process change from stamping to laser cutting. Compared to Figure 8-2 and 8-3, much more dashed blocks are observed in Figure 8-4. This difference indicates why new process technology is hard to be implemented in manufacturing systems. There are numerous factors that should be considered for successful implementation of the new process technology as presented in Figure 8-4.

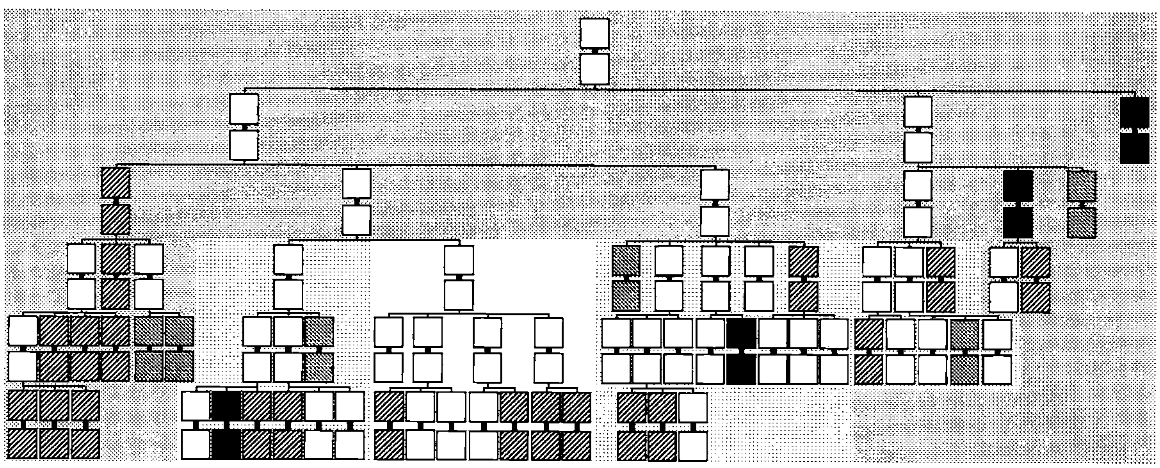


FIGURE 8-4. THE INTERACTIONS BETWEEN THE PROCESS CHANGE FROM STAMPING TO LASER CUTTING AND THE FRS AND DPS OF THE MSDD.

The new laser cutting process should first satisfy quality requirements. Operators should be trained in the new tasks associated with the laser cutting process (FR-Q111), and a standard work method should be developed and tested for consistent operator performance (FR-Q112).

Changing the production process from stamping to laser cutting has a positive effect similar to that of reducing product variety in that the impact of product variety on the manufacturing process is reduced by the increased flexibility of the process. For example, die changeover is eliminated with the laser cutting process; therefore, the operator human errors associated with setting the different dies (FR-Q113) may be reduced.

Other factors that affect manufacturing quality are machine, method, and material. Since laser cutting is a new process, information on machine assignable causes of quality problems associated with the new equipment might not be available. Through a close collaboration with the machine vendors and trial run of the equipment, however, many of the machine assignable causes can be eliminated (FR-Q12). Many other things need to be checked before the introduction of laser cutting, such as whether the new laser process is capable of processing a part within given tolerances and whether any unexpected deformation of the material happens with applied laser cutting (FR-Q13). Then the quality of the incoming materials is checked to be sure they are good enough for the laser cutting process (FR-Q14). In order to center the process output mean on the target value (FR-Q2), it is necessary to identify the process parameters of the laser cutting and understand their effects on the process output. This information can be provided by the machine vendors. Then, possible noise factors can be investigated and eliminated (FR-Q31) along with the efforts to make the process robust to the noise (FR-Q32). On the other hand, instead of resolving conflicts by modifying manufacturing, an alternative process can be sought. For example, machine assignable causes may be solved by changing the process to water jet cutting.

In the 'identifying and resolving problems' branch, the impact of the introduction of the laser cutting process should be analyzed to evaluate the ability of the shop floor to quickly respond to problems. First, the impact of laser cutting on material flow paths (FR-R112) should be identified. Then the types of production disruptions need to be predicted (FR-R113) and reflected in the feedback system. This is followed by the planning of supportive work specifications that determine who is responsible for solving each conflict (FR-R121). The existing standard method of eliminating the root causes of disruptions may be used or a new one can be developed if the existing one does not apply to the new laser cutting process (FR-R13).

In the predictable output branch, a new standard work method needs to be designed to reduce variability of task completion time (FR-P121), and it is necessary to plan the level of standard work in process (SWIP) (FR-P141) and part transportation method (FR-P142). Because a new process is implemented, some safety factors might be considered in the SWIP calculation and part transportation. More importantly, the new laser cutting process brings new requirements for the preventative maintenance program (FR-P132), which would be different from that for the stamping process.

In the delay reduction branch, the laser cutting process should be able to satisfy such requirements as ensuring automatic and manual cycle times are less than minimum takt time (FR-T221 and FR-T222). One of the most significant benefits in changing the production process from stamping to laser cutting is the reduction of run size delay. An example of this would be that where the control system allows, a run size of one can be achieved without the expense on die changeover. The changeover of laser cutting is possible by simple program change and thus, virtually no time is taken for changeover (FR-T32). This change also improves systematic operational delays by eliminating the need for die transportation, storage, management, and information management related to die changeover (FR-T5).

In the operating cost branch, autonomous running of the laser cutting process (FR-D11) should be sought along with the balance of the operators' work loops (FR-D3). Tools used for laser cutting need to be standardized and maintained properly (FR-D22). Information disruption may be reduced by eliminating die changeover information flows while some space used for die storage and maintenance may be saved (FR-I2). There can be an argument, however, with the indirect labor (FR-122) for die maintenance and transportation. While this indirect labor may be reduced, indirect labor to take care of laser cutting machines and update the software may increase.

When considering the financial benefit of the process change, it is also necessary to focus on such factors as the drastic reduction in new design preparation time from 20 days to 1 day, which leads to the improved responsiveness to customer requirement. Other benefits such as reduced run size delay and eliminated die changeover should be also reflected in the decision.

8.1.3.3 Product/process design and new equipment

When there is a conflict between a product/process design decision and the FR-DP pairs of the MSDD, two types of solutions exist. One is to change the product design or the selected process to meet manufacturing requirements. The other is to modify the manufacturing system to accommodate given product/process design decisions. It is often more economical, however, to change product/process design since the changes to a manufacturing system require a large fixed investment in many cases. The problem is that sometimes product design cannot be changed. A customer may require a specific feature on a product, for example. In this case, to resolve the conflicts between product/process design and FR-DP pairs of the MSDD, it is necessary to modify manufacturing, perhaps requiring new equipment. In other words, the conflicts between the design decisions and the FRs of the MSDD are the drivers for implementing new equipment. At Plant X, for example, the process change from stamping to laser cutting indicates that some FRs of the MSDD could not be satisfied with the existing equipment. FR-T32 (produce in sufficiently small run sizes) is a good example, since with stamping process, the ultimate run size of one cannot be achieved in order to compensate the die changeover time. In this way, several FRs may not be satisfied by the existing stamping process, which leads to the implementation of new laser cutting equipment.

When new equipment is implemented, many manufacturing system issues should be considered in addition to the processing of a part. The equipment needs to be designed that it satisfies the relevant FRs of the MSDD that are shown in Figure 8-5. Arinez [2000] describes in his decomposition-based approach to the equipment design how the FRs of the MSDD can be reflected in the design of the equipment. It is important to have right equipment (e.g., machines, fixtures, etc.) that fits with the given manufacturing system as well as the product/process design since it is most significant fixed investment item on the shop floor.

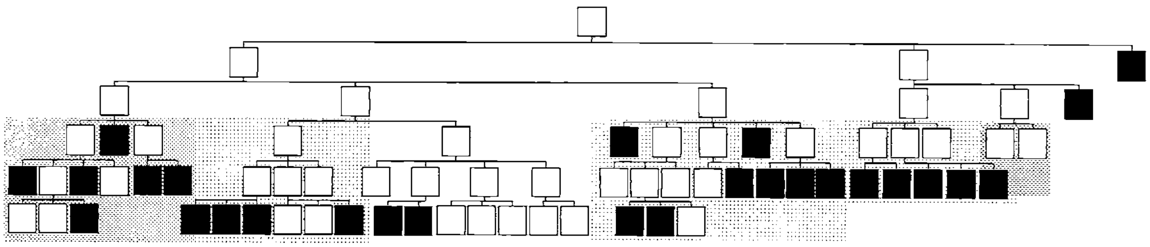


FIGURE 8-5. THE FRS OF THE MSDD RELEVANT TO EQUIPMENT DESIGN [ARINEZ 2000]

8.1.4 Conclusion

In this section, it is shown that many factors should be considered during the implementation of product/process design decisions. The standardization of the hole locations seems a simple implementation and appears to be beneficial for manufacturing but it is found that the standardization may lead to quality problems by die wear and preventative maintenance programs in the existing manufacturing system need to be modified to accommodate the new design. The process change from stamping to laser cutting is also involved with various manufacturing issues as previously discussed. As for the process selection, it is closely linked to the new equipment implementation. The conditions when new equipment is required are discussed from the manufacturability perspective.

In summary, with the given example, it is shown that the manufacturability evaluation processes can be used to identify the conflicts between design decisions and manufacturing system design.

8.2 Plant C Case

In this section, it is presented how the manufacturability evaluation process can be applied to solve the design problem discussed in section 2.2. As is discussed in section 2.2, the angled fluid channels of ASR/VDC housings cause many troubles in the manufacturing system. The application of the proposed manufacturability evaluation process reveals what went wrong with the design of the angled fluid channels and how the problems would have been prevented. Three possible solutions are presented and their advantages and disadvantages are discussed along with how the manufacturability evaluation process can be used during the problem solving. In addition, it is discussed how the manufacturability evaluation process can be applied when the existing manufacturing system is not designed according to the FRs and DPs of the MSDD.

In this section, the description of the background information on plant and product is avoided, since they are already addressed in section 2.2. Therefore, please refer to section 2.2 for the detailed information on product design and manufacturing system design of the plant C. However, the problem is stated in detail to avoid confusion.

8.2.1 Problem Statement

Before stating the problem that plant C confronts, detailed explanation on the angles holes needs to be given for further understanding of the problem. First, a schematic view of the outlook of the product is given in Figure 8-6. The product has six faces and there are holes on all of the six faces to comprise the breaking fluid channels.

There are four angled holes in ASR housings. The rest of the holes that constitute the fluid channels of the ABS are perpendicular to the faces of the housing. The direction of the angled holes relative to the faces is shown in Figure 8-7. The type I angled holes are not parallel to the planes of face 1 and 3, and face 2 and 4. Angles holes II, however, are not parallel to the face 5 and 6, but are parallel to the face 2 and 4. This difference combined with the manufacturing strategy of integrating operations causes manufacturing system problems.

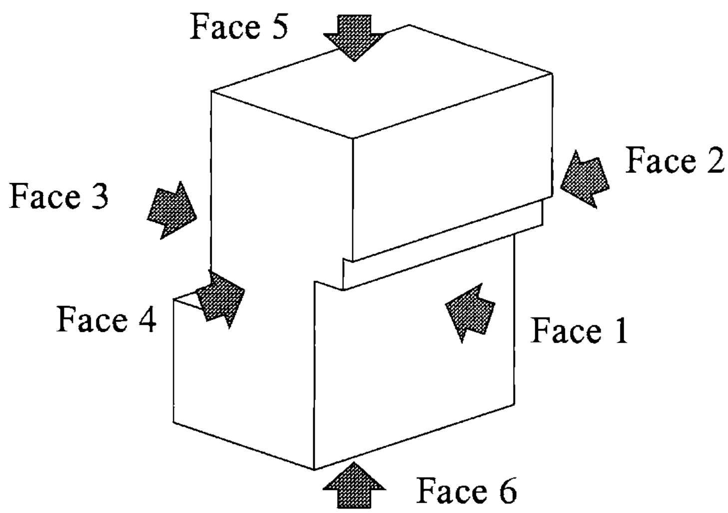


FIGURE 8-6. A SCHEMATIC VIEW OF THE ASR/VDC HOUSING DESIGN

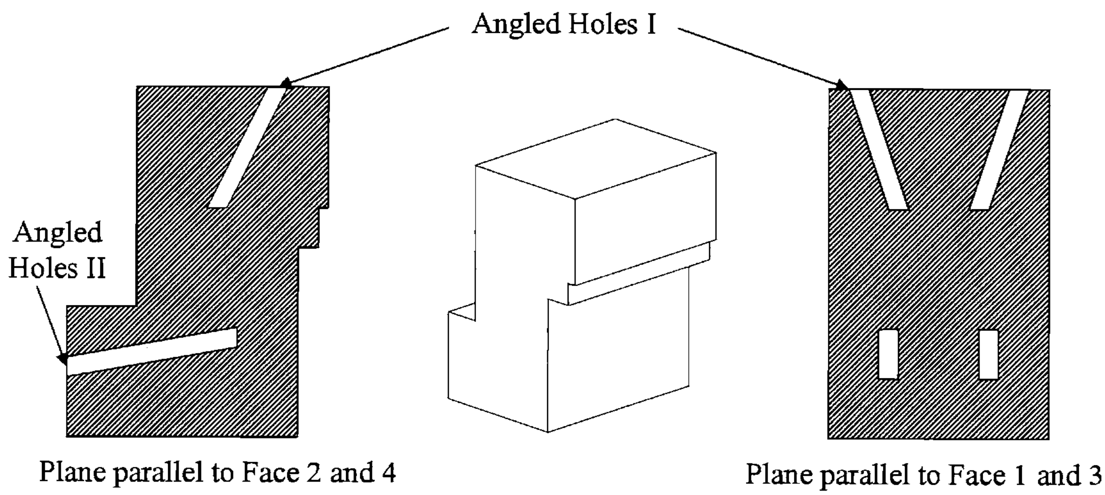


FIGURE 8-7. ANGLED FLUID CHANNELS IN THE ASR/VDC HOUSINGS.

The manufacturing strategy of plant C is to integrate as many operations as possible into one cycle of the machine so that the parts can be processed as much as possible with a single fixturing. Therefore, as is explained in section 2.2, machining centers with tombstone fixtures are implemented. In fact, since a housing can go through more than one hundred operations with only two times of fixturing, this objective seems to be achieved. ASR housings need to pass through about 170 operations on it and ABS housings have about 105 operations. However, to achieve this objective, the housings are clamped to the fixture in two positions – A and C in Figure 2-5. As is shown in Figure 8-8, clamping A is to process face 1, 2, and 4 while clamping C is to process face 3, 5, and 6. In the C clamping position, the angled holes II on the face 3 can be machined with the rotating fixture. However, the angled holes I on the face 5 cannot be machined since the holes are not perpendicular to the face 5 and they are angled relative to the plane parallel to the face 1. Therefore, clamping B is necessary to process type I holes on the face 5.

For this reason, the changeover from ABS housings to ASR housings cannot be done with a simple code change. New fixtures with clamping B are necessary and the changeover time from ABS to ASR is longer than one day to keep the required tolerances due to the required fixture changeover.

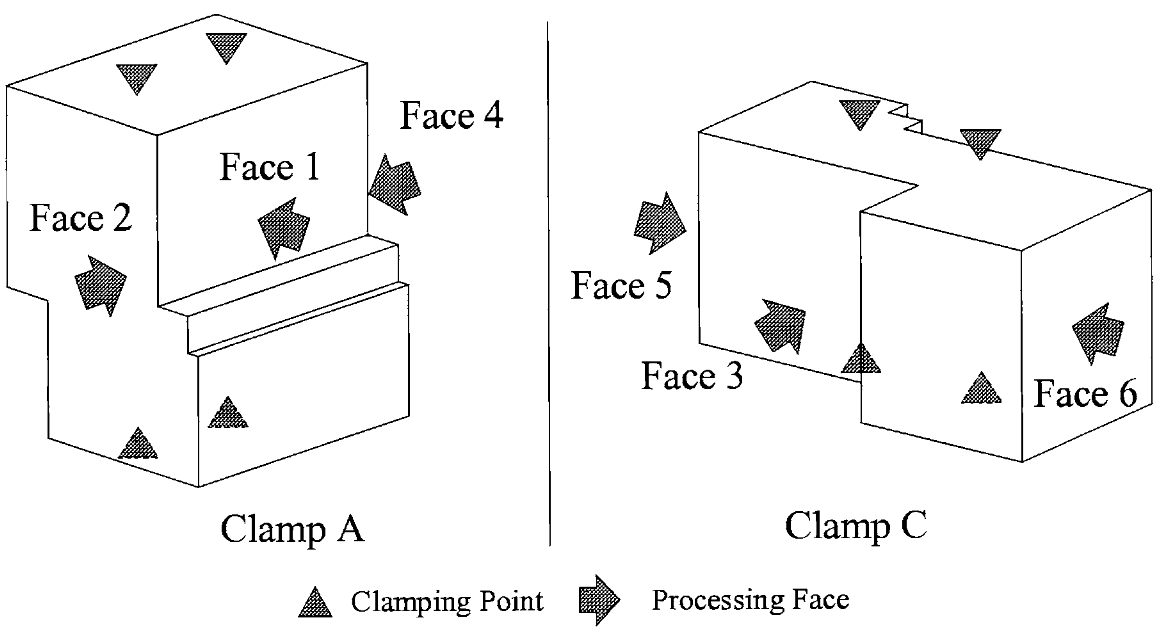


FIGURE 8-8. CLAMPING POSITIONS AND THE FACES PROCESSED BY EACH CLAMPING.

8.2.2 Application of the Manufacturability Evaluation Process

The general steps of the manufacturability evaluation process presented in Figure 7-18 are followed to check the manufacturability of the angled fluid channel design. The first step of the manufacturability evaluation process is to decide the level of abstraction or details of the analysis on the angled fluid channel design. This design decision is checked against the FRs and DPs of the MSDD. Further detailed analysis is avoided since this analysis is to see the general applicability of the proposed methodology. Plant specific analysis is not necessary for this purpose either and thus, further decomposition of the MSDD is not required.

The second step of the manufacturability evaluation process is to decide to which categories the design decision belongs. In the plant C case, the angled fluid channel design may belong to the detailed design category since the angled fluid channel design itself is a detailed design while it contributes to the differentiation of ASR housings from ABS housings along with other factors. After deciding the categories, the general interactions between two categories and manufacturing system design are reviewed as presented in section 7.2.3.

The fourth step is to review the design decision against the FRs and DPs of the MSDD, considering the general interactions of the relevant categories presented in section 7.2.3. This review is not easy since the existing manufacturing system is not designed to satisfy the FRs of the MSDD. Therefore, in the following sections, it is discussed how we can apply the proposed methodology when dealing with a manufacturing system that does not follow the principles of the MSDD or lean manufacturing. Then, the angled fluid channel design decision is first reviewed with the existing manufacturing system. During the review, it is discussed how the conflicts found can be solved, which corresponds to step 5 and 6. After this analysis, the design decision is reviewed with the assumption that a cellular manufacturing system (a 'lean' manufacturing system) is implemented. For the assumed cellular manufacturing system, the cell design proposed in the paper of Cochran et al. [Cochran et al. 2002] is used.

After the reviews with the existing manufacturing system and the new manufacturing system, the advantages and disadvantages of the various solutions presented in two reviews are discussed. This discussion presents the difficulties associated with resolving the conflicts and proposes a way to deal with the difficulties.

8.2.2.1 Reviewing the design decision with the existing manufacturing system

When a detailed design decision like the decision on the angle of fluid channels is made, many high level design decisions are already made. For example, product variety decision is likely to have been made: ABS and ASR/VDC. Product architecture design is also made (integrated) and the type of material is already selected (aluminum). In addition, it is decided to use machining processes to make the fluid channels on the housing. Therefore, these constraints should be always kept in mind during the reviewing process. Furthermore, the design of the ASR housing is based on the ABS housing since the fluid channels of the ASR are composed of the fluid channels for the ASR function added on those of the ABS [Maisch et al. 1993], [Maier and Müller 1995]. Consequently, it is acceptable to assume that the ASR production operations are developed on top of the ABS production operations and this is supported by the interviews with the engineers in plant C.

Under these conditions, the design of the four angled fluid channels affects the manufacturing system in such ways as contributing to the product differentiation between ABS and ASR housings and failing the equipment and process steps for ABS housings. The result of the reviewing process is presented in Figure 8-9. The gray colored blocks show the FRs and DPs of the MSDD that are relevant to the category but not significantly affected by the given design decision. The black colored blocks indicate the FRs and DPs that are directly related to the design decision in consideration.

In the quality branch, the most important impact of the angled fluid channel design is that the angled fluid channels cannot be machined with the fixture that is used for ABS housing production (FR-Q12) as is discussed in section 8.2.1. The CNC machining center itself is capable of meeting all machining requirements of both ABS and ASR housings. To solve this conflict, a new fixture is developed as is shown in Figure 2-5 and 7-24. However, the new fixture is not designed in a way to achieve all relevant FRs of the MSDD proposed by Arinez [2000] (Figure 8-5) except FR-Q12 (eliminate machine assignable causes). Even for the FR-Q12, the new fixture design does not solve the quality problem caused by the load of multiple parts per each cycle of the machining. As is discussed before, when chip-in-spindle problem occurs, for example, all of the loaded parts should be scrapped, which deteriorates the quality level. From this sense, the existing solution is just ad-hoc modification of the ABS housing machining operations in order to produce ASR housings. In addition to the fixture change, some other sources of the machine assignable causes should be reviewed. For example, the fixture rotation system should be stiff enough for the machining operation of the angled holes.

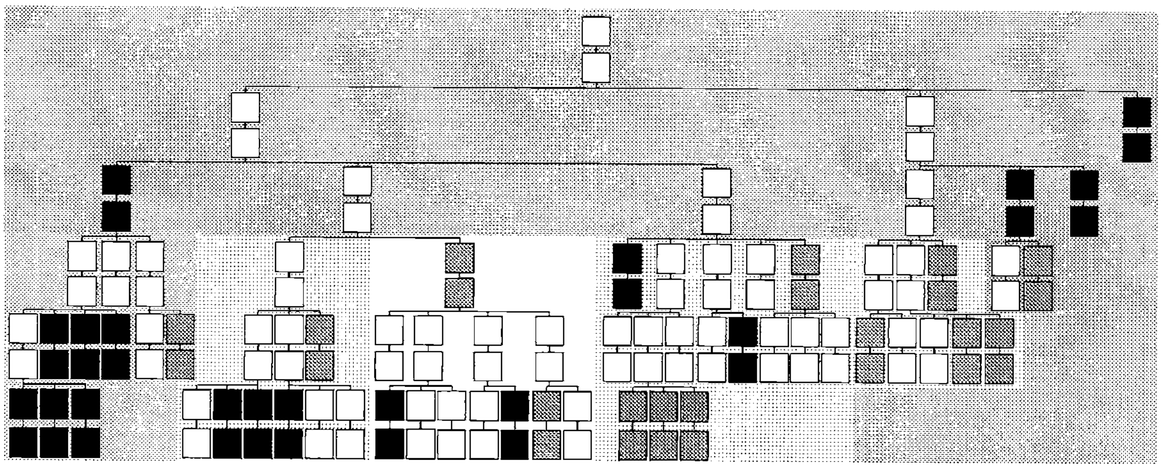


FIGURE 8-9. THE IMPACT OF ANGLED FLUID CHANNEL DESIGN ON THE FRS AND DPS OF THE MSDD FROM THE DETAILED DESIGN PERSPECTIVE.

As is explained before, the operation steps to machine the ASR housings are different from the steps for the ABS housings due to the new fixture developed to machine the angled fluid channels and other machining requirements such as increased number of fluid channels and the increased size of the housings. Therefore, the operators need to be trained on the new required tasks (FR-Q111) and new standard work methods (FR-Q112) should be developed. Training of the operators or developing the new standard work methods should not be difficult since the machining of the ASR housing is not very different from that of the ABS housing in a fundamental way. Some mistake proof devices can be developed to prevent the operators' mistakes caused by the introduction of the new fixture and the operational change (FR-Q113).

The angled fluid channel design may be linked to the method assignable causes (FR-Q3) or material assignable causes (FR-Q4). The location and direction of the angled fluid channels relative to the other fluid channels may be reviewed to see if machining processes are adequate to make those fluid channels. If there is any interference in the direction of the machining tool movement, the part design cannot be realized with the machining process. Furthermore, if the angled fluid channels are located too close to other fluid channels, the vibration and stress coming from the tool movement may cause some deformation of other fluid channels. In this case, machining may be avoided. In a similar way, the incoming material property may be checked if the material property supports the design. To use the given product design and the machining process, the material property may be improved by using forged aluminum blocks instead of casted aluminum blocks.

With regard to the FR-111, the angular tolerance of the angled fluid channels needs to be controlled in addition to the design specifications on the geometry of the housing. The angular tolerance may greatly affect the location of the end of fluid channels and additional efforts should be made to keep the angular tolerances. If there were no angled fluid channels, no angular tolerance may need to be considered except the perpendicularity from the face of the housing.

In the identifying and resolving problems branch, it should be first checked if the introduction of the new fixture and the consequent new operation pattern deteriorates the simplicity of the material flow paths within the existing manufacturing system (DP-R112). The ABS housing machining area design is not affected significantly by the introduction of the new fixture since the CNC machining centers for the ASR housing machining are more or less dedicated to the ASR housing. In addition, the ABS housing machining area is not designed to keep the material flow paths simple and thus, no significant difference arises after the introduction of the new fixture. To identify disruptions where they occur, simplified material flow paths should be sought in the existing manufacturing system.

The introduction of the new fixture and the new operational steps may lead to new types of production disruptions and the new production disruptions should be reflected to the feedback system, which is overlooked in the existing system. In addition, new supportive resources to solve the disruptions related to the new fixture and the new operational steps should be specified. This factor is not thoroughly considered in the current system.

In the predictable output branch, new standard methods to provide repeatable processing time may need to be developed due to the new operational pattern caused by the introduction of the new fixtures. Even though the machining operations are automated, loading and unloading are conducted by the operators and the operators are required to load and unload parts from three clamping positions, A, B, and C. The complexity involved may lead to variation in task completion time of the operators (FR-P121). In addition to this factor, preventative maintenance programs in use should be reviewed and modified as necessary to accommodate the introduction of the new fixture (FR-P122). FR-P141 and FR-P142 are not much affected by the introduction of the new fixture because the manufacturing system designed for ABS production does not have SWIP and the scheduling is done based on forecasting and MRP (material requirement planning) system. Instead of SWIP, a large number of inventories are kept to ensure the parts availability. Proper timing of part arrivals (FR-P142) is not necessary to ensure material availability even though fallout exists (FR-P14) since the fallouts are compensated by inventories. Compensation of variation by inventories, however, deteriorates quick response to the problems and short lead time to the customer demand (delay reduction).

In the delay reduction branch, improvement is made on the lot size of the process. The lot size of the ABS machining is twelve parts but that of the ASR machining is eight. The lot size of the ASR machining is decreased to eight since the clamping position B can hold only eight parts. This reduces the lot delay. However, this lot delay reduction is minimal since the CNC machining centers in use have three spindles and thus, can process three parts in parallel, which minimizes the lot delay. This capability contributes to the large investment made to procure the existing CNC machining centers.

FR-T221, FR-T222, and FR-T223 that are related to the takt time are not affected by the introduction of the new fixture caused by the angled fluid channels. This is because the manufacturing system design for ABS housing machining is not operated according to the takt time. Instead, FR-T2 that is to reduce process delay is partially satisfied by integrating machining operations into a cycle and operating the AGV (automated guided vehicle) system in order to minimize the process delay between machining operation and transportation operation. When the machining operations of the housings are done, the AGVs deliver the parts to the next operation, which is deburring. The buffer between the machining and the AGV transportation is usually two containers which holds about 36 parts. However, more delay reduction can be achieved by using the concept of takt time.

The FR that is most significantly affected by the introduction of the angled fluid channels is FR-T32. Within the ABS housing family, the changeover time is less than 5 minutes since it is only a matter of changing machining programming. However, to change over from ABS family to ASR family, it takes more than a day since huge tombstone fixtures need to be exchanged and complex calibrations are required. In addition, two fixtures need to be exchanged since two fixtures attached to two machining centers respectively work as a group to produce ASR housings.

In the operating cost branch, FR-122 may be affected by the introduction of the new fixtures that are developed because of the angled fluid channels. This is because two more types of fixtures are added to the fixture for the ABS housing and thus, indirect labor requirement to maintain the fixtures may be increased. In addition, the changeover from ABS to ASR requires indirect labor, which would not be necessary if the same fixture could be used for both ABS and ASR housings. Facilities cost may be also increased since more fixtures need to be managed and this may require more space.

