DEVELOPMENT OF AN AEROSPACE MANUFACTURING SYSTEM DESIGN DECOMPOSITION

by

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Submitted to the Department of Mechanical Engineering
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ABSTRACT

The Manufacturing System Design Decomposition (MSDD) has been identified by the Lean Aerospace Initiative and aerospace industry members as a possible tool for guiding the development of future manufacturing systems. Industry members however, have had reservations that the MSDD does not fully address the unique needs of the aerospace industry. This thesis presents the development of a new Aerospace Manufacturing System Design Decomposition (AMSDD) and illustrates how the AMSDD can be used as a tool to design and evaluate aerospace manufacturing systems.

First, the MSDD is presented and the decomposition approach is explained. Results are then presented from a series of visits to aerospace manufacturing facilities. These visits were used to collect feedback from industry members regarding the applicability of the MSDD to each site. The feedback from all of the sites is analyzed to determine whether sections of the MSDD should be modified, left alone, or expanded upon. The AMSDD is developed using this industry feedback. Additions to the AMSDD include a new top-level corporate goal and two new sections, Continuous Improvement and Product Design. The new top-level goal is to increase shareholder value by increasing the net present value of the company. The new sections result from industry comments stressing the importance of feedback and product design in a manufacturing system.

Finally, the AMSDD is used to develop an Aerospace Manufacturing System Design Evaluation Tool. The purpose of this tool is to provide the aerospace industry with a way to evaluate current manufacturing system designs and highlight ways to improve these designs. The Eval Tool is then used to evaluate three manufacturing system designs and suggest ways that military procurement policies may have affected these designs. The goal of this analysis is to illustrate how the Eval Tool can also be used to identify procurement policy changes necessary to improve the design of military aerospace manufacturing systems.

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Executive Summary

The Manufacturing System Design Decomposition (MSDD) decomposes the top-level goal of a company into lower-level requirements and design solutions. This decomposition process results in a generalized manufacturing system design. The generic manufacturing system design represented by the MSDD is intended to apply to manufacturing systems in a broad range of industries, rather than to a specific manufacturing system. The MSDD represents relationships that exist in any manufacturing system. These relationships affect production quality, throughput time, cost, and production investment.

When the MSDD was presented to the aerospace industry, many people expressed great interest in its implications for the industry. The MSDD was received as a possible new tool that could be used for developing future aerospace manufacturing systems. The MSDD was also viewed as a tool that could be used to understand the impact of military procurement policies on the design of aerospace manufacturing systems. While members of the aerospace industry believed that the MSDD approach was a valuable one, there was concern that a model developed from the automotive industry could not be applied to aerospace manufacturing. In response to these concerns, a research project was undertaken to develop an Aerospace Manufacturing System Design Decomposition (AMSDD). The author's hypothesis was that the resulting AMSDD would be very similar to the original MSDD.

The AMSDD was developed through extensive research at six aerospace manufacturing sites. The MSDD was used as the basis for the research and provided a framework for data collection. Structured interviews took place at aerospace manufacturing facilities producing products that included military and commercial aircraft, space launch vehicles, satellites, and electronic systems. In order to capture multiple perspectives, interviewees included multiple engineers and managers from each organization that was visited.

This research has resulted in several additions to the AMSDD, but the author argues that the original hypothesis has been proven true. The new additions presented in the AMSDD have not changed significantly the content of the original MSDD. Instead, the AMSDD has added sections to address needs of the aerospace industry that had not been explicitly addressed by the MSDD. Development of the AMSDD has built upon the existing MSDD and did not require a complete reconstruction.

The close similarities between the MSDD and the AMSDD show that many of the challenges faced by the aerospace industry are shared by the automotive and consumer products industries for which the MSDD was originally developed. In other words, many of the manufacturing system design issues that must be addressed by the aerospace industry are common to other industries with repetitive, discrete part manufacturing. Many aerospace industry members had doubted the applicability of the MSDD because of the higher volumes associated with the automotive and consumer products industries. The similarity of the AMSDD and MSDD illustrates that the manufacturing system design relationships within these manufacturing systems are independent of volume.