In the investment branch, the investment made to develop the fixtures for the ASR housing would not be necessary if the fixture for the ABS housing could be used for the ASR housing. This investment would not be necessary if the angled fluid channels are changed into the fluid channels that are perpendicular to a housing face. Even in this case, however, it needs to be compared which one is more expensive, developing new fixture for the ASR housing or developing a fixture that can be used for both ABS and ASR.

So far, the impact of the angled fluid channel design decision on the existing manufacturing system is reviewed. The possible conflicts are investigated and explained. Before looking at a couple of solution options through product design change, the evaluation of the current manufacturing system is presented in Figure 8-10. Figure 8-10 is developed based on the methods proposed by Linck [2001] and adapted from [Cochran et al. 2001a]. As is shown in Figure 8-10, the existing manufacturing system with the angled fluid channels for ASR housings does not satisfy the FRs of the MSDD very well. There is huge room for improvement.

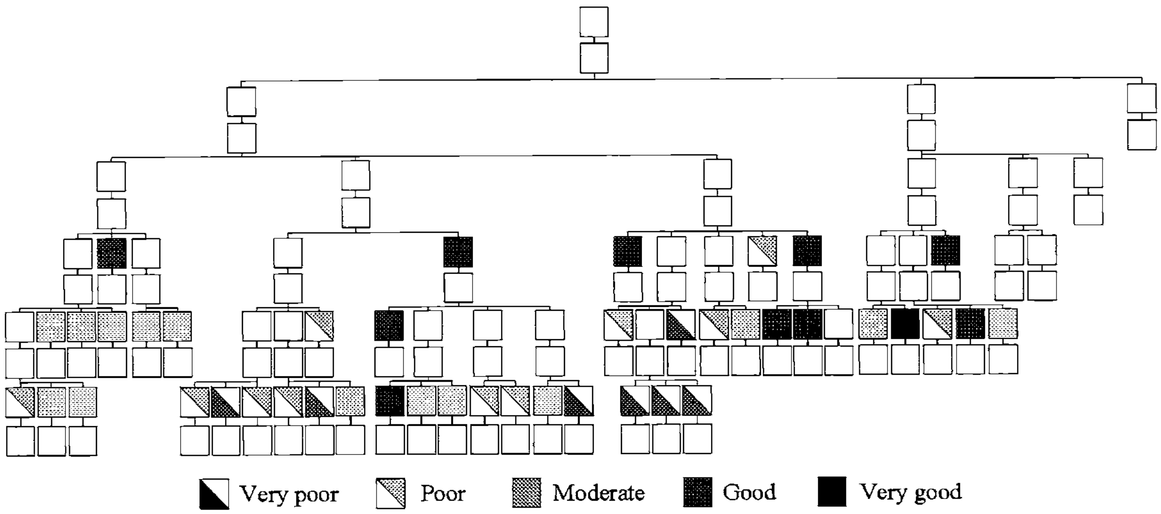


FIGURE 8-10. THE FRS OF THE MSDD THAT ARE SATISFIED BY THE EXISTING MANUFACTURING SYSTEM WITH THE ANGLED FLUID CHANNEL DESIGN (ADAPTED FROM [COCHRAN ET AL. 2001A])

The design change options to solve the conflicts caused by the angled fluid channels

There are a couple of ways to resolve the conflicts caused by the angled fluid channels from a product design perspective. First, the angled fluid channels can be replaced by the fluid channels that are perpendicular to the face of the housing. In this case, the special fixtures for ASR housings are not necessary and the same fixture can be used for both ABS and ASR housing machining, which eliminate the conflicts identified through the manufacturability evaluation process. However, while this decision eliminates for the need for the new fixtures and the new operational pattern, it is not enough to significantly contribute to the achievement of the FRs of the MSDD. FR-T32 to reduce run size delay through quick changeover can be better satisfied along with FR-Q12 to eliminate machine assignable causes. FR-13 related to the investment associated with the new fixtures may be better satisfied along with the FR-122 to reduce waste in indirect labor. Other FRs are not affected much since the manufacturing system for the ABS machining itself is not designed to satisfy the FRs of the MSDD. The modification of the manufacturing system itself is necessary.

The other way to eliminate the conflicts caused by the introduction of the angled fluid channels is to change the product architecture. For example, the fluid channels that provide ASR functions can be integrated into an ASR module and a manufacturing group can be dedicated to the production of the ASR modules. In this way, the volume and mix flexibility of the ABS and ASR housings are ensured at the assembly, which decreases the complexity involved. There is a company taking this approach [Sekiguchi et al. 1993]. When this modular approach is taken, the manufacturability of the new design should be reviewed through the manufacturability evaluation process. In addition, it is likely that a new manufacturing system is implemented to support the change in the product architecture.

The plant C adopted the first solution and the next generation ABS/ASR has fluid channels, all of which are perpendicular to the face of the housing.

8.2.2.2 Reviewing the design decision with the new manufacturing system

In the previous section, the angled fluid channel design decision is reviewed with the existing manufacturing system that is not designed to satisfy the FRs of the MSDD. In this section, it is discussed how the angled fluid channel design affects a new manufacturing system that is designed to satisfy the FRs of the MSDD. The new manufacturing system design is developed by Cochran et al. [2001a] and detailed information about the design is available at [Weidemann 1998] and [Kim 1999]. Figure 8-11 represents the manufacturing cell that substitutes the ASR housing production in the current machining area shown in Figure 2-3. The difference between the cells for the ABS housing and the ASR housing is the number of machines and operators as well as the fixtures applied to a certain machine.

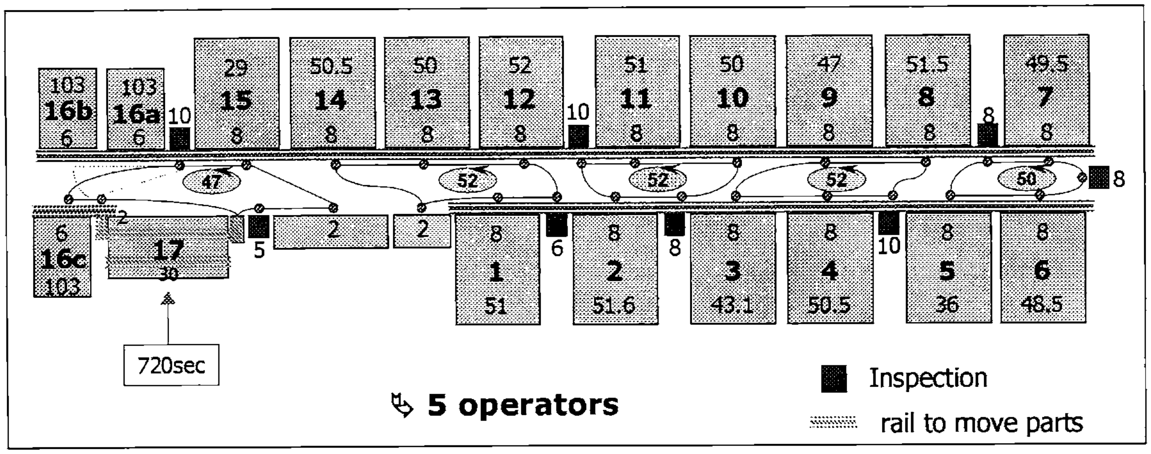


FIGURE 8-11. PROPOSED MACHINING CELL DESIGN FOR ASR HOUSING AT THE PEAK DEMAND [COCHRAN ET AL. 2001A]

In the quality branch, the introduction of the angled fluid channels does not require any special fixture since the part can be loaded in an angled position so that the rotation of the fixture is not necessary. This is possible since a small number of the operation steps are grouped and allocated to each machine within the cell. Each machine is required to perform only a small number of operations and thus, is not necessary to be complex. A simple and general-purpose CNC machining center will work. Quality problems such as the chip-in-spindle problem can be identified more quickly since the operators can perform inspection after a small number of operations. Therefore, FR-Q12 can be much better satisfied. Still, operator training (FR-Q111) and standard work method development (FR-Q112) are necessary for the ASR housing cell but they are not required because of the angled fluid channels. In addition, they are not very different from those of the ABS housing cell. More specific mistake proof devices may be applied to the machining of the angled fluid channels (FR-Q113).

The same issues as the existing manufacturing system case should be reviewed for FR-Q13, FR-Q14, and FR-111. The location and direction of the angled fluid channels relative to the other fluid channels and the faces of the housing may be reviewed to see the appropriateness of the machining process for the angled fluid channels. For example, if there is any interference in the direction of the machining tool movement, the part design cannot be realized with the machining process. In a similar way, the incoming material property needs to be checked to see if the material property supports the angled fluid channel design. With regard to the FR-111, the same requirement that the angular tolerance of the angled fluid channels needs to be controlled applies to the new manufacturing system as it does to the existing manufacturing system.

In the identifying and resolving problems branch, it should be first checked if the introduction of the angled fluid channels deteriorates the simplicity of the material flow paths of the new manufacturing system (DP-R112). In the new manufacturing system, there are only four material flow paths as is shown in Figure 8-12 and the angled fluid channels do not contribute to the material flow paths. Since the material flow paths are simple and the operations are grouped into a small number, it is easy to identify disruptions where they occur.

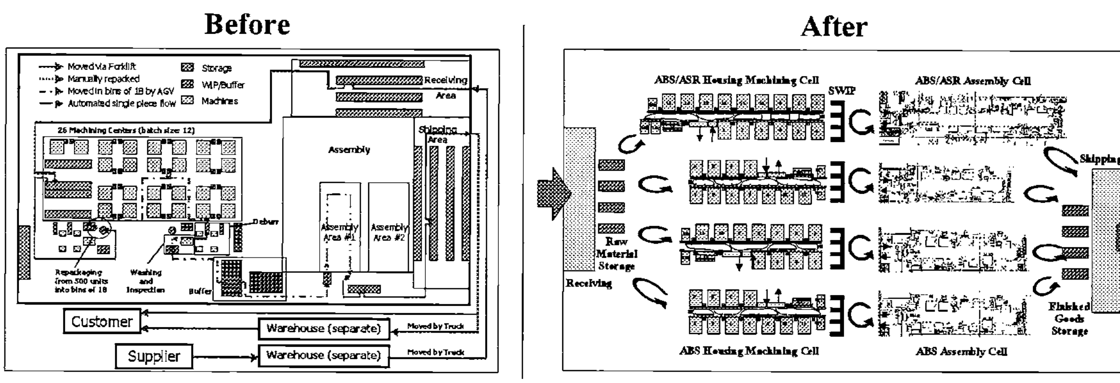


FIGURE 8-12. EXISTING MANUFACTURING SYSTEM (LEFT) VS. NEW MANUFACTURING SYSTEM (RIGHT) (ADAPTED FROM [COCHRAN ET AL. 2001A])

The angled fluid channels do not cause any new production disruptions in the new manufacturing system since there is no difference between the machining of angled fluid channels and the rest of the fluid channels (FR-R113). Still, new supportive resources to solve the disruptions related to the machining of the angled fluid channels should be specified to minimize the problem solving lead time (FR-R114). The ASR housing cell may use the same procedure to solve problems as the ABS housing cell (FR-R13).

In the predictable output branch, new standard methods to provide repeatable processing time (FR-P121) may need to be developed since the operator work loop in the ASR cell is different from that in the ABS cell due to the increased number of required operations.

Angled fluid channels contribute to the increase of the number of required operations. Preventative maintenance programs for the ABS housing cell may be applied to the ASR housing cell since there are few differences between them except the number of machines (FR-P122). FR-P141 and FR-P142 are little affected by the angled fluid channels.

In the delay reduction branch, the angled fluid channel design does not affect the lot size since a single-piece-flow is accomplished in the new manufacturing system (FR-T1). FR-T221 and FR-T222 are related to the takt time and may be affected by the angled fluid channel design. The automatic cycle time of the machine that processes the angled fluid channels should be less than the takt time. The same rule applies to the manual cycle time of the operator who is involved with the machining of the angled fluid channels. This may not be an easy task since the angled fluid channel machining operations should be grouped together and allocated to a single machine to avoid the complexity in fixturing.

The FR-T32 may be greatly affected by the introduction of the angled fluid channels. To produce ABS housings in the ASR cell, the machines used for the production of the angled holes should have the flexibility to deal with the ABS housing. For example, they should be equipped with rotating fixtures or two-step fixtures that rotate from a certain degree to a zero degree. Still the investment necessary to implement these fixtures would be much less than the investment made to make the rotating tombstone fixtures. In a similar way, the ABS housing cell cannot produce ASR housings due to the angled fluid channels. However, variations within the same product family (ABS or ASR) can be easily managed.

In the operating cost branch, FR-D23 may be affected by the angled fluid channel design. When the angled holes are machined, ergonomic interface between the worker, machine, and fixture may be broken due to the angles. When the work interface is designed, this factor should be reflected in the manufacturing system design. FR-122 and FR-123 may be little affected by the angled fluid channels.

In the investment branch, some additional investment needs to be made to develop the fixtures for the angled fluid channel machining. When the flexibility matters, the ASR housing cell need to have the flexibility to produce ABS housings and in this case, as is previously explained, the fixtures should have the flexibility. This may lead to additional investment. This investment would not be necessary if the angled fluid channels are changed into the fluid channels that are perpendicular to a housing face.

The summary result of the reviewing process is presented in Figure 8-13. As is shown in Figure 8-13, different FRs are affected by the angled fluid channel design with the different manufacturing system. The gray colored blocks show the FRs and DPs of the MSDD that are relevant to the category but not significantly affected by the given design decision. The black colored blocks indicate the FRs and DPs that are directly related to the design decision in consideration.

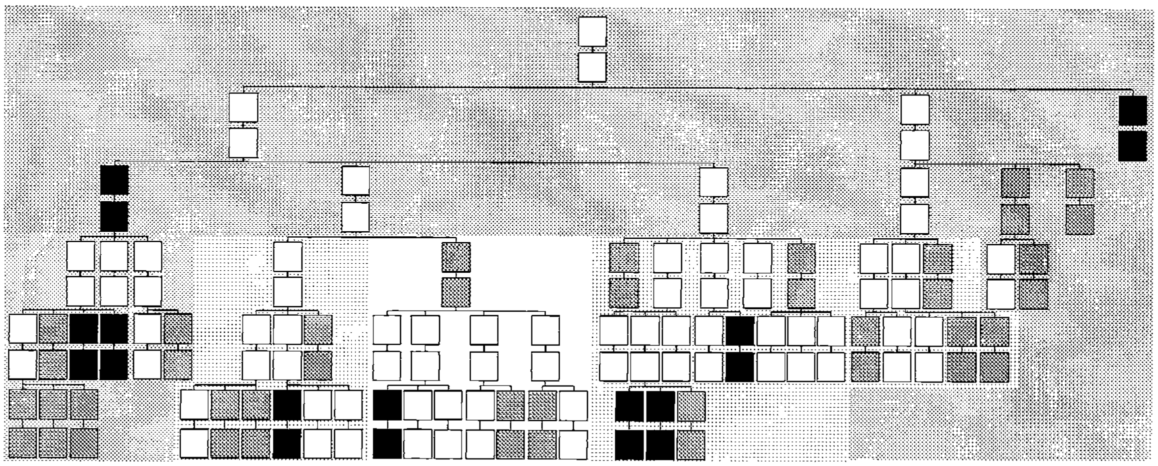


FIGURE 8-13. THE IMPACT OF THE ANGLED FLUID CHANNEL DESIGN ON THE FRS AND DPS OF THE MSDD FROM THE DETAILED DESIGN PERSPECTIVE WITH THE NEW MANUFACTURING SYSTEM.

So far, the impact of the angled fluid channel design decision on the new manufacturing system is reviewed. The possible conflicts to arise are investigated and the new requirements for the manufacturing system are presented. The evaluation of the new manufacturing system with the angled fluid channel design decision is shown in Figure 8-14. The questionnaire method proposed by Linck [2001] is used and the result is adopted from [Cochran et al. 2001a].

By replacing the angled fluid channels with the perpendicular fluid channels, more improvement in the changeover (FR-T32) is possible along with the quality (FR-111) and the investment (FR-13).

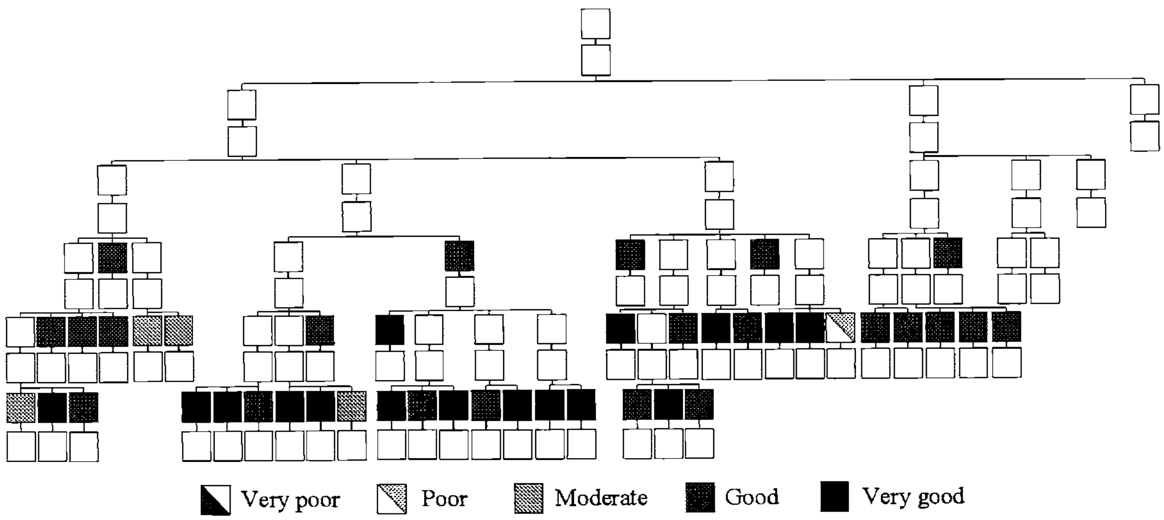


FIGURE 8-14. THE FRS OF THE MSDD THAT ARE SATISFIED BY THE NEW MANUFACTURING SYSTEM WITH THE ANGLED FLUID CHANNEL DESIGN (ADAPTED FROM [COCHRAN ET AL. 2001A]).

The plant C case shows that the manufacturability of a product design depends on the type of the manufacturing system accommodating the new design. For example, with the cellular (differential) manufacturing system, the angled hole design affects 9 FR-DP pairs while 18 FR-DP pairs are affected in the departmental (integral) manufacturing system. Therefore, the cellular manufacturing system is more flexible to the introduction of new product designs. This is partially due to the fact that the cellular (differential) manufacturing system only integrates small number of operations into a machine while the departmental (integral) manufacturing system integrates as many operations as possible into a machine. In addition, the cellular manufacturing system has the additional benefit of enhanced manufacturing system performance. Therefore, even though eliminating the angled fluid channels can solve most of the conflicts between the existing manufacturing system design and the angled hole product design, the change of manufacturing systems may be pursued for a long-term efficiency. By adopting both product design change (eliminating angled holes) and manufacturing system design change, the best performance of the manufacturing system can be achieved while the flexibility of manufacturing system to the introduction of new product design is greatly enhanced. Table 8-1 summarizes the result.

TABLE 8-1. THE RELATIONSHIP BETWEEN THE TYPE OF MANUFACTURING SYSTEMS AND PRODUCT DESIGN. (*MS: MANUFACTURING SYSTEM, PD: PRODUCT DESIGN)

Product Design \ Manufacturing System Design	Differential (Cellular)	Integral (Departmental)
With angled holes	• **Good MS performance** • **Moderate PD impact**	• **Bad MS performance** • **Significant PD impact**
Without angled holes	• **Good MS performance** • **Minor PD impact**	• **Bad MS performance** • **Minor PD impact**

8.2.2.3 Integrated vs. differential in product design and manufacturing system design

From the plant C case, a general rule can be derived that explains the role of product architecture and manufacturing system design in deciding the flexibility of the manufacturing system to product variety. This section describes the rule and discusses the impact of the type of manufacturing system design and product architecture on the system flexibility to product variety.

In product design, Phal and Beitz [1996] define differential construction as "breakdown of a component (a carrier of one or several functions) into several easily produced parts," and integral construction as "combination of several parts into a single component." The concept of differential construction and integral construction in product design is same as the concept of product architecture. Using an analogy, in manufacturing, differential construction can be seen as "breakdown of manufacturing processes (necessary to produce a part) into several easily managed segments and their allocation into machines," and integral construction as "aggregation of the processes into a machine as many as possible."

As is shown in the previous section, the differential construction of the manufacturing system is better than the integral construction at managing product variety. For example, if the machining operations are integrated into a machine, a simple change of product design (e.g., angled fluid channels) may require a significant change of the machine or a complete reorganization of the machining operations (e.g., new fixtures). On the other hand, if the machining operations are differentially constructed, a small segment of the entire machining operations may be changed according to the design change. This is a part of the reasons why lean manufacturing cell is more flexible than the traditional high-speed machining department as is presented in the previous sections.

Similar patterns are observed in product design. Differential construction of the product design combined with an appropriate strategy such as platform strategy or standardized part sharing strategy, can lead to wide product variety without unacceptably affecting the manufacturing. This is possible since customer perceived product variety can be provided with less manufacturing perceived product variety through the combination of the limited number of parts. In other words, through combination, a limited number of components can provide wide product variety to the customers. Integral construction of the product design, however, requires manufacturing to handle the same level of product variety that is provided to the customers. Therefore, integral construction is not a good way to handle the product variety. This observation is summarized in a matrix shown in Table 8-2.

Table 8-2 also shows the relationship between the above-mentioned categories of product and manufacturing system design, and the production cost. The differential manufacturing requires more machines than the integral manufacturing. To compensate the increased cost caused by the increased number of machines, the differential manufacturing uses simple machines and provides better quality. Since the manufacturing operations are allocated to the machines in small segments, simple and general-purpose inexpensive machines are enough for the allocated manufacturing operations. In addition, it is easy to find where quality problems occur and thus, quality problems can be fixed quickly. On the other hand, the integral manufacturing has the advantage of operating a small number of machines with high production rate. Therefore, increasing the utilization rate of the machines can contribute to cost saving.

In product design, the differential design saves costs associated with the product variety by sharing standardized parts. In addition, easily producible part designs enable the use of simple operations to produce them, which further reduces the manufacturing costs involved. On the other hand, the integral design has less number of parts and thus, has an advantage in the assembly and fabrication by reducing the number of operations required.

TABLE 8-2. THE RELATIONSHIP BETWEEN DIFFERENTIAL AND INTEGRAL CONSTRUCTION OF PRODUCT AND MANUFACTURING SYSTEM DESIGN.

		Manufacturing System Design: Differential	Manufacturing System Design: Integral	
Product Design	Differential*	**Very Flexible**	**Flexible**	Cost saving from using standardized part, simple process
Product Design	Integral*	**Flexible**	**Inflexible**	Cost saving from using less number of processes, less assembly
		Cost saving from simple machine, high quality	Cost saving from less number of machines, high util. rate, high production rate	

* Pahl & Beitz, 1996

This result may be compared with the matrix proposed by Ulrich [1995], which is shown in Table 8-3. In this matrix, Ulrich considers product architecture and component process flexibility. He categorizes product architecture into modular and integrated architectures, and manufacturing into low flexibility manufacturing and high flexibility manufacturing. The product variety and production lead time issues are explained in each case as is shown in Table 8-3.

The matrix shown in Table 8-2 is compatible with the matrix proposed by Ulrich since the differential manufacturing is often more flexible than the integrated manufacturing. The matrix in Table 8-2 shows how a component manufacturing can be more flexible to the product variety and the design change.

TABLE 8-3. RELATIONSHIP BETWEEN PROCESS FLEXIBILITY AND PRODUCT ARCHITECTURE [ULRICH 1995]

		Component process flexibility	
		Low	High
Product architecture	Modular	• Variety achieved by combinatorial assembly from relatively few component types • Assembly to order from component inventories is possible • Minimum lead time dictated by final assembly process	• Components may be fabricated to order as well as assembled to order • Component inventories may be kept to minimize order lead times • Infinite variety is possible when components are fabricated to order
	Integrated	• High variety is not economically feasible and would require high fixed costs (e.g., tooling), high setup costs, long order lead times and high inventory costs	• Variety can be achieved without relatively high inventory costs by fabricating components to order • Minimum order lead times dictated by both component fabrication time and final assembly time • Infinite variety is possible

8.2.3 Conclusion

In this section, the plant C case is presented. It is shown that the overlook of the product designers on the manufacturability of the detailed design can lead to manufacturing problems combined with the manufacturing system design and how the different types of manufacturing system designs respond to the design decision. In addition, it is shown how the proposed manufacturability evaluation process can be applied in case that the existing manufacturing system does not follow the FRs of the MSDD.

It is important to design the manufacturing system to satisfy the FRs of the MSDD while simultaneously considering the manufacturability issues of the product design. Considering the manufacturing system that satisfies the FRs of the MSDD when a new product design is made will lead to the new product design that does not prevent the manufacturing system to achieve the FRs of the MSDD.

8.3 Existing DFMA Approaches

The proposed framework can be used to investigate the scope of the existing DFMA approaches relative to the achievement of the objectives of manufacturing systems. In this section, the DFX approaches proposed by Boothroyd et al. [1994], and Phal and Beitz [1996] are evaluated using the proposed framework. The other approaches focusing on the communication improvement from the organizational viewpoint are excluded in this evaluation since they do not provide in-depth information about what to communicate.

Boothroyd et al. [1996] explain the manufacturability issues in the selection of materials and processes, and the product design that fits with the selected processes. The addressed DFX approaches include: design for manual assembly, electrical connections and wire harness assembly, design for high-speed automatic assembly and robot assembly, design for machining, printed circuit board design for manufacture and assembly, design for injection molding, design for sheet metal forming, design for die casting, and design for powder metal processing. The content of these DFX approaches can be reviewed using the FRs and DPs of the MSDD and the result is shown in Figure 8-15.

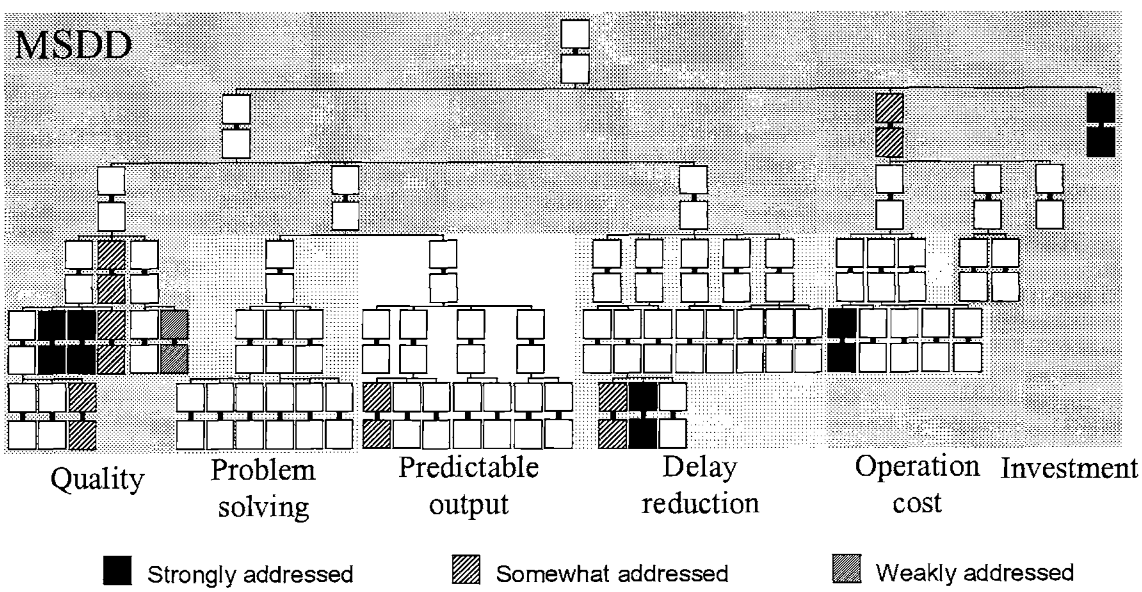


FIGURE 8-15. THE REVIEW OF THE DFX APPROACHES ADDRESSED BY BOOTHROYD, DEWHURST, AND KNIGHT [1994] AGAINST THE FRS AND DPS OF THE MSDD.

As is shown in Figure 8-15, the DFMA discussion of Boothroyd et al. centers on the manufacturing quality branch of the MSDD. They provide deep insights and guidelines to eliminate the machine assignable causes, method assignable causes, and material assignable causes of quality problems. The provided guideline is very practical and detailed in its content. However, the scope of the approach is limited to the quality so that the other manufacturing system design issues such as on-time delivery and delay reduction are neglected in this approach.

Phal and Beitz [1996] explain a series of DFX approaches to provide the guidelines for the embodiment design. The addressed DFX approaches include: design for safety, design to allow for expansion, design to allow for creep and relaxation, design against corrosion damage, design for ergonomics, design for aesthetics, design for production, design for ease of assembly, design to standards, design for ease of maintenance, design for recycling, and design for quality. The content of these DFX approaches can be reviewed using the FRs and DPs of the MSDD and the result is shown in Figure 8-16.

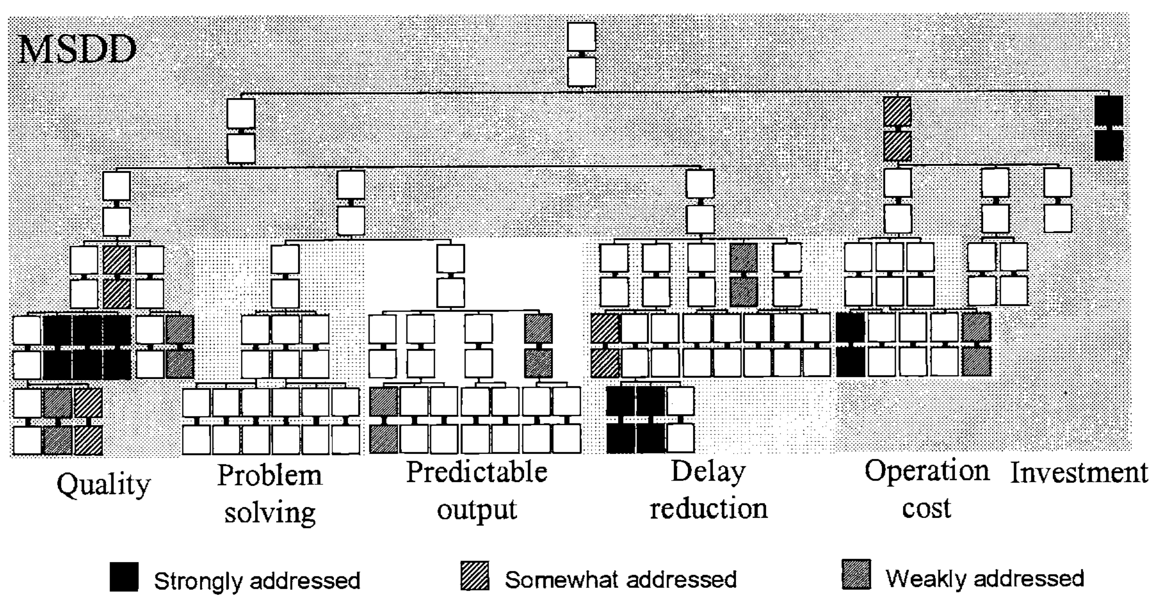


FIGURE 8-16. THE REVIEW OF THE DFX APPROACHES ADDRESSED BY PHAL AND BEITZ [1996] AGAINST THE FRS AND DPS OF THE MSDD.

As is shown in Figure 8-16, the discussion of the manufacturability in [Phal and Beitz 1996] focuses on the quality issues while addressing some delay reduction issues and operating cost issues. It contains wider scopes of the manufacturability issues in comparison with the DFMA approaches of Boothroyd et al., but still many other manufacturing system design issues are missing.

The above-mentioned DFX approaches, however, can provide the content of the proposed manufacturability evaluation process. In other words, when the conflicts between the design decision and the FRs and DPs of the MSDD are checked, the guidelines and problem examples provided by these approaches can be used to decide the conflicts. The proposed methodology systemizes the existing DFMA approaches by seeing their impact on the achievement of the FRs of the MSDD and opens a way to discover more DFMA issues in manufacturing by increasing the scope of the traditional approaches relative to the FRs of the MSDD.

In this sense, some of the best practices for smooth transition from product design phase to manufacturing phase may be replaced or supported with the proposed methodology. For example, Clark and Fujimoto [1991] stresses the use of existing manufacturing lines for prototyping and pilot production in Japanese automotive companies, which greatly contributes to resolving manufacturing problems before the actual mass production begins. The direct use of existing manufacturing lines becomes a very effective way to solve manufacturing problems since the engineers can learn the impact of new product design on the existing lines by actually producing them in the existing line. The engineers are able to experience the problems and solve the problems with the real manufacturing lines. However, this may not be done in the earlier product design phases. As the computer simulation virtually shows the result of a certain decision, the proposed methodology can show the possible conflicts in manufacturing in a virtual way. Therefore, the advantage of using the real manufacturing lines in prototyping and pilot production may be decreased with the application of the proposed manufacturability evaluation process.

8.4 Issues in Applying the Manufacturability Evaluation Process

In this section, several issues are addressed that can arise when the proposed manufacturability evaluation process is applied. First, it is addressed how to apply the manufacturability evaluation process when the manufacturing system in consideration is not designed to achieve the FRs of the MSDD. In section 8.2.2, this issue is addressed by finding the conflicts of the design decision with the MSDD first, and then evaluating the existing manufacturing system with and without the design decision modification. This is possible since the MSDD describes the general requirements and general solutions of the manufacturing system to achieve the today's manufacturing system requirements of quality, on-time delivery, short lead time, reduced operating costs, and rational long-term investment. However, the FRs become more important than the DPs when the manufacturing system is not designed to achieve the FRs of the MSDD, which indicates that the DPs of the MSDD are not accepted in the existing manufacturing system. Among the FRs of the MSDD, in addition, the high level FRs can be considered when lower level FRs are little meaningful with the given manufacturing system since the high level FRs are more general than the lower ones. However, this is not likely since the FRs and DPs of the MSDD reflects the best-known practices to achieve the objectives of the modern manufacturing system. Therefore, as is presented with the example of section 8.2.2, manufacturing system modification to satisfy the FRs of the MSDD should follow the product design modification so that true achievement of the FRs of the MSDD is made.

The second issue is about the step 6 of the manufacturability evaluation process. In the step 6, no rule is proposed to resolve the conflicts through a choice between product design modification and manufacturing system design modification. Instead, possible solutions in various situations are provided in section 7.3.1.6. In addition, in section 8.2.2, two cases are discussed when the product design is modified and manufacturing system is modified. This is because there can be other factors that affect the success of the product except the manufacturability of the product design. The ultimate objective of the product development is to succeed in the market place, not to design a manufacturable product.

8.5 Chapter Summary

In this chapter, two application examples of the manufacturability evaluation process are presented. In the first example of meter plates, it is shown how the proposed manufacturability evaluation process can be applied in case of product design change, which can be seen from product variety perspective and detailed design perspective. In addition, the items that should be considered for a process change from stamping to laser cutting are identified by applying the proposed manufacturability evaluation process. With the meter plate example, the manufacturability evaluation process is shown to effectively identify and explain the possible sources of manufacturing problems with the introduction of certain product design decisions.

In the second example of ABS housings, it is discussed in detail how the conflicts identified by the manufacturability evaluation process can be resolved. Manufacturing problems caused by designing fluid channels of braking system housings to be angled to two faces of housings are explained with the framework provided by the manufacturability evaluation process. Then, different ways of resolving the identified conflicts are reviewed in terms of their capability to resolve the conflicts and further satisfy the FRs of the MSDD. The benefits and limitations of changing product designs are provided as well as those of modifying manufacturing system designs. Both product design modification and manufacturing system design change should be pursued to maximize the satisfaction of the objectives (FRs) of manufacturing systems.

In addition, it is shown that the manufacturability of a product design can vary depending on the type of the manufacturing system accommodating the new design. Differential (cellular) manufacturing systems are observed to be more flexible to the introduction of new product designs than integral (departmental) manufacturing systems. Furthermore, combined with differential (modular) product design, cellular manufacturing systems can be more flexible to the new product design introduction.

9 THE EVALUATION TOOL

This chapter describes the development of a standardized evaluation tool. This tool evaluates the practices of a company to ensure the design of manufacturable products in terms of their scope relative to the MSDD. The issues related to the development of the evaluation tool are discussed in the following sections along with a review on the existing evaluation tools of the MSDD.

9.1 Introduction

The first round questionnaire aims to investigate what practices are made in the industry to facilitate the information exchange between product design and manufacturing. As is presented in Chapter 5, it is identified that many companies do not have standardized methods in use for the information exchange between product design and manufacturing. Even for the companies that implement standardized tools, the information regarding manufacturing system design is often neglected. Many tools in use for the early consideration of manufacturing issues are developed based on the knowledge gained from previous projects instead of relying on a systematic framework. The first-round questionnaire that is composed of open-ended questions shows this trend in the tools deployed in the automotive industry. However, the first round questionnaire shows its weaknesses in the following points:

- It is difficult to interpret the answers received
- It is difficult to receive the answers in a repeatable way
- It is difficult to compare the effectiveness of different approaches deployed in different companies

The first two problems are mainly due to the characteristics of the questions asked in the first-round questionnaire. The first round questionnaire is consisted of open-ended questions and thus, the answers are subject to the view of the respondents to the information exchange requirement between manufacturing and product development. If a respondent thinks one aspect is more important than the other, the respondent describes in detail what he/she thinks important while neglecting other aspects, which is linked to the misinterpretation of some questions. These problems coincide with the typical drawbacks of the questionnaire approach discussed by [Leedy and Ormrod 2001]. Some drawbacks such as misinterpretation are solved by the complementary interviews with the engineers but it is difficult to completely eliminate all of the drawbacks. In addition, the open-ended questions often lead to a problem in the repeatability of the questions. In other words, the respondents may think different things whenever they face the questions.

Another problem of the first round questionnaire is that it is difficult to compare the effectiveness of different approaches implemented by each individual company. For example, it is very difficult to compare the PPC (Pre-Product Check) approach of the company A with the Copy-Exact approach of company B as described in Chapter 5. These two approaches cover different areas from the interface between manufacturing and product design, too, which makes it difficult to compare the effectiveness of each approach even though enough data are available. For example, both approaches are capable of screening engineering design problems that are solely related to meeting the engineering requirements, not manufacturing system requirements.

Considering these problems of the first round questionnaire, the second round questionnaire is developed to evaluate the general approaches implemented in each company to the information exchange in the interface area of manufacturing and product design, relative to the MSDD. In this thesis, the manufacturability of a product/process design decision is understood as how well the design decision contributes to the achievement of the objectives of manufacturing systems that are represented by the MSDD. From this perspective, the second round questionnaire attempts to collect data to investigate how well the achievement of the FR-DP pairs in the MSDD are addressed by the existing approaches of each company to the information exchange between manufacturing and product design. By comparing the scope of the manufacturability-ensuring approaches in the industry relative to the MSDD, it is possible to evaluate each approach and find where the strengths and weaknesses of each approach are placed.

9.2 Issues for the Evaluation Tool

The goal of the evaluation tool (or the data collection tool for evaluation) discussed in this thesis is to enable the assessment of the industry practices that are conducted to ensure the manufacturability of product design decisions relative to the MSDD. The data collection tool must be able to relate the industry practices to the MSDD in a repeatable way. The development of such tool poses several questions as Linck [2001] addresses in detail in his dissertation. The issues related a standardized data collection tool for the MSDD based on the questionnaire include:

- Simultaneous consideration of the FR and DP
- Quantitative vs. qualitative evaluation
- Leaf FR-DP pairs (the FR-DP pairs that are not decomposed any further) vs. every FR-DP pair to be considered

The first issue is about whether the FR and DP should be considered together or only one of them needs to be considered. A DP is a solution to the corresponding FR and there can be many solutions for a FR. In other words, it does not matter so much what DP is selected to satisfy the FR as long as the FR is well satisfied and the two design axioms are satisfied. Therefore, it might be sufficient to consider only the FRs in the MSDD by measuring the achievement of the FRs. However, the zigzagging principle of the Axiomatic Design methodology indicates that without higher level DPs, lower level FRs cannot be decomposed from higher level FRs. Consequently, measuring the achievement of lower level FRs has the underlying assumption that the high level DPs are accepted. In addition, the MSDD attempts to describe the FRs and DPs that are generally applicable to discrete part manufacturing systems in many industries. The DPs in the MSDD are believed to be reasonable general solutions to satisfy the FRs. Therefore, it is desirable to see whether a design decision affect the DPs of the MSDD, which are reasonable solutions to satisfy the FRs and underlying assumptions for the lower level FRs.

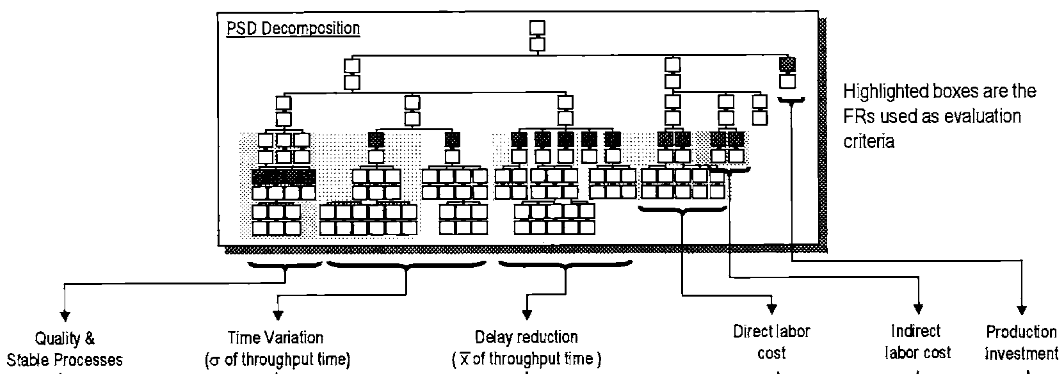
As the proposed manufacturability evaluation process considers both FRs and DPs (Chapter 7), the proposed evaluation tool take into account both FRs and DPs.

The second issue is whether to take a quantitative or qualitative approach in the evaluation tool. As is pointed out by Linck [2001], some FRs of the MSDD are difficult to be measured in a quantitative way. For example, FR-R113 and DP-R113 state to identify what the disruption is by feedback of subsystem states, which makes it difficult to develop a quantitative measure of the achievement of FR-R113. Furthermore, it is more difficult to quantitatively measure how much a product design decision affects the achievement of the FR-R113. Therefore, qualitative evaluation is adopted in the proposed evaluation tool. Qualitative evaluation by qualitative questions on the contents of the activities done to achieve the FRs allows better consideration of the behind ideas of the FR and DP in the MSDD of which meaning is limited by short sentences. However, when qualitative measures are developed, it is necessary to consider the standardization of the qualitative measures to ensure the consistency of data collection and analysis.

The third issue is about the FRs and DPs that are subject to the evaluation. Only the leaf FRs and DPs that are not further decomposed in the MSDD may be used from a perspective that the higher level FR are supposed to be satisfied by meeting the lower level FRs. However, in the case of assessing the impact of a design decision on the achievement of the FRs in the MSDD, higher level FRs should also be considered. This is because the MSDD considers the product design and process design as given while the evaluation tool aims to see how well the FRs and DPs are considered during the product development process by the existing practices in the industry. Therefore, some high level FRs and DPs that are affected by the design decision should also be considered. The decomposition of those high level FRs and DPs that are affected by the design decision is not exhaustive since the achievement of the decomposed FRs does not guarantee the achievement of the high level FR when product or process designs can change.

9.3 Comparable Existing Measurement Tools for the MSDD

In this section, the existing measurement tools based on the MSDD are reviewed. Linck [2001] provides a good review on the measurement tools for the MSDD. There are three existing evaluation approaches for the MSDD: the MSDD evaluation tool, the performance measures, and the MSDD questionnaire. The MSDD evaluation tool is proposed by Cochran [1999] and Wang [1999]. Wang [1999] provides a good explanation of the MSDD evaluation tool including an application example. The MSDD evaluation tool adopts a qualitative approach to assess a manufacturing system design relative to the MSDD. This tool measures how well a manufacturing system design satisfies sixteen FR-DP pairs of the MSDD from different levels. The FR-DP pairs considered in the MSDD evaluation tool are presented in Figure 9-1.



<table>
<tr><td rowspan="4">Upper level MSD Decomposition (FRs/DPs)</td><td colspan="16">FR: Maximize long term return on investment / DP: Manufacturing system design</td></tr>
<tr><td colspan="11">FR: Maximize sales revenue / DP: Production to maximize customer satisfaction</td><td colspan="4">FR: Minimize direct labor cost / DP: Elimination of non-value adding sources of cost</td><td rowspan="3">Minimize production investment</td></tr>
<tr><td colspan="4">FR: Deliver no defects / DP: Defect free production</td><td colspan="2" rowspan="2">FR: Deliver products on time / DP: Throughput time variation reduction</td><td colspan="5" rowspan="2">FR: Meet customer expected lead time / DP: Mean throughput time reduction</td><td colspan="2" rowspan="2">FR: Reduce waste in direct labor / DP: Elimination of non-value adding manual tasks</td><td colspan="2" rowspan="2">FR: Reduce waste in indirect labor / DP: Reduction of indirect labor tasks</td></tr>
<tr><td colspan="4">FR: Stabilize Process / DP: Elimination of assignable causes of variation</td></tr>
<tr><td>Evaluation Criteria (FRs)</td><td>Eliminate machine assignable causes</td><td>Eliminate operator assignable causes</td><td>Eliminate method assignable causes</td><td>Eliminate material assignable causes</td><td>Respond rapidly to production disruptions</td><td>Minimize production disruptions</td><td>Reduce run size delay</td><td>Reduce process delay</td><td>Reduce lot delay</td><td>Reduce transportation delay</td><td>Reduce systematic operational delays</td><td>Eliminate operators waiting on machines</td><td>Eliminate wasted motion of operators</td><td>Eliminate managerial tasks</td><td>Eliminate information disruptions</td><td></td></tr>
</table>

FIGURE 9-1. SIXTEEN EVALUATION FRS DERIVED FROM THE MSDD [WANG 1999]

Step-by-step qualitative descriptions of the ideal situation are used to assess how well a manufacturing system design satisfies each of the sixteen FRs considered in the MSDD evaluation tool. For example, for the FR to eliminate operator assignable causes, six different concrete descriptions of the shop floor are provided from level 1 to level 6. In a shop floor in a stage of level 1, "workers learn tasks by watching others and tasks may be done differently each time." This is the worst case. On the other hand, the level 6 indicates the best conformance to the proposed FR. In this stage, on the shop floor, "formal training is extended beyond the required skills by certified instructors, and the work standards are followed and upgraded by workers. Any operator mistakes are not translated defects through mistake proofing devices." Figure 9-2 shows the description of the shop floor in each level of conformance to the FR.

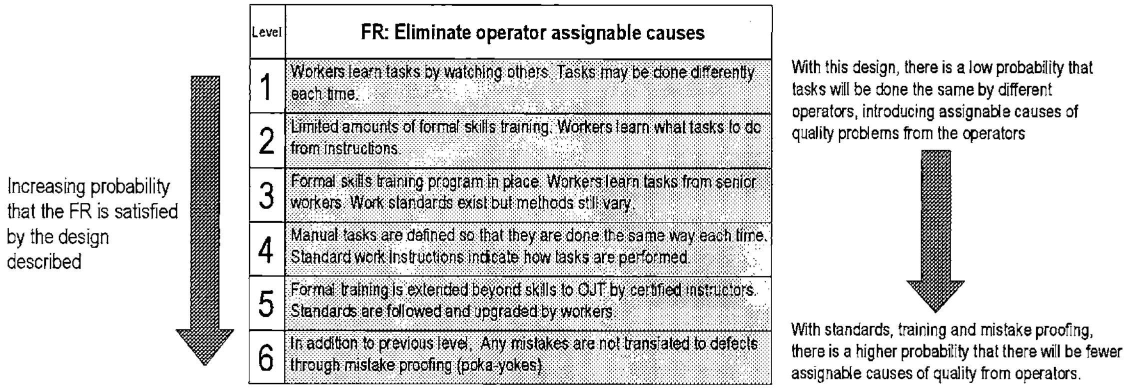


FIGURE 9-2. QUALITATIVE ASSESSMENT OF HOW WELL AN FR IS SATISFIED [WANG 1999]

These descriptions on the shop floor are very concrete and derived from the physical examples. Therefore, it is easier to understand than the often abstract statements of the FR and DP of the MSDD. A pie chart is used to assess the stage in which the considered manufacturing system design lies, since a manufacturing system can often be described by a portion of different stages. The pie chart system is shown in Figure 9-3 along with the explanation of the meanings of the partially filled pie charts.

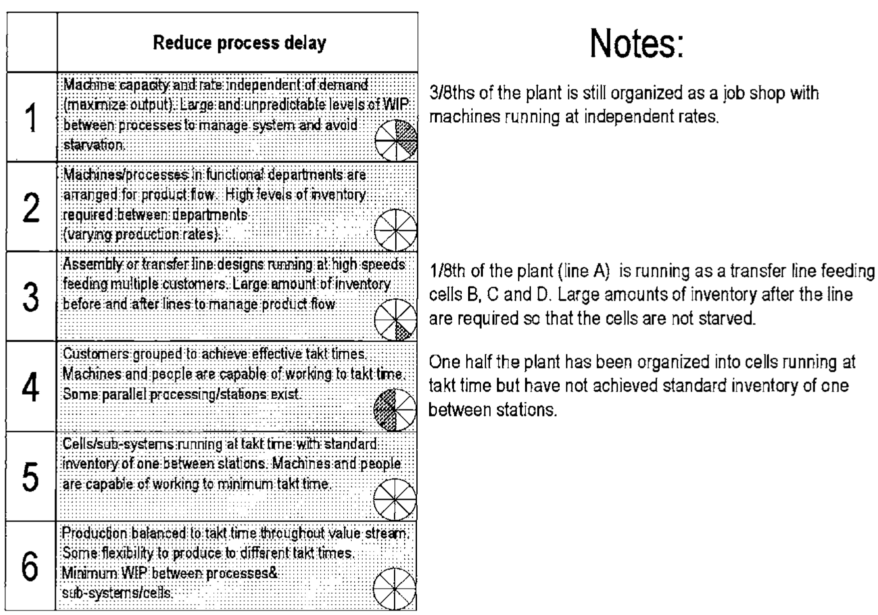


FIGURE 9-3. THE PIE-CHART SYSTEM [WANG 1999]

This form of the evaluation tool is very intuitive since it provides a physical description of the shop floor. However, it shows drawbacks when it is difficult to provide six different shop floor descriptions. In addition, the descriptions may be biased and this can cause some problems since the achievement of the FR are considered to depend on the DP in the MSDD evaluation tool. Especially in the interface area between manufacturing and product design where it is difficult to describe several stages to an ideal situation intuitively, this approach may not be appropriate to be used in the evaluation tool.

The second one is the MSDD performance measures. The MSDD performance measures are developed for each FR of the MSDD [Duda 2000], [Cochran et al. 2001b, 2001c, 2002]. The fundamental idea behind the development of the MSDD performance measures is that the performance measures for a manufacturing system should measure how well the FRs of the MSDD are satisfied by the manufacturing system. Therefore, a performance measure is developed for each FR of the MSDD and the developed performance measure attempts to quantify how well the corresponding FR is satisfied. For example, for the FR-R1 to respond rapidly to production disruptions, a performance measure of time between occurrence and resolution of disruptions is proposed.

Several problems are identified with this performance measure approach. First, while a performance measure attempts to measure the achievement of the corresponding FR, it is not obvious what magnitudes of the performance measure indicate a desirable achievement of the FR [Duda 2000], [Linck 2001]. Second, some FRs are difficult to be measured in a quantitative way. For example, the FR-T4 states to reduce transportation delay, while it is difficult to measure 'delay' since it needs a reference point. The performance measure proposed for the FR-T4 is inventory due to transportation delay. Another problem is that it is often very difficult to actually measure the proposed performance measures. For instance, the performance measure for the FR-R12 (communicate problems to the right people) is the time between identification of what the disruption is and support resource understanding what the disruption is. In a real manufacturing system, it is too cumbersome to assign specific personnel to track down this time. The tracking of the time taken between the identification and the resolution of the disruption may be impractical unless it is impossible.

The MSDD questionnaire proposed by Linck [2001] provides a standardized data collection tool to relate the knowledge on a manufacturing system gained by observations and interviews to the MSDD. The MSDD questionnaire measures the achievement of each individual FR by asking a series of questions that are directly linked to the achievement of the FR. An example is shown in Figure 9-4. In this example, for the FR-P122 (service equipment regularly) and the DP-P122 (regular preventative maintenance program), four statements are provided to see if the respondents agree with the statements, along with two questions asking specific data. The respondents are supposed to mark the point in one (strongly disagree) to five (strongly agree) points scale to each statement.

P122	**Service equipment regularly** **Regular preventative maintenance program**	*strongly disagree*				*strongly agree*	*does not apply*	
		1	*2*	*3*	*4*	*5*	*0*	*Comment*
-	We dedicate a portion of every day solely to preventive maintenance and follow the preventive maintenance schedule.	O	O	O	O	O	O	______
-	We are usually behind production schedule and have no time for preventive maintenance. Repair is our maintenance.	O	O	O	O	O	O	______
-	We emphasize proper maintenance as a strategy for achieving schedule compliance.	O	O	O	O	O	O	______
-	Our equipment and tools are in a high state of readiness at all times.	O	O	O	O	O	O	______
-	What percentage of time do you dedicate for preventive maintenance? (time for preventive maintenance / available production time)	______						
-	What percentage of time is lost due to unscheduled maintenance? (unscheduled maintenance / available production time)	______						

FIGURE 9-4. THE MSDD QUESTIONNAIRE DATA COLLECTION TOOL [LINCK 2001]

The MSDD questionnaire approach is different from the performance measures approach in respect of the characteristics of the data collected. The MSDD questionnaire asks qualitative questions to measure the achievement of the FR while the performance measures approach attempt to quantitatively measure the achievement of the FR. The MSDD questionnaire is also different from the MSDD evaluation tool in respect of the way the questions are deployed. The MSDD questionnaire states a certain aspect of the ideal situation and then asks the respondent how much the manufacturing system is close to the ideal situation. On the other hand, the MSDD evaluation tool tries to describe a series of stages of a manufacturing system to the ideal situation and then, asks the respondent in what stage the manufacturing system is. Both approaches, however, attempt to use qualitative descriptions of the activities and the situations on the shop floor that are close to the ideal situation, in order to measure the achievement of the FRs of the MSDD.

The MSDD questionnaire approach has some advantages over the other two approaches described in this section. First, the MSDD questionnaire can consider various aspects of the issues linked to the achievement of a FR simply by increasing the number of statements. In other words, the MSDD questionnaire can easily reflect new issues simply by adding statements that can describe the shop floor activities or situations that can be resulted from the achievement of the FR. As for the MSDD evaluation tool, complete restatements of the stages may be required. Second, the MSDD questionnaire approach considers the background idea beyond the abstract statements of the FRs and DPs of the MSDD through qualitative statements of the shop floor activities and situations. Therefore, it is easier for the engineers to answer the questionnaire than collect the data to calculate the performance measures. In addition, it is much easier for the respondents of the questionnaire to understand the background ideas of the MSDD than the respondents of the performance measures.

However, the MSDD questionnaire also has its weaknesses. One of the weaknesses is that some statements of the MSDD may less contribute to the achievement of the FR. For example, in the case shown in Figure 9-4, the first statement may contribute more to the achievement of the FR-P122 than the fourth statement. "Dedication of a portion of every day solely to preventive maintenance" is an activity to satisfy the FR-P122 while the "ready-to-use equipment and tools" are the result of the achievement of the FR-P122 (service equipment regularly). The "ready-to-use equipment and tools" may be the result of other factors such as the procurement of more reliable equipment and tools. However, no distinction is made between the statements in the MSDD questionnaire. The other possible problem is that some of statements may be interconnected to one another. If one statement is a restatement of the other statement, it can increase the scores for a certain FR.

9.4 The Second-Round Questionnaire

Considering the problems of the first round questionnaire described in section 9.1, the second round questionnaire is developed to evaluate the general approaches implemented in each company to the information exchange in the interface area of manufacturing and product design, relative to the MSDD. In this thesis, the manufacturability of a product/process design decision is understood as how well the design decision contributes to the achievement of the objectives of manufacturing systems that are represented by the MSDD. From this perspective, the second round questionnaire attempts to collect data to investigate how well the achievement of the FR-DP pairs in the MSDD are addressed by the existing practices of each company.

9.4.1 Development of Questionnaire

Based on the review of the existing approaches for the MSDD as presented in section 9.3, a questionnaire approach with a 5-point scale is selected as the format of the data collection tool. Therefore, the second round questionnaire is developed in a similar format as the MSDD questionnaire with much more questions in order to reflect variety of issues related to product design in addition to those related to manufacturing system design.

The second round questionnaire is composed of specific statements that are developed based on the descriptions of interactions between manufacturing and product design presented in Chapter 7. The statements in the second round questionnaire are made in a general way only to see if a certain issue is considered or not. The second round questionnaire does not attempt to identify how product development teams consider a certain issue in detail. As long as a certain issue is considered with any approach, it is considered as good. This is because there are many factors that affect a certain decision in the interface area of product design and manufacturing, and thus it is very difficult to describe generally applicable practices or situations that are linked only to the specific FR and DP. For example, for FR-R121 (identify correct support resources) and DP-R121 (specified support resources for each failure mode), such general statement as "specific support personnel are assigned to each failure mode related to purchased parts or materials at both your company and the part suppliers" is provided without further asking how specific support personnel are assigned. As long as specific support personnel are assigned to each failure mode so that the engineers know who to contact for a certain problem, it is fine from the perspective of the MSDD.

The statements in the second round questionnaire are categorized into six groups of product variety, product architecture, purchasing, material selection, process selection, and detailed design in addition to a general statement group. The general statement group indicates that the statements in this group may apply to all categories of design decisions. With this categorization, the general categorization proposed in Chapter 7 is followed. The statements are formulated for the necessary FR-DP pairs in various levels of the MSDD after an extensive review on all FR-DP pairs of the MSDD in terms of their relationship with design decisions.

The respondents' views to the statements in the second round questionnaire are measured by a five-point Likert scale. According to Leedy and Ormrod [2001], a rating scale is useful when a behavior, attitude, or other phenomenon of interest needs to be evaluated on a continuum of "strongly agree" to "strongly disagree." Rating scales were developed by Rensis Likert in the 1930s to assess people's attitudes and thus, they are sometimes called Likert scales. Linck [2001] reports that the respondents find Likert scales easy to use in his MSDD questionnaire research.

A complete list of the questions in the second round questionnaire is provided in Appendix F.

9.4.2 Reliability and Validity

Several tools are available to examine the reliability and validity of surveys, which can be applied to the second round questionnaire. Reliability indicates the consistency and repeatability of the result for each scale while validity is related to how well a tool measures what it is intended to measure. In this thesis, Linck [2001]'s approach to examine the reliability and validity of the MSDD questionnaire is adopted.

9.4.2.1 Reliability of the second round questionnaire

Leedy and Ormrod [2001] define reliability as "the consistency with which a measuring instrument yields a certain result when the entity being measured has not changed." Therefore, in the second round questionnaire case, reliability is the extent to which the second round questionnaire given to the same respondent yields the same results. In other words, reliability measures the repeatability of a study.

The most commonly accepted measure for reliability in empirical research is Cronbach's alpha [Cronbach and Meehl 1955]. The formula that determines Cronbach's alpha is is shown in Equation 9-1. Cronbach's alpha is determined by the number of items per scale (k) and the average correlation between pairs of items (r).

$$\alpha = \frac{kr}{1+(k-1)r} \tag{9-1}$$

Alpha ranges from zero to one and one is the highest possible reliability. The literature suggests a minimum acceptable Alpha value of 0.70 for internal consistency. Linck [2001] suggests using 0.60 for his MSDD questionnaire by citing Nunnally [1978] and Sakakibara et al. [1993]. Nunnally [1978] suggests allowing values as low as 0.60 for newly developed scales and the same value of 0.60 was also used by Sakakibara et al. [1993] for the JIT (Just-In-Time) measurement instrument.

9.4.2.2 Validity of the second round questionnaire

Leedy and Ormrod [2001] define the validity of a measurement instrument as "the extent to which the instrument measures what it is supposed to measure." In empirical study like the second round questionnaire, validity indicates how well the developed questions for a given scale measure the scale. For example, validity indicates how well the questions for FR-DP Q111 measure the meaning of the FR-DP pair. Leedy and Ormrod [2001] classify the following four types of validity (face validity, content validity, criterion validity, and construct validity) and provide their definitions.

- Face validity is the extent to which an instrument looks like it is measuring a particular characteristic. However, face validity relies entirely on subjective judgment and thus, is not very convincing evidence of validity.

- Content validity is the extent to which a measurement instrument is a representative sample of the content area being measured. In other words, content validity is related to how truly the questions in the second round questionnaire measure the concept they intended to measure. High content validity is achieved if the questions reflect the various parts of the content domain in appropriate proportions and if the questions contain the particular behaviors and skills that are central to that domain. In fact, one of the motivations to use a questionnaire format is to ensure high content validity. The content are is defined by the MSDD and content validity is ensured by asking several questions for each FR-DP pair. However, content validity is subjective and should be supported by a quantitative evaluation tool.
- Criterion validity is the extent to which the results of an assessment instrument (second round questionnaire) correlate with another, presumably related measure, which is called as the criterion. For instance, an instrument designed to measure a salesperson's effectiveness on the job should correlate with the number of sales the individual actually makes during the course of a business day [Leedy and Ormrod 2001].
- Construct validity is the extent to which an instrument measures a characteristic that cannot be directly observed but must instead be inferred from patterns in people's behavior.

Among these four types of validity, face validity and content validity are ensured with the second round questionnaire. However, criterion validity and construct validity are not assured in this thesis since they require a large number of data points. Assuring criterion validity and construct validity of the second round questionnaire remains as further research to be completed after collecting enough data points.

Validity has a close relationship with reliability. Reliability by itself is not sufficient to guarantee validity. For example, measuring something correctly requires measuring it consistently. However, measuring something consistently does not guarantee measuring something correctly [Leedy 2001].

9.4.3 Limitations

A few problems have been identified with the answers from the respondents to the second round questionnaire. Most of the respondents were engineers in automotive companies.

The first problem comes from the limited knowledge of the respondents. Product development involves various groups specialized in their own functions and the respondents often work for a specific function. For example, one respondent to the second round questionnaire was a design engineer specialized in suspension system design. However, the second round questionnaire contains the questions of various functions and even some questions related to the interface are between different functions, in order to obtain a system level view over the product development process. Therefore, many people showed their frustration in filling out the questionnaire since simply they did not know the answer. Sometimes, only a portion of the questionnaire could be answered by an individual person. In some sense, this problem itself shows a lack of knowledge of the relevant product development engineers in the big picture of the product development process since most of the questions asked in the second round questionnaire are quite general.

Another problem is a timing issue. Many of the activities described in the questions of the second round questionnaire are more or less conducted by many companies. The critical issue is when the activities are conducted since early consideration of manufacturing system issues are important to minimize the waste associated with design iterations. For example, many companies study the impact of new design on operators work content. However, this study is meaningful when it is done before a specific design is set. In other words, a new product design should reflect the consideration on the changes of operators work content by the new product design. The new product may be designed in a way to minimize the changes in operators work content.

In addition, lack of standardization on the definitions of the terms used causes the respondents to interpret the questions in a wrong way. For example, component design engineers often claim that they do not know answers for the questions related to product architecture. However, this is not true since the component design itself may involve an architecture design, considering its definition made in Chapter 4.

Weight factors can also be a problem with the second round questionnaire. The second round questionnaire does not give any weight factor to the questions. All questions are considered to equally affect the achievement of the corresponding FRs, which may not be true. However, this factor is somewhat compensated by asking many questions for each FR-DP pair. Therefore, this problem is significant only for the FR-DP pairs that have a relatively small number of questions.

9.5 Application of the Manufacturability Evaluation Tool

The second round questionnaire aims to collect the data necessary to evaluate the practices of companies to design manufacturable products. The second round questionnaire was sent to the same companies that answered the first round questionnaire. Two companies answered the second round questionnaire and the results are provided in the following sections. The second round questionnaire was translated into Japanese by Prof. Kawada at Meijo University in Japan for company A. The background information of the participating companies is provided in Chapter 5.

9.5.1 Company A

The response from company A was prepared by its production engineering planning division. A summary of the response is provided in Table 9-1 and graphically presented in Figure 9-5. The score for each FR-DP pair is decided by averaging the scores for the answered questions. The questions that are not answered by the respondent are excluded when average scores are calculated.

As is shown in Figure 9-5, company A highly scores for most of the FR-DP pairs of the MSDD that are related to product design decisions. This result is assured by the comments from a manager at company A who responded to the second round questionnaire. He commented that most of the items taken up as questions in the second round questionnaire are, in fact, implemented by production engineers in company A. In other words, most of the activities addressed in the questions are put into practice by the company A engineers even though the engineers are not aware of the MSDD and the manufacturability evaluation process.

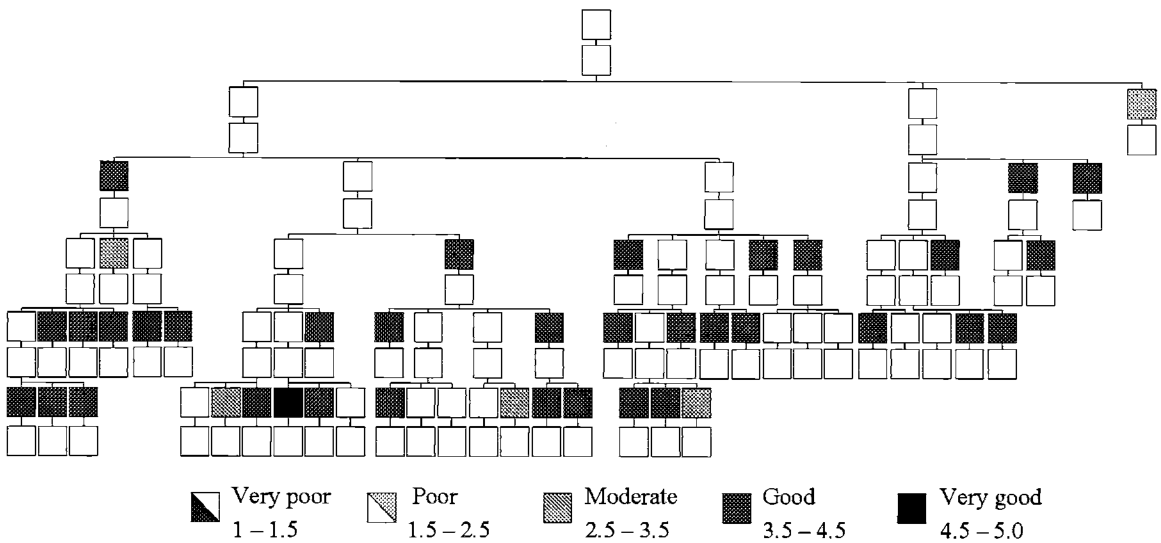


FIGURE 9-5. THE SECOND ROUND QUESTIONNAIRE RESULT OF COMPANY A

However, several blocks of relatively low scores are observed in Figure 9-5. They are FR-DP Q2 pair, FR-DP R112 pair, FR-DP P132 pair, FR-DP T223, and FR-DP 13. The FR-DP Q2 pair is about centering process mean on the target (FR-Q2: center process mean on the target, DP-Q2: process parameter adjustment). Company A scores relatively low for the questions related to process selection. The low scores indicate that company A stays in the ordinary level of excellency in understanding the manufacturing processes. Therefore, the low scores shows that company A needs to allocate more resources to better understand the impact of process parameters on process mean during product design phase. In addition, company A should collaborate with equipment vendors closely to better understand the characteristics of equipment on parameter control.

The FR-DP R112 pair is about identifying disruptions where they occur (FR-R112: identify disruptions where they occur, DP-R112: simplified material flow paths). To increase the score for the FR-DP R112 pair, product design engineers at company A need to be better aware of the material flow paths to be used for new products and the consequences of the detailed designs on the material flow paths. In addition, further consideration should be given to product architecture designs so that the impact of product architecture decisions on the material flow paths is clearly understood.

TABLE 9-1. THE SECOND ROUND QUESTIONNAIRE RESULTS OF COMPANY A

			G				PV				PA		P		MS		PS		DD				
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2	sum	#	ave
FR1	FR11	FR111	5	4	4	4	4						4		5		3		3	2	38	10	3.80
		FR-Q1																					
		FR-Q11																					
		FR-Q111					3				3		4	4	5		4	4	4		31	8	3.88
		FR-Q112	4	4			4						4		4		5		4		29	7	4.14
		FR-Q113	4	2			4				4		4		4		5		4		31	8	3.88
		FR-Q12	4				4						3		4	4	4		4		27	7	3.86
		FR-Q13	4				4				4		4		4		3	5	4		32	8	4.00
		FR-Q14					4	4			4		3		5	4	4		5		33	8	4.13
		FR-Q2													4		3	3			10	3	3.33
		FR-Q3																					
		FR-Q31	3	5									4		4		5				21	5	4.20
		FR-Q32									3		4		4		4		4		19	5	3.80
		FR112																					
		FR-R1																					
		FR-R11																					
		FR-R111																					
		FR-R112	3	3	4		4	4			2		4				4		3		31	9	3.44
		FR-R113	5				4								4		4		4		21	5	4.20
		FR-R12																					
		FR-R121	5				4				4		4		4		4		4		29	7	4.14
		FR-R122	5	5									5								15	3	5.00
		FR-R123																					
		FR-R13	4	4			4						4	5	5		4		5		35	8	4.38
		FR-P1																					
		FR-P11	5				4						4								13	3	4.33
		FR-P12																					
		FR-P121	4				3						4		4		4		4	3	26	7	3.71
		FR-P122																					
		FR-P123																					
		FR-P13																					
		FR-P131																					
		FR-P132	3	3																	6	2	3.00
		FR-P14	4	4																	8	2	4.00
		FR-P141	3				3	3					4		4	4	4		4		29	8	3.63
		FR-P142									4		5		5		4				18	4	4.50
		FR113																					
		FR-T1	4														4	5			13	3	4.33
		FR-T2																					
		FR-T21	4	4	4		4	4													20	5	4.00
		FR-T22																					
		FR-T221	3				4				3				3		4	4	4		25	7	3.57
		FR-T222	4				4				4				4		4		4		24	6	4.00
		FR-T223					4												3		7	2	3.50
		FR-T23					4				4		4								12	3	4.00
		FR-T3																					
		FR-T31					4						4								8	2	4.00
		FR-T32	4				4	3	4	4	4				4		4		4		35	9	3.89
		FR-T4	4								4		4								12	3	4.00
		FR-T5																	4		4	1	4.00
		FR-T51																					
		FR-T52																					
		FR-T53																					
	FR12	FR121																					
		FR-D1																					
		FR-D11															4		4		8	2	4.00
		FR-D12																					
		FR-D2																					
		FR-D21																					
		FR-D22					4								4		4		4		16	4	4.00
		FR-D23	4				4								4						12	3	4.00
		FR-D3	4												4		4		4		16	4	4.00
		FR122					4						4		4		4		4		20	5	4.00
		FR-I1																					
		FR-I2					4						4		4		4		4		20	5	4.00
		FR123					4						4		4		4		4		20	5	4.00
	FR13		4	3	3																10	3	3.33

The FR-DP P132 pair is about equipment maintenance (FR-P132: service equipment regularly, DP-P132: regular preventative maintenance program). More efforts are requested to keep the existing preventative maintenance program undated to fit to the new products.

The FR-DP T223 pair is to ensure level production. When different types of products are to be produced at the same station machine, product designers should more seriously seek detail designs to make their cycle times similar.

The FR-DP 13 pair is about investment (FR13: minimize investment over production system life cycle, DP13: investment based on a long term strategy). It is noteworthy that company A does not highly score for this FR-DP pair even though company A is considered as a benchmark company in the automotive industry in terms of its operational efficiency and profit generation. The low score for the FR-DP 13 pair seems to be the result of company A's view to financial result. Company A sees financial measures as consequences of its operation. In other words, efficient operation eventually leads to good financial measures. Therefore, relatively less emphasis is given to financial measures than operational measures (e.g., quality) at company A. Further explanation of company A's view to financial results is given in Chapter 5.

Table 9-2 shows a list of questions for which company A scores relatively low points (equal or less than 2 points).

TABLE 9-2. LIST OF QUESTIONS FOR WHICH COMPANY A SCORES LOW POINTS

FR-DP	Question	Scores
Q113	Manufacturing group frequently suggests product design changes for mistake-proof (poka-toke) purposes	2
FR111	Tolerances are given generously	2
R112	Product architecture decisions are made after considering their impact on material flow paths	2

In Table 9-2, the low score for the question for the FR-DP Q113 seems to indicate that little feedback is made from manufacturing to product design. However, this question is asked after another question, which asks "manufacturing, production engineering, and product design engineers work together to incorporate mistake-proof (poka-yoke) features (e.g., spider marks, colors, significantly different features, notch, special dent, etc.) into product design." Company A scores four for the latter question and thus, it might be interpreted in a different way. Poka-yoke features are already included in product design phase and thus, manufacturing groups may not need to frequently suggest product design changes for mistake-proof purposes.

As for setting product tolerances, company A is revealed somewhat strict. Considering the engineering atmosphere of company A discussed in Chapter 5, company A deals with strict tolerances with its superior manufacturing capability. However, further study needs to be made to achieve the required product functionality with more generous tolerances in order to minimize manufacturing efforts to meet the required tolerance.

It is remarkable that company A scores relatively low points for the question that address a popular tool of product development. The question for the FR-DP R112 shown in Table 9-2 is closely related to a popular strategy that attempts to minimize the impact of product variety by postponing the differentiation point proposed by Lee [1993]. Company A is revealed to little consider this factor. A production engineering manager said that company A faithfully follows the principle of level production instead of following this strategy. However, company A may further leverage this postponement strategy.

The reliability cannot be checked since only one response is collected from company A. However, the response is a result of discussion among several engineers and thus, is assumed to reflect the general practices of company A.

9.5.2 Company F

The response from company F is prepared by a design engineer in the bus division. A summary of the response is provided in Table 9-3 and graphically presented in Figure 9-6. The score for each FR-DP pair is decided by averaging the scores for the answered questions. The questions that are not answered by the respondent are excluded when average scores are calculated. The FR-DP pairs for which no answers are made are represented as meshed blocks in Figure 9-6.

As is shown in Figure 9-6, company F scores high points for many FR-DP pairs of the MSDD that are related to product design decisions. However, the number of the FR-DP pairs with high scores is smaller than company A. For example, company A has three FR-DP pairs that are moderately satisfied but there are nine FR-DP pairs that are moderately satisfied by the practices of company F. Those nine FR-DP pairs are: FR-DP 111, FR-DP Q2, FR-DP Q32, FR-DP R13, FR-DP T221, FR-DP D11, FR-DP D23, FR-DP D3, and FR-DP 122.

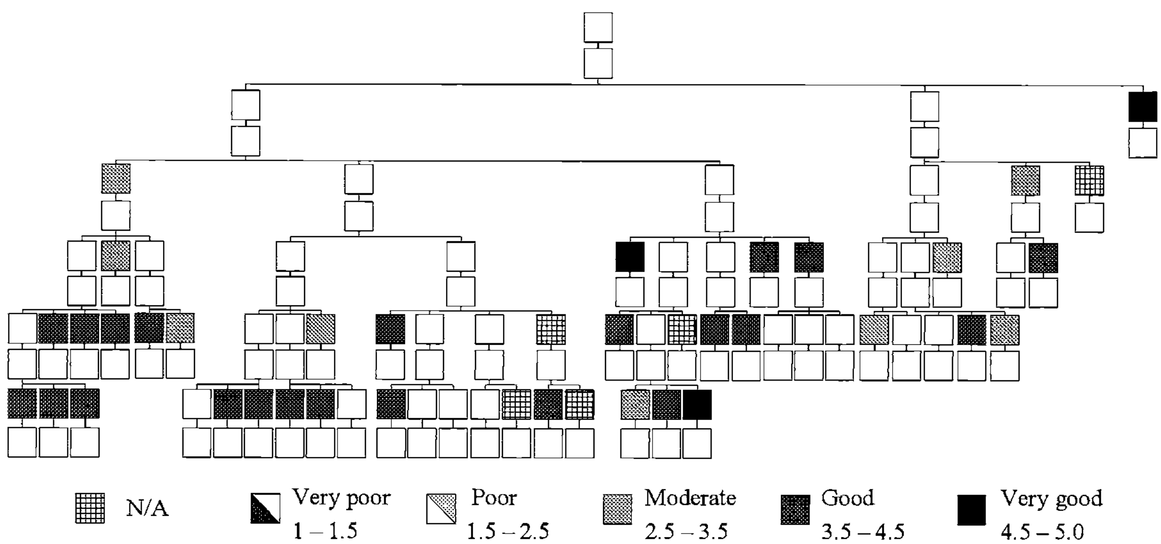


FIGURE 9-6. THE SECOND ROUND QUESTIONNAIRE RESULT OF COMPANY F.

The FR-DP 111 pair is closely linked to the tolerances of a product design (FR111: manufacture products to target design specifications, DP111: production processes with minimal variation from the target). Company F shows its weakness in setting consistent tolerances across different product types within a product family through a close collaboration between manufacturing, production engineering, and product design groups. In addition, company F needs to further improve the relationship with its part suppliers so that part suppliers participate in the tolerance decision process more actively.

The FR-DP Q2 pair is about centering process mean on the target (FR-Q2: center process mean on the target, DP-Q2: process parameter adjustment). Company F scores relatively low for a question related to equipment design. Company F should collaborate with equipment vendors closely to better understand the characteristics of equipment on process parameter control.

The FR-DP Q32 is about reducing impact of input noise on process output by robust design of process (FR Q32: Reduce impact of input noise on process output, DP Q32: robust design). Company F is revealed to have room for improvement in making different processes robust to input noise across various types of products within a product family. In addition, more consideration should be given for a robust assembly of purchased parts.

The FR-DP R13 pair is linked to immediate solving of identified problems (FR P3: solve problems immediately, DP R13: standard method to identify and eliminate root causes). Company F shows its weakness in setting standard procedures to solve disruption problems in advance during product development.

The FR-DP D23 is about minimizing wasted motion in operators' work tasks (FR-D23: minimize wasted motion in operators' work tasks, DP-D23: ergonomic interface between the worker, machine, and fixture). The respondent scored relatively low (3 points) for all questions for this FR-DP pair. Therefore, more efforts should be made to consider the impact of new product design on ergonomic design of operators' work tasks and eliminate any conflict between new product design and operators' work task design.

The rest of the FR-DP pairs with low scores (FR-DP T221, D11, D3, and 122) are the results of the fact that the respondent was not able to answer most of the questions and scored low for a small number of answered questions. Therefore, it is not very meaningful to analyze the results for those FR-DP pairs.

TABLE 9-3. THE SECOND ROUND QUESTIONNAIRE RESULTS OF COMPANY F.

			G				PV				PA		P		MS		PS		DD				
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2	Q1	Q2	sum	#	ave
FR1	FR11	FR111	5	4	4	2	2						3		3		3		4	2	32	10	3.20
		FR-Q1																					
		FR-Q11																					
		FR-Q111					4				4		4	3	3		3	5	4		30	8	3.75
		FR-Q112	2	4			4				4		4		3		4		5		30	8	3.75
		FR-Q113	4	5			4				4		4		0		4		3		28	7	4.00
		FR-Q12	5				4						4		3	3	3		4		26	7	3.71
		FR-Q13	4				4				4		5		4		3	5	4		33	8	4.13
		FR-Q14					4	0			4		0		4	4	3		5		24	6	4.00
		FR-Q2													0		4	3			7	2	3.50
		FR-Q3																					
		FR-Q31	3	5									4		4		4				20	5	4.00
		FR-Q32									3		3		0		4		4		14	4	3.50
		FR112																					
		FR-R1																					
		FR-R11																					
		FR-R111																					
		FR-R112	4	4	4		3	4			3		0				0		4		26	7	3.71
		FR-R113	4				5								4		4		4		21	5	4.20
		FR-R12																					
		FR-R121	5				4				5		4				4		4		26	6	4.33
		FR-R122	3	4									4								11	3	3.67
		FR-R123																					
		FR-R13	4	4			5				3		0	2	2		2		2		24	8	3.00
		FR-P1																					
		FR-P11	3				5						3								11	3	3.67
		FR-P12																					
		FR-P121	4				3				4		5		3		4		4	5	32	8	4.00
		FR-P122																					
		FR-P123																					
		FR-P13																					
		FR-P131																					
		FR-P132	0	0																	0	2	0.00
		FR-P14	0	0																	0	2	0.00
		FR-P141	5				3	5					0		4	4	4		5		30	7	4.29
		FR-P142					0				0		0		0		0				0	4	0.00
		FR113																					
		FR-T1	0														0	5			5	1	5.00
		FR-T2																					
		FR-T21	3	4	0		0	4			0										11	3	3.67
		FR-T22																					
		FR-T221	3				3				0				0		0	0	0		6	2	3.00
		FR-T222	2				0				4				0		0		5		11	3	3.67
		FR-T223					5												5		10	2	5.00
		FR-T23					0				0		0								0	3	0.00
		FR-T3																					
		FR-T31					4						0								4	1	4.00
		FR-T32	4				5	4	4	4	4				4		3		5		37	9	4.11
		FR-T4	3								3		5								11	3	3.67
		FR-T5															4		5		9	2	4.50
		FR-T51																					
		FR-T52																					
		FR-T53																					
	FR12	FR121																					
		FR-D1																					
		FR-D11															0		3		3	1	3.00
		FR-D12																					
		FR-D2																					
		FR-D21																					
		FR-D22					3								4		0		4		11	3	3.67
		FR-D23	3				3								3				3		12	4	3.00
		FR-D3	3												3		0		0		6	2	3.00
		FR122					0				0		0		3		3		3		9	3	3.00
		FR-I1																					
		FR-I2					3						4		0		0		4		11	3	3.67
		FR123					0				0		0		0		0		0		0	5	0.00
	FR13		5	0	0																5	1	5.00

It is noteworthy that the respondent marked more 'do not know' boxes for the questions for the right side branches of the MSDD. The respondent commented that the production engineering division might know the answers for those questions he was not able to answer. This result may be interpreted that product design engineers at company F are not very familiar with other manufacturing issues than quality. However, the number of data points is too small to accept this conclusion as valid one. Further case study with company F should be made to collect more data points that support this conclusion.

9.5.3 Conclusion

In this section, it is presented how the evaluation tool can be applied to real companies and how the collected data can be interpreted. The data collection protocol used in this section is the second round questionnaire that is composed of a list of questions for each FR-DP pair.

Two industry case examples are presented. The data collected from the respondents at each company are analyzed to evaluate the current practices of the participating companies. The areas that need further improvement are recommended according to the analysis of the data.

In the first and second round questionnaire case studies, it is observed that company A which is known as a benchmark for its minimum manufacturing problems caused by product design is not very different from other companies in terms of the application of popular solutions such as modular product design and cross functional product development teams. In order to achieve manufacturable product designs, more concerns should be given to the satisfaction of the FRs of manufacturing systems represented by the MSDD, instead of relying on radical popular solutions such as modular product design, manufacturability simulation software, and cross functional product development teams. In other words, simple solutions that support the satisfaction of the FRs in the MSDD should be extensively applied rather than solving all problems with the introduction of big solutions such as modular product design. As long as the conflicts between manufacturing system design and product design decisions are eliminated, the product design is manufacturable and thus, there is no need to desperately pursue a certain product design strategy for manufacturability purposes.

However, the validity of the second round questionnaire cannot be checked since the number of collected data points is too small. About thirty data points are necessary to check the validity of the second round questionnaire. Each data point should be the result of one company (or one division of a company). In addition, the small number of collected data points prevents to check the reliability of the second round questionnaire. More rigorous case study is requested to check the validity and reliability of the second round questionnaire approach to collect the data points necessary for the evaluation of the company practices assuring manufacturable product designs.

In order to improve the validity of the conclusions derived from the data collected by the second round questionnaire, different data collection protocol may be used. For example, the responses for the second round questionnaire can be supported by supplementary interviews with design engineers and personal observation (or experience) on the company practices.

9.6 Chapter Summary

In this chapter, the evaluation tool derived from the proposed manufacturability evaluation process is presented. The evaluation tool aims to evaluate the practices of a company for desining manufacturable products. The data collection protocol used for the evaluation tool is the second round questionnaire that is composed of a list of questions for each FR-DP pair linked to product design decisions.

Several issues associated with the development of an evaluation tool are discussed and comparable existing evaluation tools based on the MSDD are reviewed. As a consequence of these studies, Linck [2001]'s questionnaire approach is adopted for its advantages over other evaluation approaches. The advantages of the questionnaire approach include: 1) good to consider various aspects of the issues linked to the achievement of a FR and 2) good to consider the background idea beyond the abstract statements of the FRs and DPs of the MSDD through qualitative statements. The first advantage also improves the content validity of the data collection protocol.

Two industry case studies are presented in order to show how the practices of a company ensuring the design of manufacturable products can be evaluated relative to the MSDD. Several recommendations are made based on the collected data through the second round questionnaire.

Due to the small number of data points collected from industry, the validity and reliability of the second round questionnaire was not able to be checked with the presented case study examples. However, sevearl ways to check the validity and reliavility of the data collection protocol, the second round questionnaire, are discussed and one way to check the reliability is provided in section 9.4.2.1. Further study is requested to check the reliability of the second round questionnaire and evantually the validity of the evaluation tool.

10 CONCLUSION AND FURTHER RESEARCH PROBLEMS

10.1 Summary of the Research

In this thesis, an approach to capture the impact of product design decisions on manufacturing systems is presented. The objective of the proposed approach is to provide industry with a structured methodology to evaluate the manufacturability of product designs. The manufacturability evaluation process proposed in Chapter 7 of this thesis shows how the product design decisions affect manufacturing system design by investigating the impact of the product design decisions on the functional requirements (FRs) and design parameters (DPs) of the Manufacturing System Design Decomposition (MSDD), which represents the "lean" manufacturing system.

The research of this thesis is comprised of two parts. The first part is the development of the manufacturability evaluation process and the second part is the validation of the manufacturability evaluation process.

The development of the proposed process to evaluate the manufacturability of product designs is closely related to the resolution of the first three subproblems of the four subproblems presented in Chapter 1 and 3. They are:

1) How can we represent manufacturing system design?
2) How can we represent product development? What decisions in product development affect manufacturing system design?
3) How can we see the interactions between product design and manufacturing system design?

In this thesis, the first subproblem is solved by developing the MSDD that represents the objectives and their corresponding solutions of manufacturing systems. The second subproblem is solved by investigating the design decisions that affect manufacturing system design and categorizing the product design decisions into six general groups of product variety, product architecture, purchasing, material selection, process selection, and detailed design. The third subproblem is solved by identifying the FRs and DPs of the MSDD that are affected by a specific product design decision. Based on these solutions, the manufacturability evaluation process shown in Figure 7-18 is proposed.

To investigate the solutions to the first three subproblems, vast literature is consulted (Chapter 4) and industry practices implemented in auto industry are investigated (Chapter 5). The first round questionnaire is used to collect the information regarding the industry practices of six companies to facilitate the design of producible products.

The second part of the thesis is the validation of the proposed manufacturability evaluation process and is closely related to the fourth research subproblem.

4) What are the examples of interactions? How can the existing approach be viewed with the new methodology?

A couple of case study examples are presented to show the application of the proposed manufacturability evaluation process. In addition, the DFMA approach proposed by [Boothroyd et al. 1994] and [Phal and Beitz 1996] are viewed using the framework of the manufacturability evaluation process. In addition, a manufacturability evaluation tool is proposed in Chapter 9 to see the differences of the practices pursued by different companies in terms of their scope relative to the FRs of the MSDD. The second round questionnaire of the proposed evaluation tool attempts to collect data to investigate how well the achievement of the FR-DP pairs in the MSDD are addressed by the existing practices of each company on the information exchange between manufacturing and product design. Several case studies are presented to show how the proposed evaluation tool can be applied in real industry cases. Several recommendations on the current practices are made for each company based on the analysis of the collected data through the second round questionnaire. However, due to the limited number of collected data points, the reliability and validity of the data collection protocol are not checked and left for future research. In this thesis, using the proposed evaluation tool, the difference in the scopes of the practices of company A that is considered as a benchmark of designing manufacturable products and company F that is rapidly growing in the U.S. market is presented. By showing company A covers more FRs of the MSDD than company F during the product development, the proposed manufacturability evaluation process is supported.

The resolution of the four subproblems results in resolving the two main questions of the research: (1) how product development decisions interact with manufacturing system design and (2) how we can systematically identify the interactions. The proposed manufacturability evaluation process answers these two questions.

The manufacturability evaluation process, however, only shows the steps and methods of evaluating the manufacturability of a design decision. Its content is subject to changes as the requirements for manufacturing systems change and the knowledge on the interactions between manufacturing and product design is accumulated. Therefore, the efforts to reveal the interrelationship between product design and manufacturing should be maintained in order to enrich the content of the proposed approach.

The real strength of the proposed approach is to expand the scope of the traditional DFMA methods from the manufacturing process level into the manufacturing system level. This expansion is done by identifying the requirements of manufacturing systems and investigating how product design decisions affect the achievement of these requirements. The manufacturability of a product/process design decision should be understood as how well the design decision contributes to the achievement of the objectives of manufacturing systems that are represented by the MSDD.

10.2 Recommendation for Further Research

10.2.1 Long-Terms Studies

In this thesis, two examples on the application of the proposed manufacturability evaluation process are presented. In these examples, however, the focus is given to how well the proposed approach can explain the possible manufacturability issues of the cases. Only the possible benefits from the application of the proposed approach are discussed instead of providing real benefits that were gained through the application of the proposed approach. Therefore, it is desirable to apply the manufacturability evaluation process in companies that are in the process of developing a new product. This kind of case study will reveal the difficulties and limitations of applying the proposed approach while providing data to reveal the actual benefits of the proposed approach. It may be difficult, however, to conduct the case study since the product development lead time is often in the range of several years in the automotive industry. A development project of a simple product with short product development time can be chosen to overcome the time constraints. The development of a cellular phone may be a good candidate considering its short product development time.

In addition, it is desirable to apply the evaluation tool derived from the manufacturability evaluation process to many companies. First, the application of the evaluation tool in a large number of companies can help the validation of the second round questionnaire in terms of its reliability and validity to collect the data. Furthermore, by analyzing the data obtained from the second round questionnaire of the evaluation tool and the actual performance of product development of each company, it is possible to identify the effectiveness of the proposed manufacturability evaluation approach. If enough data points are collected, the validation of the proposed methodology is possible through statistical analysis of the data.

The final goal of the studies on the interface area between manufacturing and product development may be a clear representation of the relationships between product development and manufacturing system design. Based on a clear understanding of the relationships, it is possible to carefully sequence the activities of product development and manufacturing system design so that no late iteration of product design or manufacturing system design is required. One way to achieve this goal is to develop a decomposition that incorporates the FRs and DPs of both manufacturing system design and product development. The next section explains the benefits and the difficulties associated with the development of a decomposition of both product development and manufacturing system design.

10.2.2 Extension of the MSDD

In this section, further extension of the MSDD into product development is discussed. Expected benefits of the extension are presented along with the limitations and difficulties associated with the extension. Existing decompositions attempting to model product development and integrate product development and manufacturing system design are reviewed. A summary of the characteristics of the existing decompositions is provided. Several recommendations are provided for the decomposition that covers both manufacturing system design and product development.

10.2.2.1 Existing decompositions of product development

The decomposition approaches using the Axiomatic Design methodology to model product development have several benefits over the traditional process-oriented approaches that are discussed in section 7.2.2.1. First, the Axiomatic Design methodology clearly separates the objectives from the means to achieve them. The separation of goals from means makes it possible to see the interrelationship between the objectives of product development and the solutions to achieve the objectives. Therefore, the decomposition approach makes it easier to satisfy the objectives, compared to other approaches that investigate the interactions only between the solutions. Second, the decomposition approach can show how a low level DP contribute to the achievement of a high level FR. By relating low level decisions to high level system objectives, low level decisions that better contribute to the achievement of high level system objectives can be made. Furthermore, the decomposition approach enables clear identification of the interactions between FRs and DPs in different branches, which leads to better understanding of the interrelationships among the different elements of product development. Better understanding of the interrelationships helps avoiding local optimizations. Finally, the developed decomposition works as a communication tool that delivers the ideas throughout the entire organization.

In order to leverage these benefits of the decomposition approach, there have been several attempts to develop a decomposition of product development and integrate the product development decomposition with the existing manufacturing system design decomposition (MSDD). The three design decompositions of product development presented in Chapter 7 are good examples of the existing attempts. A summary of the characteristics of the three decompositions is shown in Table 10-1. For detailed discussion of the three decompositions, please refer to section 7.2.2.2.

TABLE 10-1. A SUMMARY OF THE CHARACTERISTICS OF THE THREE DECOMPOSITIONS OF PRODUCT DEVELOPMENT.

	PD3	PDSDD	AMSDD
Scope	• Product development • Designing a product that satisfies both internal and external customers • Focuses on aerospace industry cases	• Product development • Organization issues • Information flow management	• Producible product design and manufacturing system design • Focuses on aerospace industry cases
Strengths	• Covers various aspects of product development in detail • Covers the development of individual product (e.g., material selection)	• Attempts to model the organizational issues of product development • Provides the FRs and DPs related to the efficient coordination of design activities	• Tries to integrate product design and manufacturing system design • Tries to decompose the elements that affect manufacturing system design only to avoid complex decomposition of entire product development
Weaknesses	• Limited scope – little consideration of manufacturing system design issues • Decoupling between product design and manufacturing is unsatisfactory	• Limited scope – little consideration of manufacturing system design issues • Focuses on information flow management only – does not provide the appropriate content of the information flows	• Manufacturing system design issues are buried in the design matrix • Limited scope in product development – only designing a producible product is considered.

However, all of the three decompositions show a common weakness. All three decompositions are unsuccessful in providing a clear explanation of the relationships among the FRs and DPs in terms of their functional dependencies. As discussed in Chapter 6, the Axiomatic Design methodology clearly dictates to maintain the functional independency between FRs and DPs as its first independence axiom. Therefore, according to the independence axiom, the design matrices that define the relationships between the FRs and DPs of the three decompositions should be diagonal or at least triangular to maintain the functional independency. The proposed matrices of the three decompositions are all triangular at least. However, there can be an argument in the proposed design matrices of the three decompositions. For example, it is not very clear how to deal with the issues of considering manufacturing in early product development phase. As is presented in Chapter 7 and 8 of this thesis, various design decisions in six categories affect manufacturing system design and sometimes, negatively affect the achievement of the goals of manufacturing systems. The negative effects should be thoroughly studied and eliminated by modifying the product design in advance or modifying manufacturing system design, which indicates the coupling between manufacturing and product design. However, in a product development decomposition, by the nature of the independence axiom, the DPs should be developed to independently satisfy the FRs of product design and manufacturing. The PD^3 and the AMSDD attempt to go around this problem by providing a branch of "producible product design." In these two decompositions, all design issues related to the manufacturability of the product design are supposed to be dealt by the "producible product design" branch so that the product design to satisfy the customer requirements can be done separately. In other words, a product is designed first to satisfy the customer requirements of its functions and then the manufacturability of the design is assured by the "producible product design" branch. One of the problems with this approach is that some DPs in the "producible product design" branch often affect the FRs in the branches to design a product to satisfy the customer requirements. Detailed discussion on the problems associated with the suggested "producible product design" branches of the two decompositions are presented in section 7.2.2.2. The PDSDD goes around the same problem by focusing on organizing the information flows to deliver downstream (manufacturing) constraints to upstream product development processes. Still, as is discussed in section 7.2.2.2, the PDSDD does not address the content of the information.

In order to develop a decomposition that integrates both manufacturing system design and product development, the dependencies between product design and manufacturing system design should be clearly identified.

10.2.2.2 Integrated product development and manufacturing system design decomposition (IPMD)

As discussed in the previous section, a decomposition approach adopting the Axiomatic Design methodology can provide several benefits over process-oriented approaches. Therefore, if a decomposition adopting the Axiomatic Design methodology that integrates product development and manufacturing system design is developed, the same benefits can be obtained, which can lead to better understanding of the relationship between product development and manufacturing system design. In addition to the benefits addressed in the previous section, the decomposition incorporating both manufacturing system design and product development can provide the following benefits:

1) It is possible to overview how a product is developed and manufactured from a system level view point.

2) It is possible to know the right sequence of product development and manufacturing system design, which eliminates what Suh [2001] calls "time-independent imaginary complexity" caused by not knowing the design matrix. The controllability of the entire process is assured since the applied independent axiom ensures that each FR can be satisfied independently.

3) Organization of product development teams can be designed around the decomposition since the decomposition dictates the FRs and DPs of product development and manufacturing system design along with the relationship between the FRs and DPs.

4) The content of the information flows between functional organizations can be identified through the decomposition.

Even though these huge benefits are expected with the integrated product development and manufacturing system design decomposition (IPMD), it is not easy to integrate product development and manufacturing system design into one decomposition due to several reasons.

First, the design process is usually helical, not serial, which makes it difficult to keep the independence axiom in the IPMD. For example, when a product is designed, a rough functional design is first made in a high level of abstraction. Then, a material is selected for the rough design along with production processes. After the material is selected and the production processes are chosen, further detailed design is made. The detailed design is also subject to the same decisions of material selection and process selection in order to physically realize the design. In this helical way, a product design is completed. Therefore, it is difficult to separate these three groups of product development activities. Considering manufacturing process selection is closely linked to manufacturing system design, clear separation of product design activities from manufacturing system design activities is hard to be achieved. In other words, it is difficult to make product design independent from manufacturing system design.

In the Axiomatic Design methodology, this helical product design process is explained as zigzagging among three design domains of functional (FRs), physical (DPs), and process (PVs). Therefore, it is difficult to explain the helical product design using only two domains – functional domain and physical domain without the process domain. In fact, the Axiomatic Design methodology does not provide a clear explanation on the zigzagging design process among all three design domains while focusing on the zigzagging process between the functional domain and the physical domain.

Second, as previously discussed in section 7.2.2.2, manufacturability issues arise when physical realization of the product design matters. Therefore, in order to investigate the manufacturability of a product design, a detailed decomposition of a product itself is necessary to be developed. However, the decomposition of a product is usually case-specific while the IPMD should be generally applicable. Consequently, any case-specific product design decomposition should be avoided in the IPMD. In other words, the IPMD needs to describe the general FRs and DPs of product development and manufacturing system design, while the manufacturability issues may not be identified without the case-specific detailed design decomposition of a product, which is contradictory.

The third cause is the creativity involved with product design. One of the reasons that the MSDD can effectively reflect manufacturing system design is that manufacturing systems produce products according to drawings released from product development teams. The released drawings, by its nature, serve as a reference point to enable the distinction between good parts from bad parts. More importantly, the released drawings provide information on the shape of a product to be made. Therefore, this standard (drawing) is essential for frequent reviews on a product to check if the product is being produced according to the plan at different phases of manufacturing. The frequent reviews make it possible to identify defective parts after a small portion of the total necessary operations are done to parts, which allows quickly resolving corresponding problems or reworking defective parts. In product development, however, nothing plays a role of a drawing in manufacturing. Rather, product designers are supposed to use their creativity to develop new drawings for a new product to meet the specifications on the functional requirements for the product according to aggressive time schedules. In other words, product development has to deal with new products all the time. The effect of a new product design on manufacturing systems is often different from that of the existing products and is also unclear in the design stage. Therefore, the IPMD should be able to deal with the manufacturability issues of new products by defining general FRs and DPs, which is not easy considering there is no generally accepted theory explaining the interface area between manufacturing and product development. The manufacturing evaluation process proposed in this thesis provides a framework to capture the interactions between manufacturing system design and product development but does not propose principles that explain all aspects of the interactions.

In spite of all the problems addressed in this section, a decomposition approach can provide many advantages that are discussed early in this section. Therefore, a study on the development of the IPMD is necessary in a long run. Some comments for the development of the IPMD are:

- To make the IPMD generally applicable, the general product development activities should be decomposed rather than a specific product itself. For example, instead of decomposing a FR for a specific product such as "to contain liquid" for a bottle, a FR for general product development activities such as "to identify customer requirements" should be decomposed.

- Product development related branches should come in the left to the branches linked to manufacturing system design. In general, product design is done prior to manufacturing system design. In rare cases, however, manufacturing leads product design. For example, a furniture company, IKEA, reuses the left-over materials to produce cheap products. Product design is made to efficiently reuse the left-over materials and manufacturing systems are thoroughly studied to carefully coordinate manufacturing activities in order to maximize the utilization of the manufacturing systems.
- It may need to develop the product design branch of the IPMD in a way that product design provides perfect product designs that reflect every aspects of manufacturing systems so that there is no manufacturing problem with the introduction of new product designs. In this way, the independence axiom of the Axiomatic Design methodology can be kept between the FRs and DPs of product design and manufacturing system design.
- It may be a good idea to develop the decomposition to eliminate the sources of manufacturability problems.

10.2.3 Further development of the Axiomatic Design methodology

Another way to investigate the interface area between manufacturing system design and product development is to further develop the Axiomatic Design methodology so that it can clearly present the design process. In the previous sections, the limitations of the current Axiomatic Design methodology are presented. The most significant one regarding the manufacturability of a product design lies in the unclear relationship between process domain (PV), and functional (FR) and physical domain (DP). Further study should be conducted to answer the following questions:

- How should the zigzagging between process domain and design domain be done?
- What are the characteristics of process variables (PVs) in process domain?
- What are the examples of the zigzagging among the three domains of functional domain, physical domain, and process domain?

- In what level of the product design decomposition, does physical elements appear in physical domain as DPs?

In addition to the efforts to fine-tune the Axiomatic Design methodology, the four design domain model itself may be challenged as Sohelenius [2000] did. Figure 4-5 shows his model integrating manufacturing system design domains into the conventional four design domain model of the Axiomatic Design methodology. It is noteworthy that the process domain of this model includes both process requirements and manufacturing system design requirements to reflect manufacturing system issues in product design. Still, this model lacks the detailed explanation of the design steps or the interactions between the modified process domain and physical domain. Therefore, further study is required to complete the detail of the model. For example, the relationship between physical domain and process domain needs to be clearly defined and the product design steps that the model suggests need to be explained in detail along with many examples.

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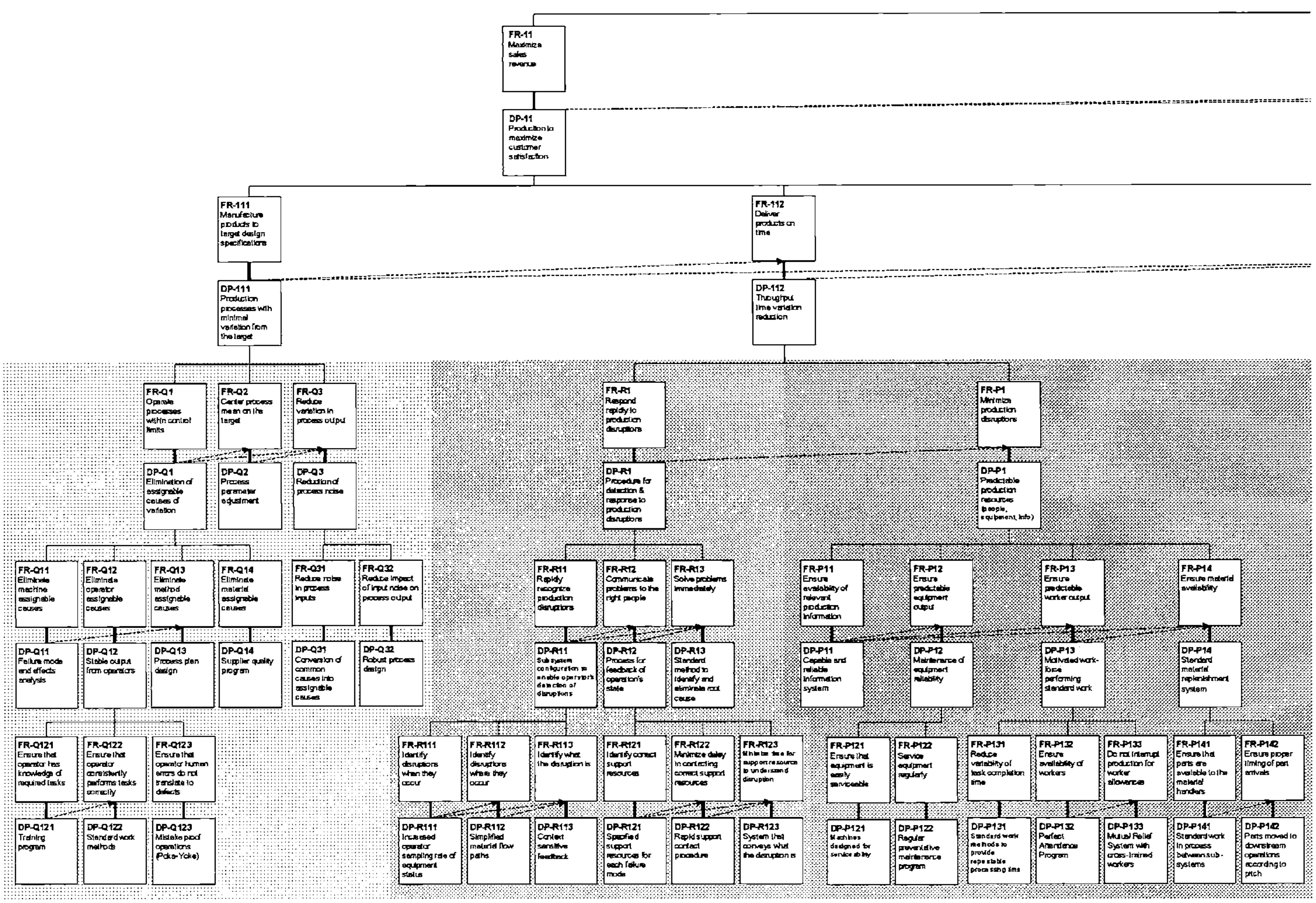
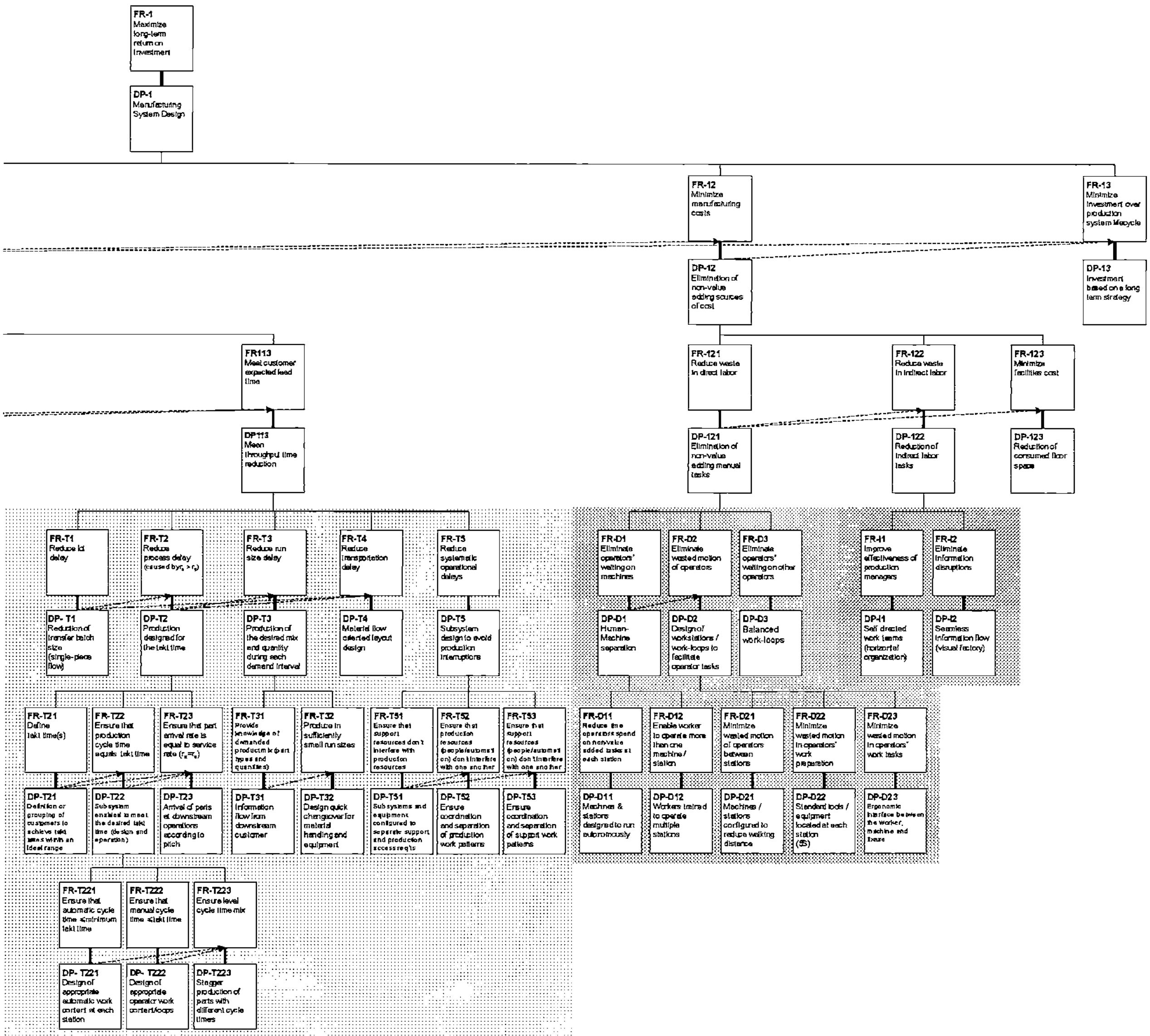
APPENDIX A THE MSDD

Manufacturing System Design Decomposition (MSDD) (page 1 of 2)



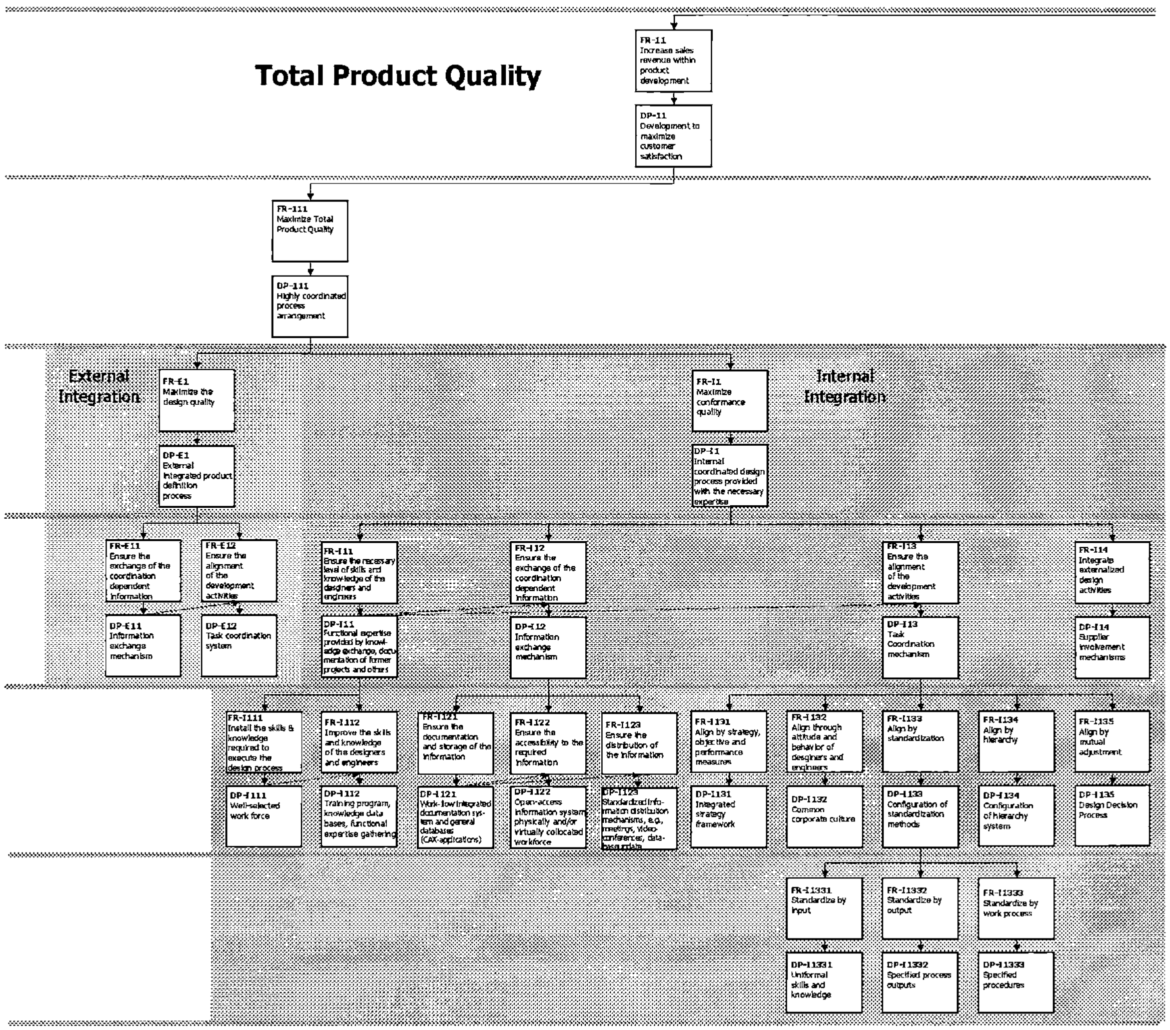
MANUFACTURING SYSTEM DESIGN DECOMPOSITION V5.1," PRODUCTION SYSTEM DESIGN LAB, DIRECTOR: PROFESSOR DAVID S. COCHRAN, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2000.

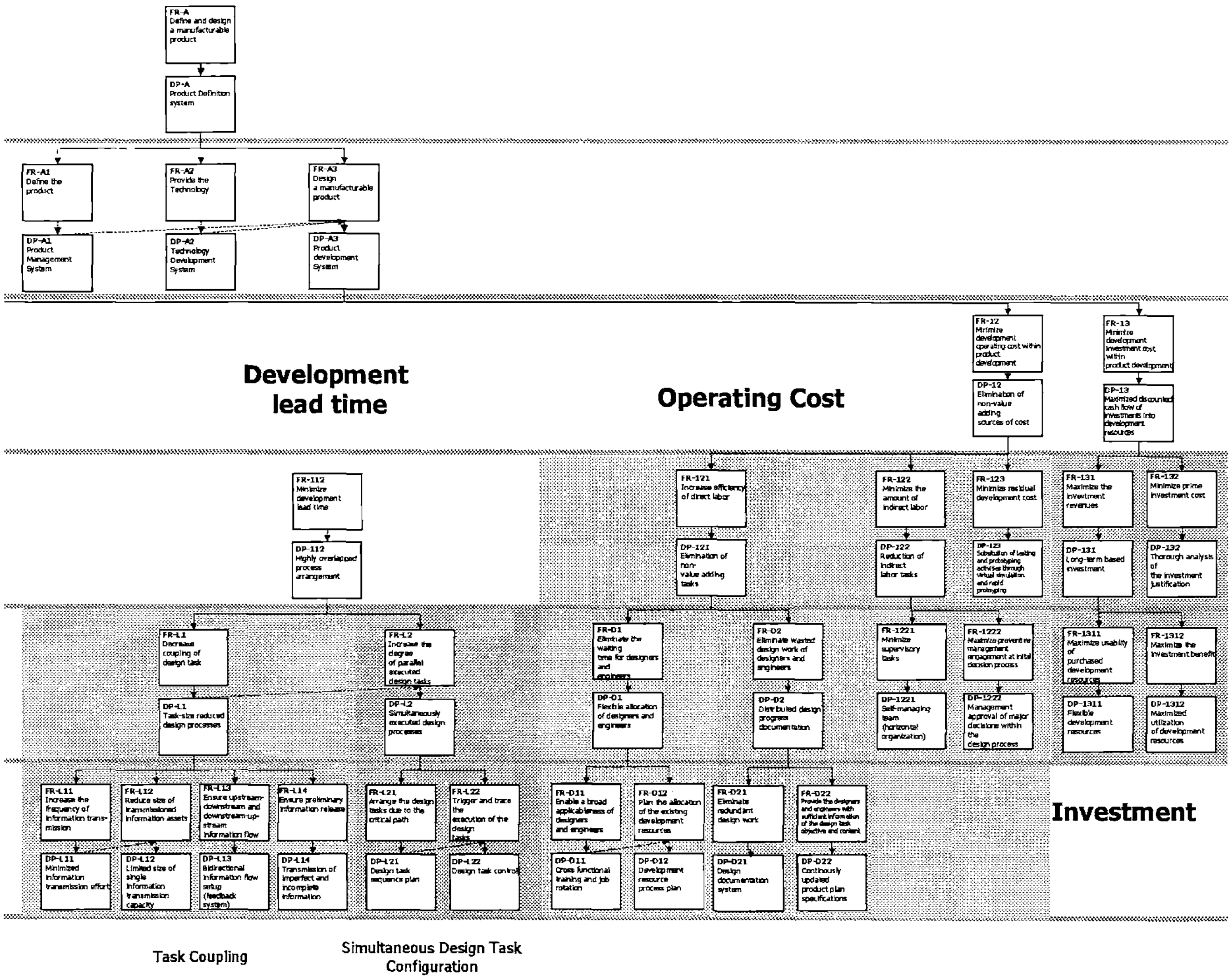
Manufacturing System Design Decomposition (MSDD) (page 2 of 2)



APPENDIX B. PRODUCT DEVELOPMENT DESIGN DECOMPOSITION (PD3) [BOCANEGRA 2001]

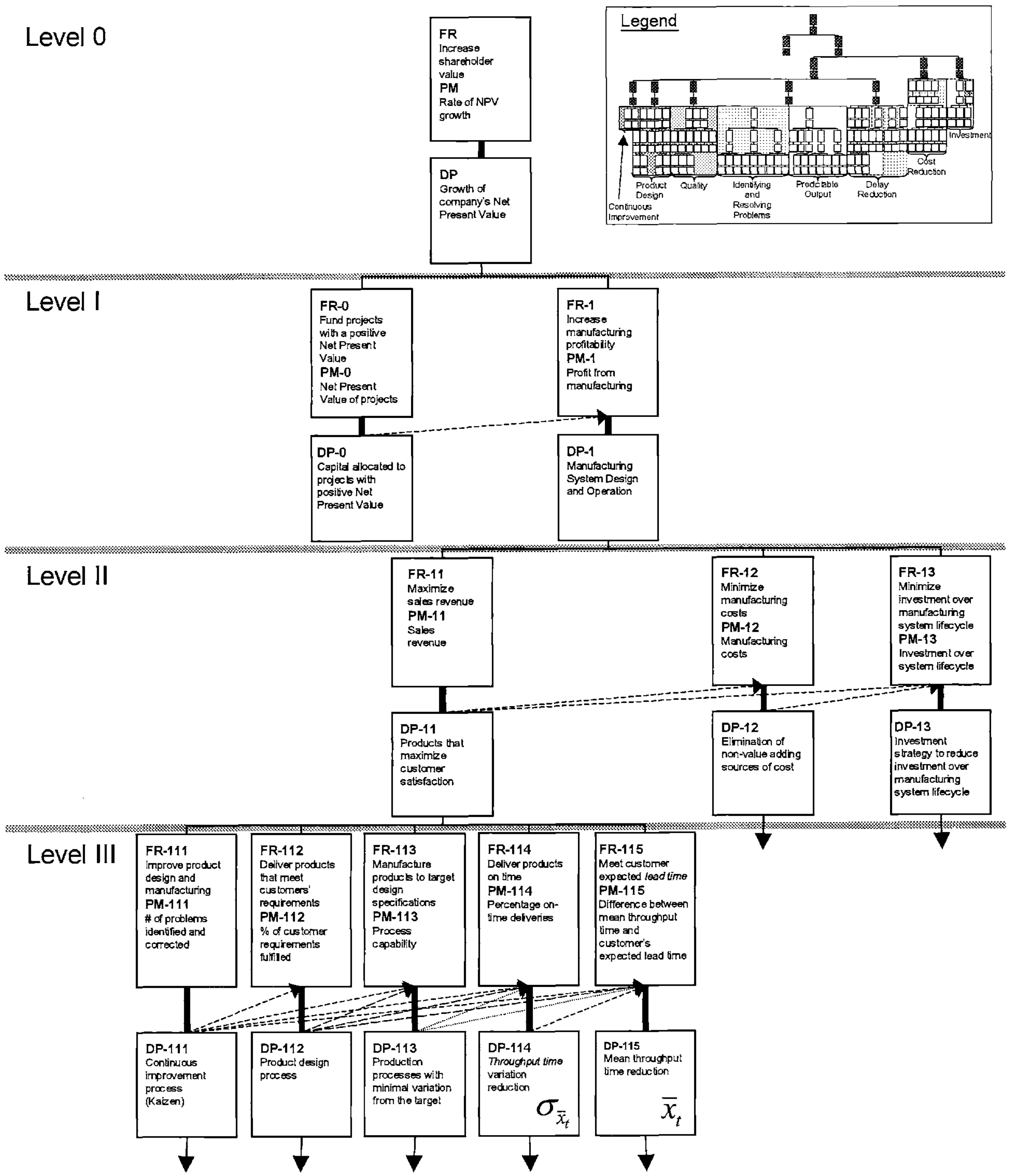
APPENDIX C. PRODUCT DEVELOPMENT SYSTEM DECOMPOSITION [LENZ 1999]

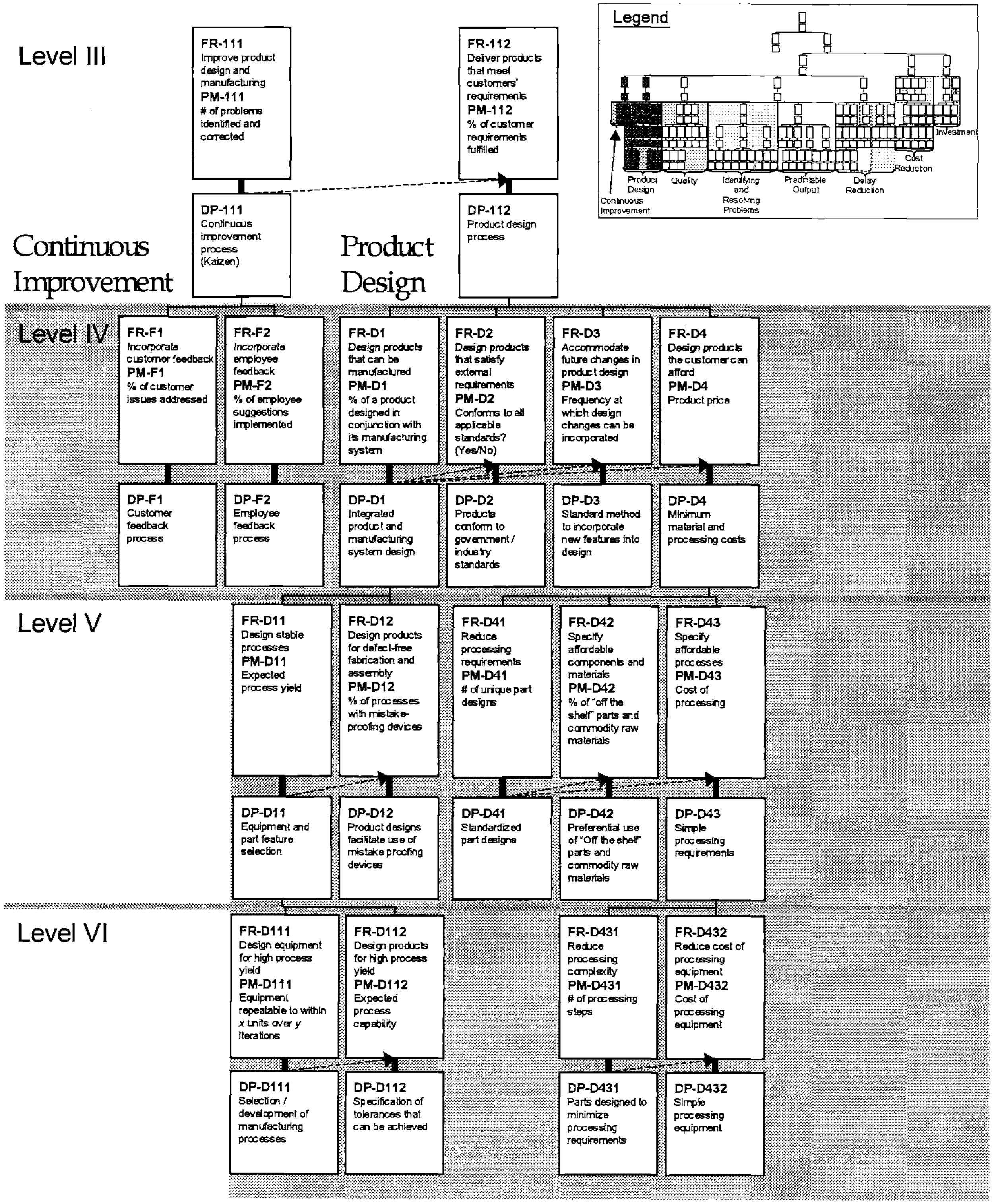


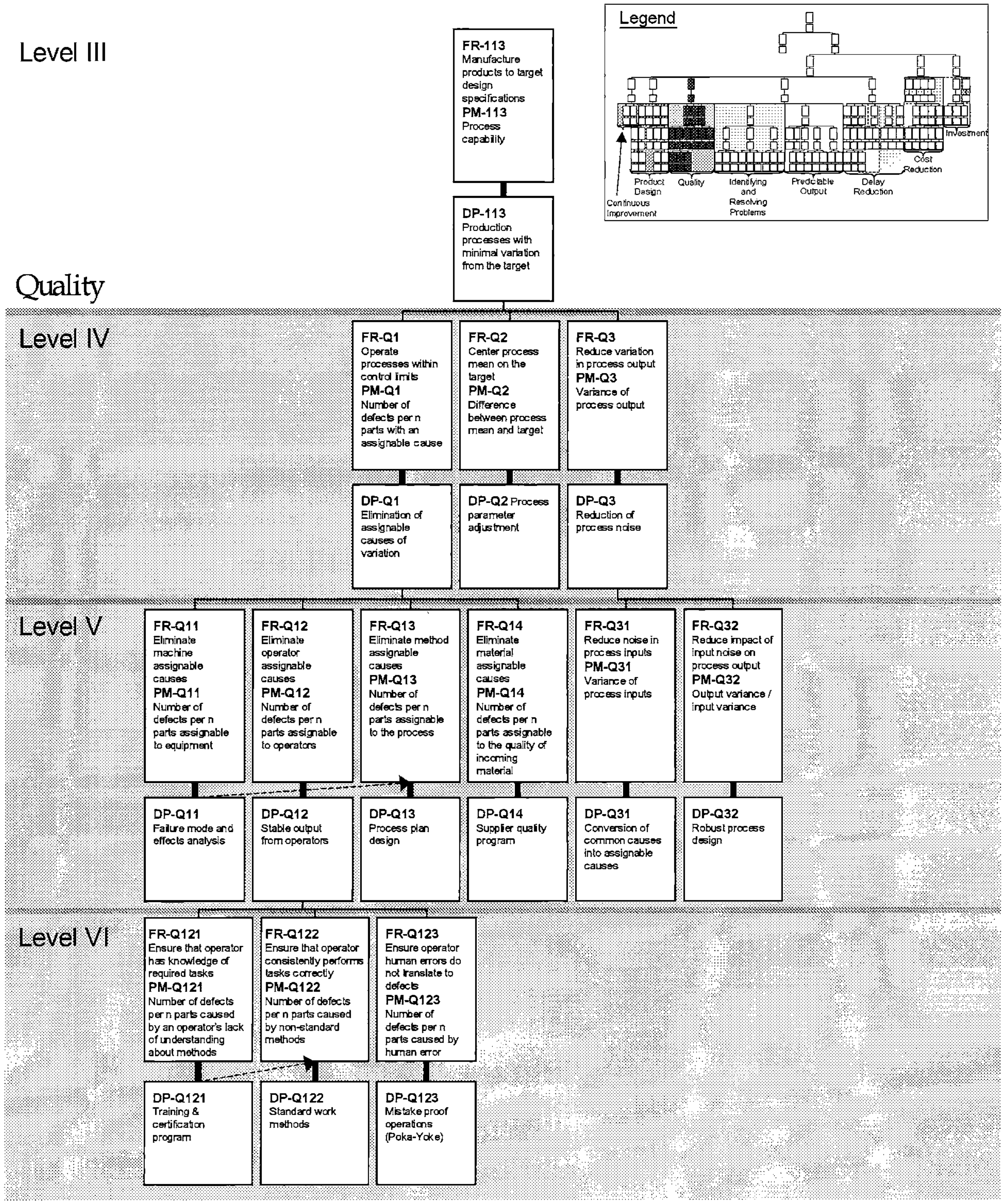


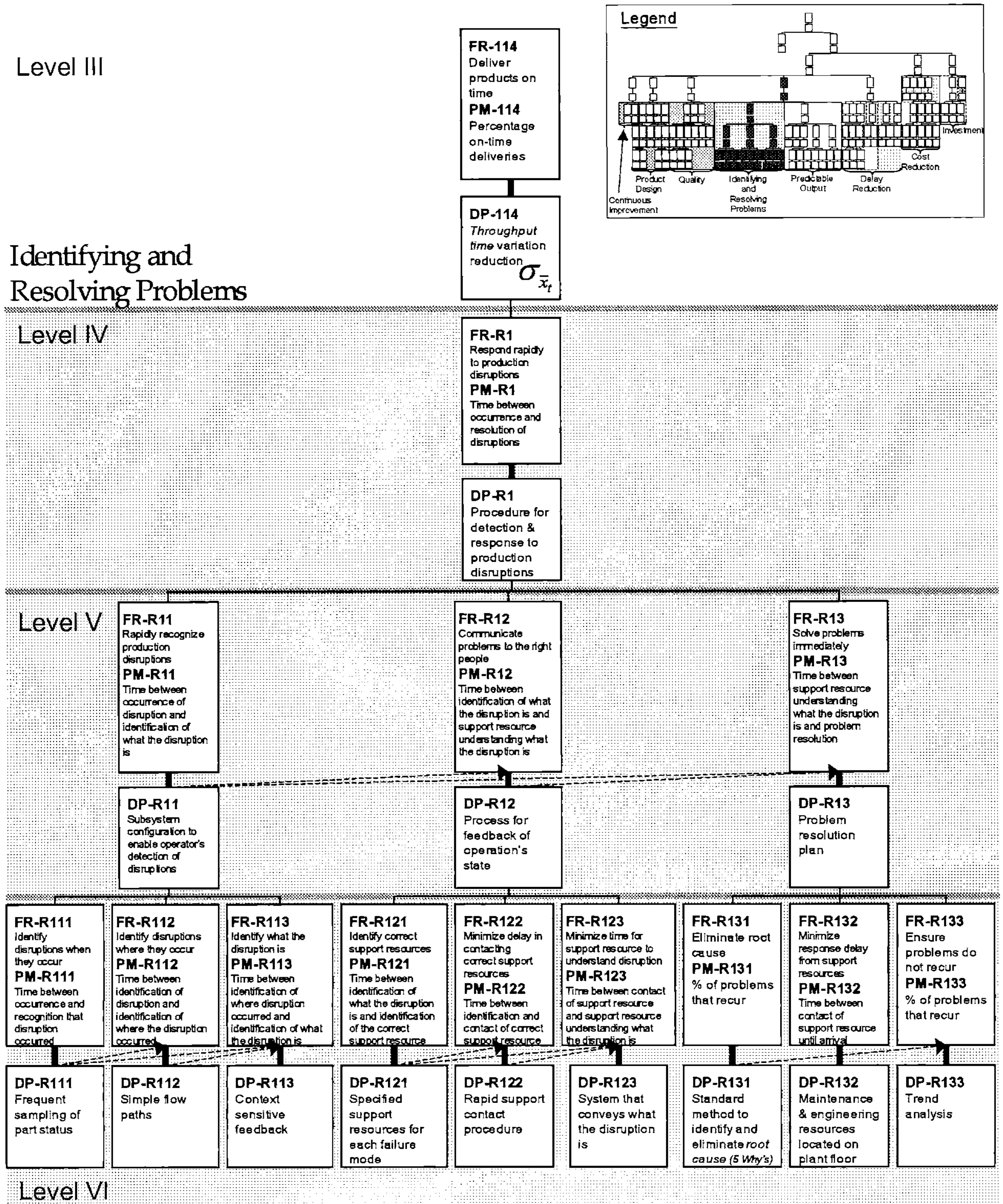
FR-A Define and design a manufacturable product
DP-A Product Definition system
FR-A1 Define the product
FR-A2 Provide the Technology
FR-A3 Design a manufacturable product
DP-A1 Product Management System
DP-A2 Technology Development System
DP-A3 Product development System
Development lead time
Operating Cost
Investment
FR-112 Minimize development lead time
DP-112 Highly overlapped process arrangement
FR-L1 Decrease coupling of design task
FR-L2 Increase the degree of parallel executed design tasks
DP-L1 Task-size reduced design processes
DP-L2 Simultaneously executed design processes
Task Coupling
Simultaneous Design Task Configuration

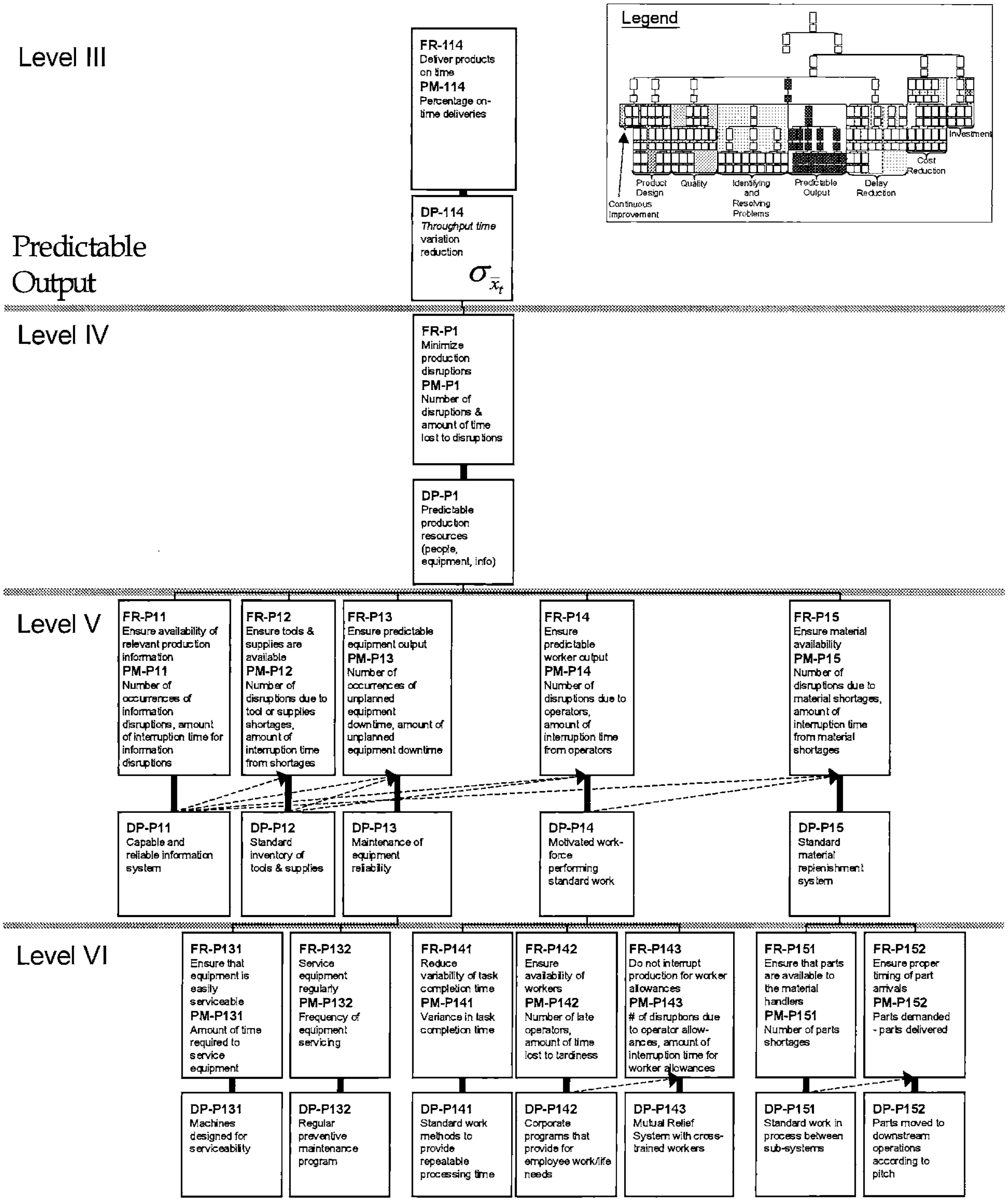
APPENDIX D. AEROSPACE MANUFACTURING SYSTEM DESIGN DECOMPOSITION [DOBBS 2001]

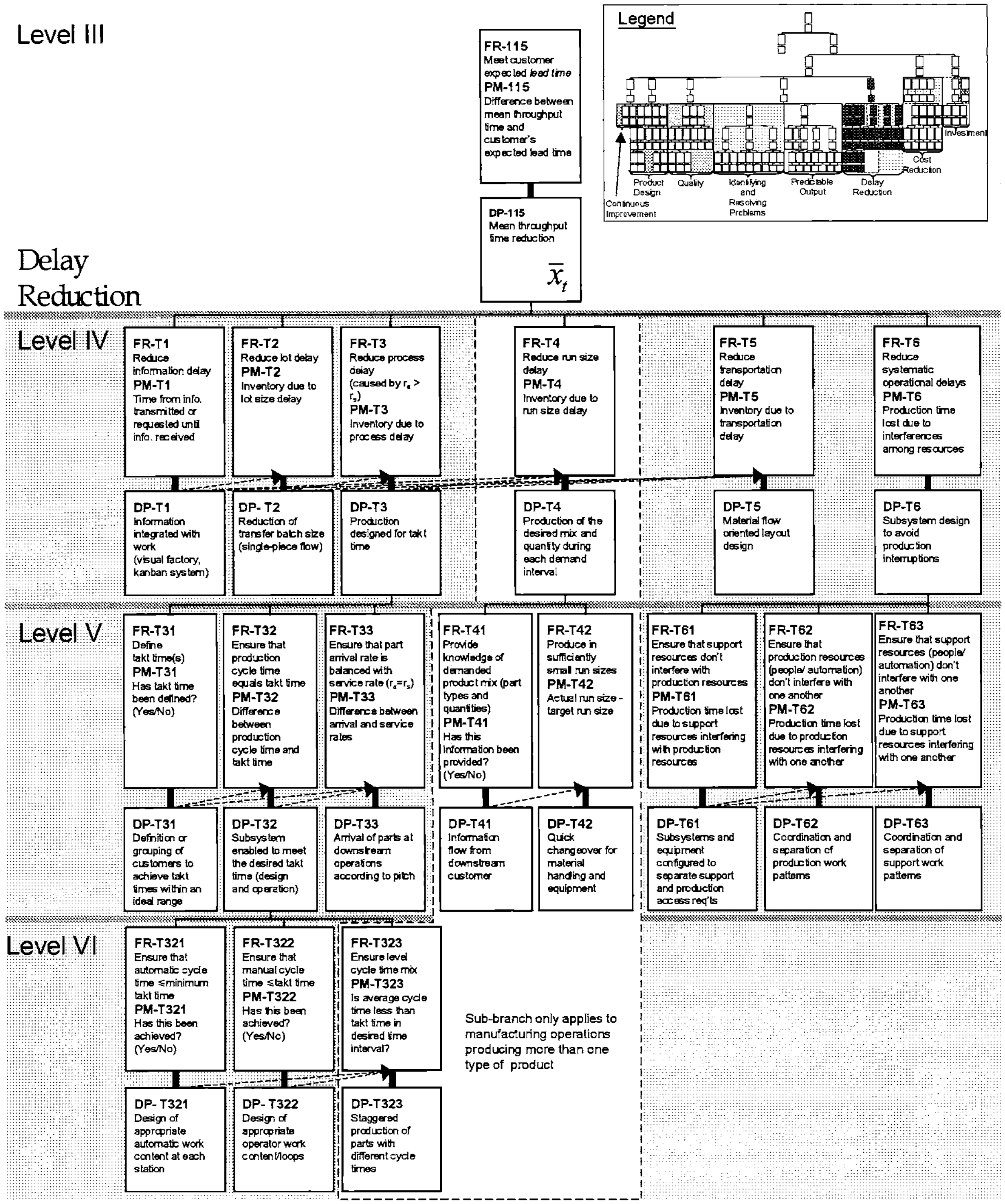


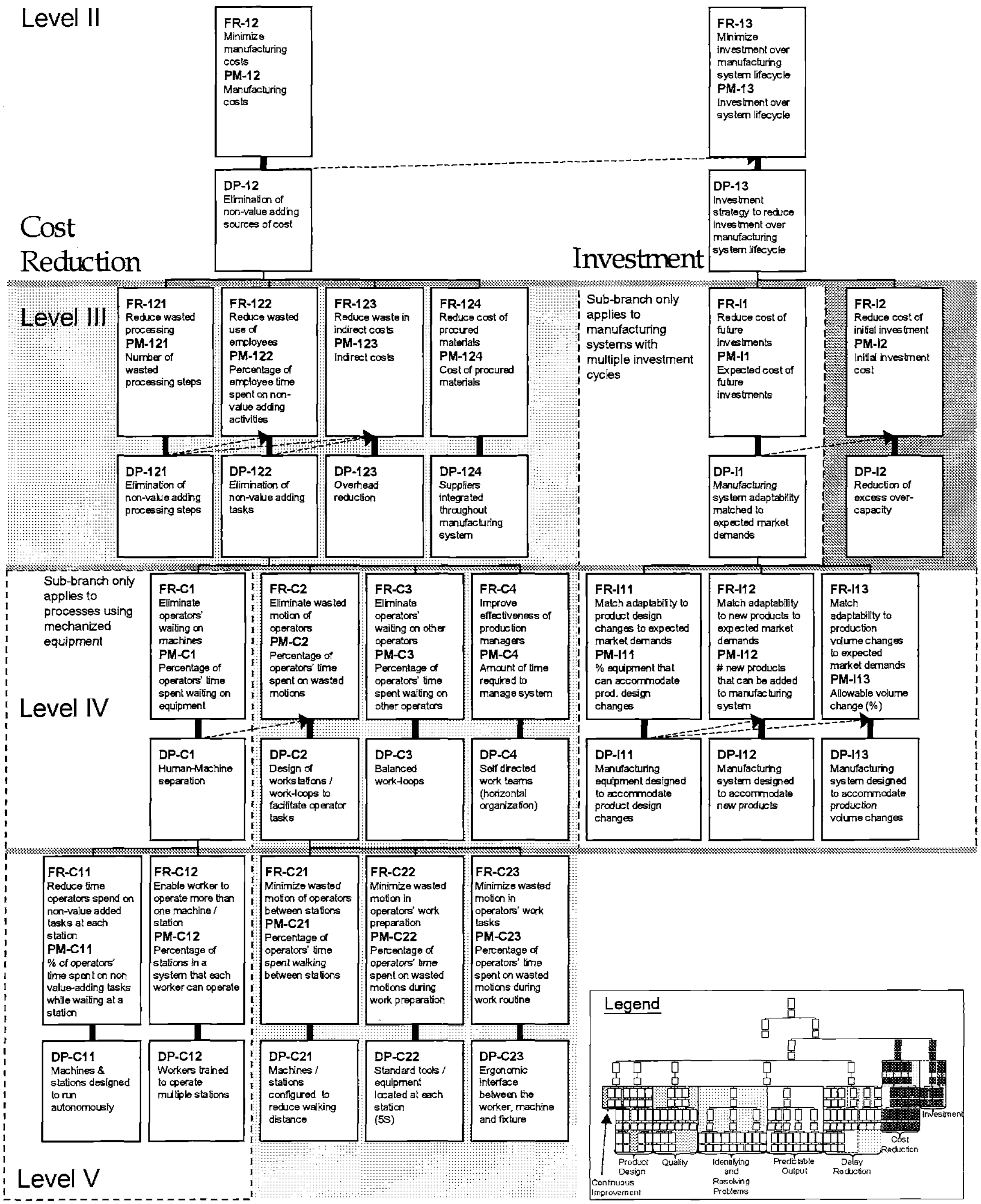

Legend
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Cost Reduction
Investment
Continuous Improvement
Level III
FR-111 Improve product design and manufacturing PM-111 # of problems identified and corrected
FR-112 Deliver products that meet customers' requirements PM-112 % of customer requirements fulfilled
DP-111 Continuous improvement process (Kaizen)
DP-112 Product design process
Continuous Improvement
Product Design
Level IV
FR-F1 Incorporate customer feedback PM-F1 % of customer issues addressed
FR-F2 Incorporate employee feedback PM-F2 % of employee suggestions implemented
FR-D1 Design products that can be manufactured PM-D1 % of a product designed in conjunction with its manufacturing system
FR-D2 Design products that satisfy external requirements PM-D2 Conforms to all applicable standards? (Yes/No)
FR-D3 Accommodate future changes in product design PM-D3 Frequency at which design changes can be incorporated
FR-D4 Design products the customer can afford PM-D4 Product price
DP-F1 Customer feedback process
DP-F2 Employee feedback process
DP-D1 Integrated product and manufacturing system design
DP-D2 Products conform to government / industry standards
DP-D3 Standard method to incorporate new features into design
DP-D4 Minimum material and processing costs
Level V
FR-D11 Design stable processes PM-D11 Expected process yield
FR-D12 Design products for defect-free fabrication and assembly PM-D12 % of processes with mistake-proofing devices
FR-D41 Reduce processing requirements PM-D41 # of unique part designs
FR-D42 Specify affordable components and materials PM-D42 % of "off the shelf" parts and commodity raw materials
FR-D43 Specify affordable processes PM-D43 Cost of processing
DP-D11 Equipment and part feature selection
DP-D12 Product designs facilitate use of mistake proofing devices
DP-D41 Standardized part designs
DP-D42 Preferential use of "Off the shelf" parts and commodity raw materials
DP-D43 Simple processing requirements
Level VI
FR-D111 Design equipment for high process yield PM-D111 Equipment repeatable to within x units over y iterations
FR-D112 Design products for high process yield PM-D112 Expected process capability
FR-D431 Reduce processing complexity PM-D431 # of processing steps
FR-D432 Reduce cost of processing equipment PM-D432 Cost of processing equipment
DP-D111 Selection / development of manufacturing processes
DP-D112 Specification of tolerances that can be achieved
DP-D431 Parts designed to minimize processing requirements
DP-D432 Simple processing equipment


Level III
Legend
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Cost Reduction
Investment
Continuous Improvement
FR-113 Manufacture products to target design specifications
PM-113 Process capability
DP-113 Production processes with minimal variation from the target
Quality
Level IV
FR-Q1 Operate processes within control limits
PM-Q1 Number of defects per n parts with an assignable cause
FR-Q2 Center process mean on the target
PM-Q2 Difference between process mean and target
FR-Q3 Reduce variation in process output
PM-Q3 Variance of process output
DP-Q1 Elimination of assignable causes of variation
DP-Q2 Process parameter adjustment
DP-Q3 Reduction of process noise
Level V
FR-Q11 Eliminate machine assignable causes
PM-Q11 Number of defects per n parts assignable to equipment
FR-Q12 Eliminate operator assignable causes
PM-Q12 Number of defects per n parts assignable to operators
FR-Q13 Eliminate method assignable causes
PM-Q13 Number of defects per n parts assignable to the process
FR-Q14 Eliminate material assignable causes
PM-Q14 Number of defects per n parts assignable to the quality of incoming material
FR-Q31 Reduce noise in process inputs
PM-Q31 Variance of process inputs
FR-Q32 Reduce impact of input noise on process output
PM-Q32 Output variance / input variance
DP-Q11 Failure mode and effects analysis
DP-Q12 Stable output from operators
DP-Q13 Process plan design
DP-Q14 Supplier quality program
DP-Q31 Conversion of common causes into assignable causes
DP-Q32 Robust process design
Level VI
FR-Q121 Ensure that operator has knowledge of required tasks
PM-Q121 Number of defects per n parts caused by an operator's lack of understanding about methods
FR-Q122 Ensure that operator consistently performs tasks correctly
PM-Q122 Number of defects per n parts caused by non-standard methods
FR-Q123 Ensure operator human errors do not translate to defects
PM-Q123 Number of defects per n parts caused by human error
DP-Q121 Training & certification program
DP-Q122 Standard work methods
DP-Q123 Mistake proof operations (Poka-Yoke)


Level III
FR-114 Deliver products on time
PM-114 Percentage on-time deliveries
DP-114 Throughput time variation reduction $\sigma_{\bar{x}_t}$
Legend
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Cost Reduction
Investment
Continuous Improvement
Identifying and Resolving Problems
Level IV
FR-R1 Respond rapidly to production disruptions
PM-R1 Time between occurrence and resolution of disruptions
DP-R1 Procedure for detection & response to production disruptions
Level V
FR-R11 Rapidly recognize production disruptions
PM-R11 Time between occurrence of disruption and identification of what the disruption is
FR-R12 Communicate problems to the right people
PM-R12 Time between identification of what the disruption is and support resource understanding what the disruption is
FR-R13 Solve problems immediately
PM-R13 Time between support resource understanding what the disruption is and problem resolution
DP-R11 Subsystem configuration to enable operator's detection of disruptions
DP-R12 Process for feedback of operation's state
DP-R13 Problem resolution plan
FR-R111 Identify disruptions when they occur
PM-R111 Time between occurrence and recognition that disruption occurred
FR-R112 Identify disruptions where they occur
PM-R112 Time between identification of disruption and identification of where the disruption occurred
FR-R113 Identify what the disruption is
PM-R113 Time between identification of where disruption occurred and identification of what the disruption is
FR-R121 Identify correct support resources
PM-R121 Time between identification of what the disruption is and identification of the correct support resource
FR-R122 Minimize delay in contacting correct support resources
PM-R122 Time between identification and contact of correct support resource
FR-R123 Minimize time for support resource to understand disruption
PM-R123 Time between contact of support resource and support resource understanding what the disruption is
FR-R131 Eliminate root cause
PM-R131 % of problems that recur
FR-R132 Minimize response delay from support resources
PM-R132 Time between contact of support resource until arrival
FR-R133 Ensure problems do not recur
PM-R133 % of problems that recur
DP-R111 Frequent sampling of part status
DP-R112 Simple flow paths
DP-R113 Context sensitive feedback
DP-R121 Specified support resources for each failure mode
DP-R122 Rapid support contact procedure
DP-R123 System that conveys what the disruption is
DP-R131 Standard method to identify and eliminate root cause (5 Why's)
DP-R132 Maintenance & engineering resources located on plant floor
DP-R133 Trend analysis
Level VI


Level III
FR-114 Deliver products on time
PM-114 Percentage on-time deliveries
DP-114 Throughput time variation reduction
$\sigma_{\bar{x}_t}$
Predictable Output
Legend
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Cost Reduction
Investment
Continuous Improvement
Level IV
FR-P1 Minimize production disruptions
PM-P1 Number of disruptions & amount of time lost to disruptions
DP-P1 Predictable production resources (people, equipment, info)
Level V
FR-P11 Ensure availability of relevant production information
PM-P11 Number of occurrences of information disruptions, amount of interruption time for information disruptions
FR-P12 Ensure tools & supplies are available
PM-P12 Number of disruptions due to tool or supplies shortages, amount of interruption time from shortages
FR-P13 Ensure predictable equipment output
PM-P13 Number of occurrences of unplanned equipment downtime, amount of unplanned equipment downtime
FR-P14 Ensure predictable worker output
PM-P14 Number of disruptions due to operators, amount of interruption time from operators
FR-P15 Ensure material availability
PM-P15 Number of disruptions due to material shortages, amount of interruption time from material shortages
DP-P11 Capable and reliable information system
DP-P12 Standard inventory of tools & supplies
DP-P13 Maintenance of equipment reliability
DP-P14 Motivated work-force performing standard work
DP-P15 Standard material replenishment system
Level VI
FR-P131 Ensure that equipment is easily serviceable
PM-P131 Amount of time required to service equipment
FR-P132 Service equipment regularly
PM-P132 Frequency of equipment servicing
FR-P141 Reduce variability of task completion time
PM-P141 Variance in task completion time
FR-P142 Ensure availability of workers
PM-P142 Number of late operators, amount of time lost to tardiness
FR-P143 Do not interrupt production for worker allowances
PM-P143 # of disruptions due to operator allowances, amount of interruption time for worker allowances
FR-P151 Ensure that parts are available to the material handlers
PM-P151 Number of parts shortages
FR-P152 Ensure proper timing of part arrivals
PM-P152 Parts demanded - parts delivered
DP-P131 Machines designed for serviceability
DP-P132 Regular preventive maintenance program
DP-P141 Standard work methods to provide repeatable processing time
DP-P142 Corporate programs that provide for employee work/life needs
DP-P143 Mutual Relief System with cross-trained workers
DP-P151 Standard work in process between sub-systems
DP-P152 Parts moved to downstream operations according to pitch


Level III
Legend
Investment
Cost Reduction
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Continuous Improvement
FR-115 Meet customer expected lead time
PM-115 Difference between mean throughput time and customer's expected lead time
DP-115 Mean throughput time reduction $\overline{x}_t$
Delay Reduction
Level IV
FR-T1 Reduce information delay
PM-T1 Time from info. transmitted or requested until info. received
FR-T2 Reduce lot delay
PM-T2 Inventory due to lot size delay
FR-T3 Reduce process delay (caused by $r_a > r_s$)
PM-T3 Inventory due to process delay
FR-T4 Reduce run size delay
PM-T4 Inventory due to run size delay
FR-T5 Reduce transportation delay
PM-T5 Inventory due to transportation delay
FR-T6 Reduce systematic operational delays
PM-T6 Production time lost due to interferences among resources
DP-T1 Information integrated with work (visual factory, kanban system)
DP-T2 Reduction of transfer batch size (single-piece flow)
DP-T3 Production designed for takt time
DP-T4 Production of the desired mix and quantity during each demand interval
DP-T5 Material flow oriented layout design
DP-T6 Subsystem design to avoid production interruptions
Level V
FR-T31 Define takt time(s)
PM-T31 Has takt time been defined? (Yes/No)
FR-T32 Ensure that production cycle time equals takt time
PM-T32 Difference between production cycle time and takt time
FR-T33 Ensure that part arrival rate is balanced with service rate ($r_a=r_s$)
PM-T33 Difference between arrival and service rates
FR-T41 Provide knowledge of demanded product mix (part types and quantities)
PM-T41 Has this information been provided? (Yes/No)
FR-T42 Produce in sufficiently small run sizes
PM-T42 Actual run size - target run size
FR-T61 Ensure that support resources don't interfere with production resources
PM-T61 Production time lost due to support resources interfering with production resources
FR-T62 Ensure that production resources (people/ automation) don't interfere with one another
PM-T62 Production time lost due to production resources interfering with one another
FR-T63 Ensure that support resources (people/ automation) don't interfere with one another
PM-T63 Production time lost due to support resources interfering with one another
DP-T31 Definition or grouping of customers to achieve takt times within an ideal range
DP-T32 Subsystem enabled to meet the desired takt time (design and operation)
DP-T33 Arrival of parts at downstream operations according to pitch
DP-T41 Information flow from downstream customer
DP-T42 Quick changeover for material handling and equipment
DP-T61 Subsystems and equipment configured to separate support and production access req'ts
DP-T62 Coordination and separation of production work patterns
DP-T63 Coordination and separation of support work patterns
Level VI
FR-T321 Ensure that automatic cycle time ≤minimum takt time
PM-T321 Has this been achieved? (Yes/No)
FR-T322 Ensure that manual cycle time ≤takt time
PM-T322 Has this been achieved? (Yes/No)
FR-T323 Ensure level cycle time mix
PM-T323 Is average cycle time less than takt time in desired time interval?
DP- T321 Design of appropriate automatic work content at each station
DP- T322 Design of appropriate operator work content/loops
DP-T323 Staggered production of parts with different cycle times
Sub-branch only applies to manufacturing operations producing more than one type of product



Level II
FR-12 Minimize manufacturing costs PM-12 Manufacturing costs
FR-13 Minimize investment over manufacturing system lifecycle PM-13 Investment over system lifecycle
DP-12 Elimination of non-value adding sources of cost
DP-13 Investment strategy to reduce investment over manufacturing system lifecycle
Cost Reduction
Investment
Level III
FR-121 Reduce wasted processing PM-121 Number of wasted processing steps
FR-122 Reduce wasted use of employees PM-122 Percentage of employee time spent on non-value adding activities
FR-123 Reduce waste in indirect costs PM-123 Indirect costs
FR-124 Reduce cost of procured materials PM-124 Cost of procured materials
Sub-branch only applies to manufacturing systems with multiple investment cycles
FR-I1 Reduce cost of future investments PM-I1 Expected cost of future investments
FR-I2 Reduce cost of initial investment PM-I2 Initial investment cost
DP-121 Elimination of non-value adding processing steps
DP-122 Elimination of non-value adding tasks
DP-123 Overhead reduction
DP-124 Suppliers integrated throughout manufacturing system
DP-I1 Manufacturing system adaptability matched to expected market demands
DP-I2 Reduction of excess over-capacity
Sub-branch only applies to processes using mechanized equipment
Level IV
FR-C1 Eliminate operators' waiting on machines PM-C1 Percentage of operators' time spent waiting on equipment
FR-C2 Eliminate wasted motion of operators PM-C2 Percentage of operators' time spent on wasted motions
FR-C3 Eliminate operators' waiting on other operators PM-C3 Percentage of operators' time spent waiting on other operators
FR-C4 Improve effectiveness of production managers PM-C4 Amount of time required to manage system
FR-I11 Match adaptability to product design changes to expected market demands PM-I11 % equipment that can accommodate prod. design changes
FR-I12 Match adaptability to new products to expected market demands PM-I12 # new products that can be added to manufacturing system
FR-I13 Match adaptability to production volume changes to expected market demands PM-I13 Allowable volume change (%)
DP-C1 Human-Machine separation
DP-C2 Design of workstations / work-loops to facilitate operator tasks
DP-C3 Balanced work-loops
DP-C4 Self directed work teams (horizontal organization)
DP-I11 Manufacturing equipment designed to accommodate product design changes
DP-I12 Manufacturing system designed to accommodate new products
DP-I13 Manufacturing system designed to accommodate production volume changes
FR-C11 Reduce time operators spend on non-value added tasks at each station PM-C11 % of operators' time spent on non value-adding tasks while waiting at a station
FR-C12 Enable worker to operate more than one machine / station PM-C12 Percentage of stations in a system that each worker can operate
FR-C21 Minimize wasted motion of operators between stations PM-C21 Percentage of operators' time spent walking between stations
FR-C22 Minimize wasted motion in operators' work preparation PM-C22 Percentage of operators' time spent on wasted motions during work preparation
FR-C23 Minimize wasted motion in operators' work tasks PM-C23 Percentage of operators' time spent on wasted motions during work routine
DP-C11 Machines & stations designed to run autonomously
DP-C12 Workers trained to operate multiple stations
DP-C21 Machines / stations configured to reduce walking distance
DP-C22 Standard tools / equipment located at each station (5S)
DP-C23 Ergonomic interface between the worker, machine and fixture
Level V
Legend
Investment
Cost Reduction
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Continuous Improvement

APPENDIX E. A FULL LIST OF THE FIRST-ROUND QUESTIONNAIRE

Design for Manufacturing

Product design guideline from the manufacturing side:

- Some literature addresses the frequent use of product design guideline originated from manufacturing in benchmark companies. This document contains the requirements from the manufacturing or production engineering side to product design side. Does your company use a formal document like this?

If your company has the equivalent one:

- How has it been developed?
- What is its content?
- How is it related to their manufacturing system design? Is there any good example of design constraints imposed by manufacturing system issues?
- Is there any performance measure for product designers related to this issue? (Are product designers evaluated by being committed to this guideline?)

If your company does not have the equivalent one:

- How are the manufacturing requirements fed back to the product design side?
- Which one is more frequently used for the feedback process, documented (written) information or tacit knowledge through human network?
- If a manufacturing engineer found a product design problem, for example, how would the problem be informed to the product designers? (e.g., product development team meeting, product development process gate review, etc.)
- What activities are done to prevent repeating problems?

Product design and manufacturing:

- What is the system interface between manufacturing and product design during the product development processes?
- Is there any standardized information exchange between two parties? For example, when designing a steering gear, is there exchange of standardized (e.g., information contents are pre-specified) information such as manufacturing rate, capacity of existing line, process capability, etc.?
- How is that information (capacity of existing line, process capability, etc.) reflected in product design?
- What kind of information is transformed and shared between two functional parties?
- What does your company do to make that information exchange really happen?
- Is there any performance measure to enhance this information exchange?
- What is the problem solving process if the trans plant overseas finds some manufacturing problems associated with product design? Does she ask for design modification to product designers in the mother company?
- When is it decided during the product development processes where to produce the new product? Even in case that there is only one plant available for a certain type of product (for example, your company may have only one plant for a bumper production), it should be decided which production lines/machines within the plant will product the new product)

Product design decision:

- What is the basic strategy of your company in product design? How are the products of your company different from those of your competitors in terms of external design, performance, etc.?
- How is you company different from others on its design decision processes?
- What are the decision criteria for product variety? How does your company decide product variety?

- What is your company's perspective on customer desire for product variety? How does your company optimize between customer requirements and manufacturing constraints? Is there any optimization strategy?

Manufacturing System Design

- Does your company have a pre-defined manufacturing system design steps?
- What are the general processes of designing a new manufacturing system or modifying an existing manufacturing system?
- How does your company do the capacity planning?
- What feedback is used from the previous manufacturing system design projects?
- What efforts are made to enable a 'vertical/super-fast' ramp up?
- How does your company decide on the mix-capability of each production line?

Product variety and manufacturing flexibility:

- What kind of role does product design or product variety play in the decision process of detailed manufacturing system design?
- Is their any special strategy or methodology pursued to maintain manufacturing flexibility?
- What are the challenges your company sees from the mix production? How does your company handle them?
- How does your company schedule the mix of production?
- How does your company optimize between the cost of system and the simplicity? For example, how the number of cells is decided? (if your company has many cells, your company can have focused flows to each customer but in that case system cost may not be minimized)

Planning and actual happening:

- What is the role or meaning of planning at your company?
- How does your company fill in the gap between planning and actual happening?

Performance Measurement

- What is your company's financial accounting system used for the internal control purpose?
- What does your company has as performance measures for a plant as a whole?
- How are those performance measures different from each level of plant management? (operator level, engineers level, line managers level, and plant manager level, etc.)
- What efforts are made to keep your company's employees fully motivated? (For example, some companies make a lot of effort to keep its people's sense of 'emergency' for everyday operation. Is there any equivalent effort in your company?)

APPENDIX F. A FULL LIST OF THE SECOND-ROUND QUESTIONNAIRE

Design for Manufacturing Systems Questionnaire

Company name: ____.

Respondent's position/function: ______________________________.

Plant location: ____.

Products involved: ____.

Question Index

G: General questions – this category includes general questions related to all other categories.

PV: Product Variety – product variety category includes questions related to product variety.

PA: Product architecture – product architecture means the mapping of functional elements on physical elements. Product architecture decides physical partition of a product. Product architecture is closely related to product variety issues since such strategies as component sharing, part standardization, and modular design are closely linked to product architecture design.

P: Purchasing – make or buy decision is one of the most critical decisions that significantly affect manufacturing system design. Once a product is decided to be made in house, categories like material selection and detailed design should be considered. If a product is to be purchased, different considerations are made for smooth supply from the vendors.

MS: Material selection – this is about the selection of raw material for a product. Usually raw material is purchased from outside suppliers and thus, the purchasing of raw material is dealt in this category, separately from the purchasing category.

PS: Process selection – in this category, the impact of process selection on manufacturing system design are presented in terms of questions. Even though new processes usually come with new equipment, equipment design issues are excluded in this category to keep the focus on process selection.

DD: Detailed design – detailed design affects manufacturing system design in many ways. In this category, general questions are asked with regard to the impact of detailed design on manufacturing system design.

Q111	Ensure that operator has knowledge of required tasks **Training program**	strongly disagree ___ strongly agree 1 2 3 4 5	does not apply 0	comments
PV	The consequence of the product variety decision on required operator knowledge is studied during the design phase.	☐ ☐ ☐ ☐ ☐	☐	______
PA	We study the impact of new product layout on required operator knowledge.	☐ ☐ ☐ ☐ ☐	☐	______
P	Training need for the assembly operators to learn how to assemble purchased parts is studied.	☐ ☐ ☐ ☐ ☐	☐	______
	Workers who handle purchased parts are trained to fully understand the characteristics of purchased parts (e.g., what to be careful of, etc.).	☐ ☐ ☐ ☐ ☐	☐	______
MS	Newly required operators' knowledge of their work tasks due to the introduction of new material is identified and studied during material selection phase.	☐ ☐ ☐ ☐ ☐	☐	______
PS	Operators' capabilities and knowledge on processes are reviewed and considered when major decision on process design is made.	☐ ☐ ☐ ☐ ☐	☐	______
	Newly required operators' knowledge for a new process is identified and studied during process selection phase.	☐ ☐ ☐ ☐ ☐	☐	______
DD	The consequence of product geometry decision on the operators' work content is well understood during the product design phase.	☐ ☐ ☐ ☐ ☐	☐	______

Q112	Ensure that operator consistently performs tasks correctly **Standard work method**	strongly disagree ___ strongly agree 1 2 3 4 5	does not apply 0	comments
G	Line operators participate in the design of standard operators' work method during product development processes.	☐ ☐ ☐ ☐ ☐	☐	______
	Operators' standardized work in existing lines is reviewed during the design phase. Any significant change is discussed with operators for its feasibility.	☐ ☐ ☐ ☐ ☐	☐	______

PV	Possible confusion of operators when they perform various work tasks required for product variety is considered and reflected in the design of work methods during product development.	☐	☐	☐	☐	☐	☐	______
PA	We study the impact of product architecture (product layout) on the existing standard work methods.	☐	☐	☐	☐	☐	☐	______
P	Standard assembly method is planned for purchased parts.	☐	☐	☐	☐	☐	☐	______
MS	The consequence of new material on standard work methods is reviewed and considered during material selection phase of product development.	☐	☐	☐	☐	☐	☐	______
PS	A new standard work method for a new process is planned and considered during process selection phase.	☐	☐	☐	☐	☐	☐	______
DD	The consequence of new detailed design on existing standard work methods is reviewed and design changes are made accordingly if necessary.	☐	☐	☐	☐	☐	☐	______

Q113	**Ensure that operator human errors do not translate to defects** **Mistake proof operations (poka-yoke)**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Manufacturing, production engineering, and product design engineers work together to incorporate mistake-proof (poka-yoke) features (e.g., spider marks, colors, significantly different features, notch, special dent, etc.) into product design.	☐	☐	☐	☐	☐	☐	______
	Manufacturing group frequently suggests product design changes for mistake-proof (poka-yoke) purposes.	☐	☐	☐	☐	☐	☐	______
PV	Products are designed in a way that operators can easily identify different types of products or components.	☐	☐	☐	☐	☐	☐	______
PA	Product architecture design supports product variety strategies to minimize effective product variety exposed to operators.	☐	☐	☐	☐	☐	☐	______

P	Incorporation of poka-yoke features into purchased parts for easy assembly is discussed with the part suppliers.	☐	☐	☐	☐	☐	☐	______
MS	Poka-yoke feature for new material is considered according to the material characteristics (e.g., grain of wood, texture of cloth, etc.)	☐	☐	☐	☐	☐	☐	______
PS	The typical operators human mistakes caused by the introduction of new process are studied and mistake-proof methods are planned during process selection phase.	☐	☐	☐	☐	☐	☐	______
DD	Products are designed for easy and obvious assembly. It is easy to locate a part in the right position and direction.	☐	☐	☐	☐	☐	☐	______

Q12	Eliminate machine assignable causes Failure mode and effects analysis (FMEA)	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	We keep records of manufacturing defects for every machine. The records are available to product designers to see if product design may be changed to avoid some machine assignable quality problems.	☐	☐	☐	☐	☐	☐	______
PV	Flexibility of existing equipment (e.g., machine, fixture, tools) is reviewed and considered when product variety decision is made.	☐	☐	☐	☐	☐	☐	______
P	Suitability of purchased parts to existing assembly equipment is ensured during purchasing decision phase.	☐	☐	☐	☐	☐	☐	______
MS	Failure Mode and Effects Analysis (FMEA) data are reviewed to investigate the effect of materials on the failure of existing equipment	☐	☐	☐	☐	☐	☐	______
	Suitability of new material to existing equipment is reviewed.	☐	☐	☐	☐	☐	☐	______
PS	FMEA data of new equipment for new process is obtained from equipment suppliers and reviewed. Machine assignable causes are minimized from the beginning through careful study of new equipment, process, and design.	☐	☐	☐	☐	☐	☐	______

DD	The consequence of the detailed design on the reusability of existing equipment is reviewed and design changes are made accordingly to maximize the reuse of existing equipment.	☐	☐	☐	☐	☐	☐	____

Q13	**Eliminate method assignable causes** **Process plan design**	strongly disagree 1	 2	 3	strongly agree 4	 5	does not apply 0	comments
G	There is a knowledge base available for method assignable causes. Product designers review the knowledge base to avoid problems made in the past from recurring.	☐	☐	☐	☐	☐	☐	____
PV	The flexibility of existing method is reviewed and assured for planned product variety.	☐	☐	☐	☐	☐	☐	____
PA	The production method in use conforms to the given product architecture.	☐	☐	☐	☐	☐	☐	____
P	Assembly method of purchased parts is designed with part suppliers to prevent defective parts due to wrong method.	☐	☐	☐	☐	☐	☐	____
MS	It is reviewed if existing production methods are adequate for new material. If not, a new method should be designed.	☐	☐	☐	☐	☐	☐	____
PS	When processes are selected for product design, process characteristics are fully understood by design engineers.	☐	☐	☐	☐	☐	☐	____
	The capability of the selected method is checked to assure that it is adequate for given product design and tolerance.	☐	☐	☐	☐	☐	☐	____
DD	The consequence of detail design on the selected method is reviewed and design changes are made accordingly (e.g., detail design to support a specific method such as casting and automated assembly).	☐	☐	☐	☐	☐	☐	____

Q14	Eliminate material assignable causes Supplier quality program	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	The selected material is studied to ensure it is appropriate for the various product designs during product development.	☐	☐	☐	☐	☐	☐	______
	The quality of incoming materials is ensured to be good enough to meet various processing requirements caused by product variety.	☐	☐	☐	☐	☐	☐	______
PA	During product architecture design, the compatibility of materials used in individual components of a product is reviewed.	☐	☐	☐	☐	☐	☐	______
P	New supplier quality program is prepared when new purchasing is considered.	☐	☐	☐	☐	☐	☐	______
MS	When material is selected, suppliers collaborate with product designers so that stable supply of quality material is ensured from the early stage of product design.	☐	☐	☐	☐	☐	☐	______
	We study if the selected material is adequate for the production methods in use.	☐	☐	☐	☐	☐	☐	______
PS	The impact of a new process on the material in use is studied.	☐	☐	☐	☐	☐	☐	______
DD	It is checked if new detail design is appropriate with the current quality level of incoming materials.	☐	☐	☐	☐	☐	☐	______

Q2	Center process mean on the target Process parameter adjustment	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
MS	Material properties are thoroughly studied and the interactions of those properties with process parameters are well understood during the material selection process.	☐	☐	☐	☐	☐	☐	______
PS	Impacts of process parameters on process mean are well understood during the product design phase.	☐	☐	☐	☐	☐	☐	______
	The characteristics of equipment on parameter control are well understood through the close collaboration with equipment vendors.	☐	☐	☐	☐	☐	☐	______

Q31	Reduce noise in process inputs **Conversion of common causes into assignable causes**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Conversion of common causes into assignable causes is recorded and stored in a database. This information is available to product designers and production engineering engineers.	☐	☐	☐	☐	☐	☐	______
	Plant environment is considered when the production site is decided.	☐	☐	☐	☐	☐	☐	______
P	Your company studies if any source of noise can be carried by purchased parts during the purchasing decision phase.	☐	☐	☐	☐	☐	☐	______
MS	Your company studies if any source of noise can come from the selected material.	☐	☐	☐	☐	☐	☐	______
PS	You carefully study the effect of noise on the output quality of the selected process.	☐	☐	☐	☐	☐	☐	______

Q32	Reduce impact of input noise on process output **Robust process design**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PA	Your company carefully studies how to make different processes robust to input noises for all types of products within a product family.	☐	☐	☐	☐	☐	☐	______
P	Purchased parts assembly processes are designed to be robust to the variation of purchased parts.	☐	☐	☐	☐	☐	☐	______
MS	Your company studies if the production process for a selected material is robust to the material property variation.	☐	☐	☐	☐	☐	☐	______
PS	Robust product and process design is considered when a selected process is significantly affected by noise.	☐	☐	☐	☐	☐	☐	______
DD	Products are designed to be robust to variation of process output caused by input noise.	☐	☐	☐	☐	☐	☐	______

FR111	Manufacture products to target design specifications Production processes with minimal variation from the target	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	There is a clearly defined communication channel with manufacturing, production engineering, and product design groups to solve quality problems caused by product/process design.	☐	☐	☐	☐	☐	☐	______
	Product designers understand what and how products are produced in a specific manufacturing site.	☐	☐	☐	☐	☐	☐	______
	Products are designed without internal errors (e.g., parts are designed to fit together).	☐	☐	☐	☐	☐	☐	______
	Manufacturing, production engineering, and product design engineers work together when setting tolerances.	☐	☐	☐	☐	☐	☐	______
PV	Similar level of tolerance is set for different product types within the same product family in order to avoid manufacturing complexity.	☐	☐	☐	☐	☐	☐	______
P	Tolerances for purchased parts are set through discussion with part suppliers.	☐	☐	☐	☐	☐	☐	______
MS	Meaningful tolerance levels according to the material types are well understood and reflected in material selection (e.g., achievable tolerance of wood is different from that of aluminum alloy).	☐	☐	☐	☐	☐	☐	______
PS	Impacts of process parameters on process capability are well understood and considered during product development (e.g., sensitivity of the process on a certain process parameter is studied.)	☐	☐	☐	☐	☐	☐	______
DD	Process capability (Cp) of the existing production line is known by product designers and reflected in design specifications.	☐	☐	☐	☐	☐	☐	______

R112	Identify disruptions where they occur Simplified material flow paths	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Material flow paths in the selected plant are well understood by product designers.	☐	☐	☐	☐	☐	☐	______
	Product design engineers know which value stream will be used for the production of new product	☐	☐	☐	☐	☐	☐	______

	Product design, production engineering, and manufacturing engineers work together to keep the simplicity of material flow paths even with the production of new product designs.	☐	☐	☐	☐	☐	☐	______
PV	Product family strategy and corresponding production facility planning are done concurrently.	☐	☐	☐	☐	☐	☐	______
	Product family decisions, product variety decisions, and product architecture decisions are made after considering the capability of the selected value stream and production site.	☐	☐	☐	☐	☐	☐	______
PA	Product architecture decisions are made after considering their impact on material flow paths.	☐	☐	☐	☐	☐	☐	______
P	The consequence of purchasing decisions on the material flow paths of the selected production site is studied.	☐	☐	☐	☐	☐	☐	______
PS	The impact of new processes (or new equipment for new process) on the material flow within a selected production site is thoroughly studied and simplest material flow paths are sought.	☐	☐	☐	☐	☐	☐	______
DD	Product designers understand the consequences of detailed design in the selected value stream.	☐	☐	☐	☐	☐	☐	______

R113	**Identify what the disruption is** **Feedback of sub-system state**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Failure modes are analyzed and categorized according to the root causes behind them. The gained information is stored and reviewed by product designers.	☐	☐	☐	☐	☐	☐	______
PV	The consequence of product variety decisions on the production disruption states of each station is studied.	☐	☐	☐	☐	☐	☐	______
MS	Possible disruption states due to new materials are studied and reflected in the feedback system (e.g., new material can damage tools in certain conditions, etc.).	☐	☐	☐	☐	☐	☐	______

PS	Possible disruption states due to new processes are studied and reflected in the feedback system (e.g., casting may show different types of disruptions from machining).	☐	☐	☐	☐	☐	☐	______
DD	Possible disruption states due to new detailed designs are studied and reflected in the feedback system.	☐	☐	☐	☐	☐	☐	______

R121	**Identify correct support resources** **Specified support resources for each failure mode**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	Manufacturing engineers know who to contact in product design and production engineering groups for product/process design related issues.	☐	☐	☐	☐	☐	☐	______
PV	The need for additional support personnel due to product variety is estimated and reflected in the product variety decision and the strategy decision to achieve the appropriate variety level (e.g., modular design, etc.)	☐	☐	☐	☐	☐	☐	______
PA	Specific support personnel are assigned to the failures related to product architecture.	☐	☐	☐	☐	☐	☐	______
P, MS	Specific support personnel are assigned to each failure mode related to purchased parts or materials at both your company and the part suppliers.	☐	☐	☐	☐	☐	☐	______
PS	Specific support personnel in manufacturing, production engineering, and product design groups are assigned to each failure mode related to the process.	☐	☐	☐	☐	☐	☐	______
DD	There are specific support resources in manufacturing, production engineering, and product design groups assigned to each failure mode related to detail designs.	☐	☐	☐	☐	☐	☐	______

R122	**Minimize delay in contacting correct support resources** **Rapid support contact procedure**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	A clearly defined communication channel between manufacturing, production engineering, and product design groups is planned to solve product design related production problems.	☐	☐	☐	☐	☐	☐	______
	Manufacturing engineers know how to contact product design and production engineering groups for product design related issues.	☐	☐	☐	☐	☐	☐	______
P	During purchasing decision, the communication channels with part suppliers are planned and reviewed to ensure a quick exchange of disruption information.	☐	☐	☐	☐	☐	☐	______

R13	**Solve problems immediately** **Standard method to identify and eliminate root causes**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	We create a knowledge base that contains past experience of problems and solutions. This knowledge base is extensively used during the problem solving processes.	☐	☐	☐	☐	☐	☐	______
	You study the database of previous failure modes to see if the product can be designed to minimize production disruptions.	☐	☐	☐	☐	☐	☐	______
PV	The consequence of product variety decision on standard method to resolve production disruption problems is reviewed in the product variety decision phase.	☐	☐	☐	☐	☐	☐	______
PA	Product architecture is designed in a way that the disruption related to the design of a component can be solved without affecting other components, which may enhance the speed of problem solving.	☐	☐	☐	☐	☐	☐	______
P	Part suppliers are evaluated based on their ability to immediately respond to and solve the disruption problems related to purchased parts.	☐	☐	☐	☐	☐	☐	______
	Standard procedures to solve the disruption problems associated with purchased parts are prepared in advance during product development.	☐	☐	☐	☐	☐	☐	______

		1	2	3	4	5	0	comments
MS	Standard procedures to solve the disruption problems associated with new material are prepared in advance during product development.	☐	☐	☐	☐	☐	☐	______
PS	Standard procedures to solve the disruption problems associated with new processes are prepared in advance during product development.	☐	☐	☐	☐	☐	☐	______
DD	Standard procedures to solve the disruption problems associated with detail designs are prepared in advance during product development.	☐	☐	☐	☐	☐	☐	______

P11	**Ensure availability of relevant production information** **Capable and reliable information system**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	Product design related information is available to operators and manufacturing engineers.	☐	☐	☐	☐	☐	☐	______
PV	Additional production information generated by planned product variety is studied. It is reviewed if total necessary production information can be processed with the capability of the existing information system.	☐	☐	☐	☐	☐	☐	______
P	The sharing of relevant production information with part suppliers is planned during product development.	☐	☐	☐	☐	☐	☐	______

P121	**Reduce variability of task completion time** **Standard work methods to provide repeatable processing time**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	Product design, production engineering, and manufacturing groups work together to eliminate sources of variability of task completion time.	☐	☐	☐	☐	☐	☐	______
PV	Operators may find it difficult to properly handle product variety. Standard work methods are designed to provide clear distinction between product types and obvious instruction of required tasks.	☐	☐	☐	☐	☐	☐	______

		1	2	3	4	5	0	comments
PA	We study the impact of a product architecture design (product layout) on assembly in terms of task completion time variation.	☐	☐	☐	☐	☐	☐	______
P	Task completion time variation related to the assembly of purchased parts is studied and the result is reflected in both purchasing decision and work method design.	☐	☐	☐	☐	☐	☐	______
MS	The effect of the introduction of new material on task completion time is reviewed during product development.	☐	☐	☐	☐	☐	☐	______
PS	The standardized work methods for a new process are developed to ensure a constant task completion time (e.g., fatigue, ergonomic issues, etc.)	☐	☐	☐	☐	☐	☐	______
DD	Detail design is reviewed to avoid designs that can cause variable task completion time.	☐	☐	☐	☐	☐	☐	______
	Parts are designed to be easy to handle.	☐	☐	☐	☐	☐	☐	______

P132	**Service equipment regularly** **Regular preventative maintenance program**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Preventative maintenance program is considered in capacity calculation when a production site decision is made during product development (e.g., no 3 shifts model when capacity is planned).	☐	☐	☐	☐	☐	☐	______
	The consequence of new product design on existing preventative maintenance programs is reviewed and appropriate changes are made accordingly.	☐	☐	☐	☐	☐	☐	______

P141	Ensure that parts are available to the material handlers **Standard work in process between sub-systems**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Use of 'off-the-shelf' parts is strongly recommended.	☐	☐	☐	☐	☐	☐	______
PV, PA	The consequence of product variety strategy (e.g., modular design) on the level of standard work in process (SWIP) is carefully studied during product development. Adequate level of SWIP is placed in the production site according to the study.	☐	☐	☐	☐	☐	☐	______
	Part sharing strategy is considered to minimize the SWIP between sub-systems.	☐	☐	☐	☐	☐	☐	______
PA	Product architecture design supports product variety strategies.	☐	☐	☐	☐	☐	☐	______
P	A proper level of SWIP for a purchased part is planned considering various factors such as transportation distance from the suppliers.	☐	☐	☐	☐	☐	☐	______
MS	It is reviewed if the selected material can be reliably supplied.	☐	☐	☐	☐	☐	☐	______
	Product designers strive to use commodity materials for reliable supply.	☐	☐	☐	☐	☐	☐	______
PS	The proper level of SWIP is planned for a new process.	☐	☐	☐	☐	☐	☐	______
DD	Detail design that enables part sharing (use of common component part within a product family) is considered.	☐	☐	☐	☐	☐	☐	______

P142	**Ensure proper timing of part arrivals** **Parts moved to downstream operations according to pace of customer demand**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	The impact of a product variety decision on part transportation is analyzed and reflected in product variety decisions.	☐	☐	☐	☐	☐	☐	______

PA	Part transportation methods, routes, and schedules according to the product architecture are carefully planned to ensure the part supply at proper timing during product development.	☐	☐	☐	☐	☐	☐	____
P	Delivery of purchased parts from the storage area to the point of use according to pace of customer demand is planned during product development.	☐	☐	☐	☐	☐	☐	____
MS	It is reviewed if new material can be supplied according to pace of customer demand in a just-in-time base.	☐	☐	☐	☐	☐	☐	____
PS	Transportation of the parts to and from the new process is planned in terms of frequency and part counts during product development, considering customer demand pace.	☐	☐	☐	☐	☐	☐	____

P14	**Ensure material availability even though fall out exists** **Standard material replenishment approach**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Product designers consider containers used in the selected production site. A special set of containers may be used if new products cannot be transported/stored with existing containers (e.g., dimension, chemical property, etc.).	☐	☐	☐	☐	☐	☐	____
	Number of parts that can be held in a container is considered with new product design. If the number of parts in a container has to be different from the current one, its consequence on the production line is thoroughly studied (e.g., AGVs may have to transport more containers, etc.).	☐	☐	☐	☐	☐	☐	____

T1	**Reduce lot delay** **Reduction of transfer batch size (single piece flow)**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Production engineering understands the consequence of using a batch size larger than one on production with a given product design (e.g., less flexibility, special fixtures, etc.).	☐	☐	☐	☐	☐	☐	____

		1	2	3	4	5	0	comments
PS	The characteristics of different production processes are considered to decide the adequate lot size (e.g., casting of small parts may be done in a batch). The decided lot size is then considered in the process selection.	☐	☐	☐	☐	☐	☐	______
	Minimum lot size is pursued with the introduction of new processes.	☐	☐	☐	☐	☐	☐	______

T21	**Define the desired production pace(s) (or takt time)** **Definition or grouping of customers to achieve desired production pace (or takt time) within an ideal range.**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	Product design, production engineering, and manufacturing groups work together to assign the production of new product designs to adequate production sites.	☐	☐	☐	☐	☐	☐	______
	Future enterprise-wide capacity planning information is available to the cross-functional product development team and used to determine production sites.	☐	☐	☐	☐	☐	☐	______
	Future capacity expansion is considered when a production site is selected (e.g., enough free space available?)	☐	☐	☐	☐	☐	☐	______
PV	Product family decision reflects estimated demand volume scenarios according to the customer groupings to achieve desired production pace (or takt time) within an ideal range.	☐	☐	☐	☐	☐	☐	______
	Strategies to facilitate product variety (e.g., component sharing) are considered to have the takt time within an ideal range.	☐	☐	☐	☐	☐	☐	______
PA	The consequence of product architecture decisions on takt time calculation is studied. For example, the customer demand volume for a specific component is decided by product architecture design.	☐	☐	☐	☐	☐	☐	______

T221	Ensure that automatic cycle time ≤ minimum desired production pace (or takt time) **Design of appropriate automatic work content at each station**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Product design, production engineering, and manufacturing groups work together to keep automatic cycle time less than takt time.	☐	☐	☐	☐	☐	☐	______
PV	Estimated automatic cycle times for different product types at each station are assured to be shorter than minimum takt time.	☐	☐	☐	☐	☐	☐	______
PA	Different product architecture options are studied when automatic cycle time is longer than minimum takt time.	☐	☐	☐	☐	☐	☐	______
MS	The consequence of new material on automatic cycle time is thoroughly studied. It is assured automatic cycle time with new material is shorter than minimum takt time. Otherwise, alternative materials are studied to keep automatic cycle time under minimum takt time.	☐	☐	☐	☐	☐	☐	______
PS	Estimated automatic cycle time of a new process is assured to be shorter than minimum takt time. Otherwise, alternative processes are considered.	☐	☐	☐	☐	☐	☐	______
	Production processes are allocated to each machine in a way that the total cycle time is less than minimum takt time. Otherwise, some of the processes are allocated to another machine.	☐	☐	☐	☐	☐	☐	______
DD	Detail design changes are sought to keep automatic cycle time under minimum takt time.	☐	☐	☐	☐	☐	☐	______

T222	Ensure that manual cycle time ≤ desired production pace (takt time) **Design of appropriate operator work content/loop**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Product design, production engineering, and manufacturing groups work together to keep manual cycle time less than takt time.	☐	☐	☐	☐	☐	☐	______
PV	Estimated manual cycle times for different product types at each station are assured to be shorter than minimum takt time.	☐	☐	☐	☐	☐	☐	______

PA	Different product architecture options are studied when manual cycle time is longer than minimum takt time.	☐	☐	☐	☐	☐	☐	______
MS	The consequence of new material on manual cycle time is thoroughly studied. It is assured manual cycle time with new material is shorter than minimum takt time. Otherwise, alternative materials are considered to keep manual cycle time under minimum takt time.	☐	☐	☐	☐	☐	☐	______
PS	Estimated average manual cycle time for a new process is assured to be shorter than minimum takt time. Otherwise, alternative processes are sought.	☐	☐	☐	☐	☐	☐	______
DD	Detail design changes are considered when manual cycle time is longer than desired production pace.	☐	☐	☐	☐	☐	☐	______

T223	**Ensure level cycle time mix** **Stagger production of parts with different cycle times**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	If different types of products are produced at the same station/machine, we do our best not to have their cycle times very different.	☐	☐	☐	☐	☐	☐	______
DD	If different types of products are to be produced at the same station/machine, product designers seek detail designs to make their cycle times similar.	☐	☐	☐	☐	☐	☐	______

T23	**Ensure that part arrival rate is equal to service rate** **Arrival of parts at downstream operations according to the pace of customer demand.**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	Balancing of different production groups (department or cell) to downstream operations is carefully coordinated according to the product variety strategy (e.g., modular product design) in order to assure proper part arrival rate.	☐	☐	☐	☐	☐	☐	______
PA	When product architecture is determined, material flows in the selected production site are planned and balancing of different production groups is sought. The balancing is reflected to product architecture design.	☐	☐	☐	☐	☐	☐	______

P	Purchased parts arrival rate to the point of use is determined according to the pace of customer demand. The amount of delivery per each shipment is determined considering other factors such as transportation distance and cost.	☐	☐	☐	☐	☐	☐	______

T31	Provide knowledge of demanded product mix (part types and quantities) **Information flow from downstream customer**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	More careful and complex handling of production mix information is required for more product variety. During the review process of various product variety strategies (e.g., modular design), the modification of information system according to the planned strategy is considered as a decision criterion.	☐	☐	☐	☐	☐	☐	______
PA	Product architecture is designed to support the selected product variety strategy to minimize the effective level of product variety.	☐	☐	☐	☐	☐	☐	______
P	The sharing of production mix information with part suppliers is reviewed and designed for sequenced delivery of parts in just-in-time base during purchasing plan phase.	☐	☐	☐	☐	☐	☐	______

T32	Produce in sufficiently small run sizes **Design quick changeover for material handling and equipment**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Changeover difficulties in manufacturing are well understood by product designers and production engineers.	☐	☐	☐	☐	☐	☐	______
PV	Product variety decision is made through close collaboration with manufacturing engineers considering mix-capability of selected production lines.	☐	☐	☐	☐	☐	☐	______
	A family of products is designed together to minimize set up changeover.	☐	☐	☐	☐	☐	☐	______

		1	2	3	4	5	0	comments
	When multiple product types are to be produced in a production line, manufacturing engineers always double check possible problems associated with setup changeover.	☐	☐	☐	☐	☐	☐	______
	You study if the mix flexibility of existing lines is adequate for planned product variety under the selected variety strategy (i.e., modular design).	☐	☐	☐	☐	☐	☐	______
PA	Product architecture is designed to support the selected product variety strategy to minimize the effective level of product variety.	☐	☐	☐	☐	☐	☐	______
	Product variety is achieved by attaching different components to a common body rather than using different bodies, which eliminates need for changeover itself.	☐	☐	☐	☐	☐	☐	______
MS	New material that helps quick changeover is continuously sought to support production (e.g., new painting material that support changeover between colors).	☐	☐	☐	☐	☐	☐	______
PS	New process to support quick changeover or eliminate changeover itself is sought in case of high level of product variety during product development.	☐	☐	☐	☐	☐	☐	______
DD	Product design engineers strive for minimizing setup changeover by changing detail designs (e.g., standardizing the location of holes of various products to eliminate the stamping die changeover).	☐	☐	☐	☐	☐	☐	______

T4	**Reduce transportation delay** **Material flow oriented layout design**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	Product designers understand the difference between material flow oriented layout design (cellular or lean) and process oriented departmental layout design (mass).	☐	☐	☐	☐	☐	☐	______
PA	Product designers understand how the product architecture may affect existing plant layout designs and reflect it during the product architecture design.	☐	☐	☐	☐	☐	☐	______
P	Direct delivery of purchased parts to the point of use is considered as a part supply method during product development.	☐	☐	☐	☐	☐	☐	______

T5	Reduce systematic operational delays **Subsystem design to avoid production interruption**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PS	A new process is considered to eliminate the need for supportive activities (e.g., using laser trimming instead of stamping will eliminate the need for die transportation activity).	☐	☐	☐	☐	☐	☐	______
DD	Products are designed to eliminate the need for some supporting activities (e.g., standardizing hole location in stamping process eliminates the need for die changeover and thus, die transportation activity).	☐	☐	☐	☐	☐	☐	______

D11	**Reduce time operators spend on non-value added tasks at each station** **Machines and stations designed to run autonomously**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PS	Feasibility of automating new processes is carefully studied.	☐	☐	☐	☐	☐	☐	______
DD	Product designers consider automated processes and reflect them into detail design to facilitate autonomous run of equipment.	☐	☐	☐	☐	☐	☐	______

D22	**Minimize wasted motion in operators' work preparation** **Standard tools/equipment located at each station (5S)**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	Tool requirements for planned product variety are estimated during product development.	☐	☐	☐	☐	☐	☐	______
MS	The special tool requirement of new material is studied and its standardization is pursued. If special tools are necessary, they are prepared and located at designated locations considering timing of use and sharing.	☐	☐	☐	☐	☐	☐	______

PS	Tools necessary for new process are identified and their storage is planned considering various factors such as the frequency of changeover and operators' walking distance.	☐	☐	☐	☐	☐	☐	______
DD	The consequence of detail design on tool requirements is studied and reflected in the current set of standard tools.	☐	☐	☐	☐	☐	☐	______

D23	**Minimize wasted motion in operators' work tasks** **Ergonomic interface between the worker, machine, and fixture**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	Product designers and production engineers take ergonomic issues associated with production of new products into consideration.	☐	☐	☐	☐	☐	☐	______
PV	Product variety may require various work tasks performed at each station. All work tasks are designed to be ergonomic and machine & fixture support ergonomic work tasks.	☐	☐	☐	☐	☐	☐	______
MS	You study if a new material affects the existing ergonomic design of interfaces between machine, fixture, and people.	☐	☐	☐	☐	☐	☐	______
DD	We study the impact of detailed designs on ergonomic interfaces and seek for a design to support the ergonomic interfaces.	☐	☐	☐	☐	☐	☐	______

D3	**Eliminate operators' waiting on other operators** **Balanced work-loops**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
G	When process cycle time needs to be adjusted due to balancing problems, product designers consider product design changes as one of options.	☐	☐	☐	☐	☐	☐	______
MS	The effect of new material on existing operator work loops is studied and reflected during material selection process.	☐	☐	☐	☐	☐	☐	______

		strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PS	The impact of new processes on existing operator work loops is thoroughly studied.	☐	☐	☐	☐	☐	☐	______
DD	You study if operators' work loops are balanced for new detail design. If not, minor detail design modification is sought to regain the balance.	☐	☐	☐	☐	☐	☐	______

FR122	**Reduce waste in indirect labor** **Reduction of indirect labor tasks**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
PV	Higher level of product variety usually requires more indirect labor to coordinate complicated work tasks necessary (e.g., more complex scheduling). The consequence of product variety decisions on indirect labor requirement is studied thoroughly.	☐	☐	☐	☐	☐	☐	______
PA	We study the impact of product architecture on indirect labor requirement for information management.	☐	☐	☐	☐	☐	☐	______
P	It is reviewed how a purchasing decision affects the existing work of purchasing department. The impact of new purchasing decisions on the capacity and capability of purchasing functional group is considered.	☐	☐	☐	☐	☐	☐	______
MS	The consequence of the use of new material on indirect labor requirement is reviewed and considered during material selection process (e.g., special material may require indirect labor to inspect and store it).	☐	☐	☐	☐	☐	☐	______
PS	The consequence of the introduction of new processes on indirect labor requirement is thoroughly studied and reflected in process selection (e.g., laser cutting substituting stamping eliminates the need for indirect labors that transport/maintain dies used in stamping).	☐	☐	☐	☐	☐	☐	______
DD	The consequence of new detail design on indirect labor requirement is studied and reflected in design.	☐	☐	☐	☐	☐	☐	______

I2	**Eliminate information disruption** **Seamless information flow (visual factory)**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
PV	Under high product variety, information flow management can be very difficult. The impact of product variety strategy (e.g., modular design) on information flow is studied and reflected in product variety decision process.	☐	☐	☐	☐	☐	☐	______
P	The information flow to and from suppliers is reviewed and sources of information disruption are identified and eliminated.	☐	☐	☐	☐	☐	☐	______
MS	The effect of the introduction of new material on information flow is studied	☐	☐	☐	☐	☐	☐	______
PS	The effect of new processes on information flow is studied (i.e., laser cutting substituting stamping eliminates the need for die changeover information flow).	☐	☐	☐	☐	☐	☐	______
DD	The effect of new detailed design on information flow is studied (e.g., communizing hoe location in stamping process eliminates the information flow for die changeover).	☐	☐	☐	☐	☐	☐	______

FR123	**Minimize facility cost** **Reduction of consumed floor space**	strongly disagree 1	2	— 3	4	strongly agree 5	does not apply 0	comments
PV	The impact of product variety on consumed floor space is studied. Product variety may lead to increased level of WIP or more tools/equipment to be used, which take floor space.	☐	☐	☐	☐	☐	☐	______
PA	We study the impact of a product architecture design on consumed floor space.	☐	☐	☐	☐	☐	☐	______
P	Storage areas for purchased parts are planned and minimization of them is pursued while meeting the requirements from other MSDD branches during product development.	☐	☐	☐	☐	☐	☐	______

		1	2	3	4	5	0	comments
MS	You study if the use of a new material requires additional space for storage and if there is space available in the selected production site.	☐	☐	☐	☐	☐	☐	______
PS	The effect of new processes on floor space consumption is reviewed.	☐	☐	☐	☐	☐	☐	______
DD	The effect of new detail design on floor space consumption is reviewed. Detail design is modified to reduce floor space consumption by supporting component sharing, etc.	☐	☐	☐	☐	☐	☐	______

FR13	**Minimize investment over production system life cycle** **Investment based on a long term strategy**	strongly disagree 1	2	3	4	strongly agree 5	does not apply 0	comments
G	Minimization of new investment is sought.	☐	☐	☐	☐	☐	☐	______
	Net present value (NPV) analysis is made to estimate the economic impact of decisions made during product development.	☐	☐	☐	☐	☐	☐	______
	Economic benefit of operation improvement (quality, delivery time, etc.) is considered in the NPV analysis.	☐	☐	☐	☐	☐	☐	______