The changes that were made to the AMSDD as a result of aerospace industry feedback are not necessarily unique to the aerospace industry. This commonality further supports the claim that the manufacturing system design relationships that exist in the aerospace industry are common to other industries. The new concepts that were added at the suggestion of aerospace industry members, however, do reveal a focus on different manufacturing issues between the aerospace industry and automotive or consumer product industries. The impact of product design on manufacturing system design was consistently pointed to as missing from the MSDD. The impact of product design on manufacturing system design is very important to the automotive industry. A couple of possible reasons that this omission has gone largely unnoticed by the higher volume industries, but not the aerospace industry, are that:

- In many of the higher volume industries, tens of thousands of the exact same product are produced between design changes. These high-repetition production runs may allow manufacturing engineers to spend more of their time fine-tuning manufacturing processes, rather than readjusting equipment and process plans to accommodate design changes.
- In the aerospace industry, on the other hand, production volumes may be a single unit for highly customized products or several hundred units for relatively high-volume products. Aerospace manufacturing engineers, therefore, may spend a considerably higher percentage of their time determining how to manufacture new products and implementing design changes to existing products.

Most of the aerospace industry members who were interviewed were interested in learning improved manufacturing methods from other industries. Some of these engineers and managers were critical of the aerospace industry for not improving its manufacturing system designs and for making too many excuses why these manufacturing systems couldn't be improved. The feeling among these interviewees was that the aerospace industry could use the MSDD to design manufacturing systems if the industry was willing to discipline itself. One plant manager explained that the manufacturing system at his plant had evolved over time. He said that the system is designed as though it had been extrapolated from a small engineering project into a company. He suggested that the MSDD could be a useful tool for guiding the design of aerospace manufacturing systems. On the other hand, some industry members questioned the value of focusing on manufacturing system design, which they cited as only 10 percent of the total cost of a program. They believed that their efforts would be better spent on other areas in the company, such as overhead reduction and improving product design. Other industry members, however, countered this argument by saying that improving the manufacturing system would drive other improvements within the company.

Some aerospace industry members may initially question how well the AMSDD applies to the entire industry, because a large number of the sites visited were in the space sector. The actual breakdown was half aircraft and half space sector sites. At these sites, some electronics assembly work was observed. No sites from the engine sector were visited for this research. Nonetheless, it is assumed that the AMSDD developed in this thesis is applicable to all sectors of the aerospace industry. This assumption is based upon the fact that the AMSDD and the MSDD, although developed for very different industries, are very similar. Sectors within the aerospace industry vary widely, but it is arguable that the space sector is the least similar to the industries used for the original MSDD. The space sector frequently produces custom designed products and may experience multiple design changes during the production of a single product design.

Therefore, if the AMSDD can be applied to the space sector, it is likely that the AMSDD applies to the entire aerospace industry.

The sample analysis of three space sector manufacturing systems, using the Eval Tool developed in this thesis, revealed that the manufacturing system of Plant C corresponded to the AMSDD much closer than the manufacturing systems of the other two sites did. The key difference between Plant C and the other plants was that Plant C was designed primarily for its commercial business. The products at all three plants are sold to both military and commercial customers, so Plant C, along with the other sites, received military funding for tooling and had to conform to military procurement policies. When designing its manufacturing system, however, Plant C invested a large amount of its own capital to lay out the entire factory to minimize transportation. Plant C also designed manufacturing processes to enable the product to be paced according to takt time. By designing the entire manufacturing system, instead of focusing solely on individual processes, Plant C was able to better satisfy the functional requirements of the AMSDD. This result suggests two important implications for military procurement policies:

- First, the military should be more actively concerned about the actual manufacturing system with which its products are produced and how that system is designed.
- Second, for purely military programs, following the AMSDD may require significant changes to military procurement policies. Plant C was able to justify the risk of investing its own capital to design the overall manufacturing system, because of the profit expected from the commercial business. In a purely military program, the government must be more willing to share in potential risks as well as benefits of cost saving programs. A company is not likely to invest its own capital into manufacturing system improvements if the benefits are absorbed by the government during the next procurement cycle.

There are several strengths and weaknesses associated with using an Axiomatic Design approach to manufacturing system design. The Aerospace Manufacturing System Design Decomposition provides a way to see and understand how specific shop floor practices contribute to achieving the top-level goals of a company. The AMSDD also reveals the interrelationships between practices within a manufacturing system. A weakness of the AMSDD is that it is not an implementation methodology. It is not possible to use the AMSDD as an ordered set of steps to follow when designing a manufacturing system. Another weakness is that the AMSDD may initially be non-intuitive and intimidating. Manufacturing system designers must make an effort to understand the Axiomatic Design methodology and to be able to understand the AMSDD.

The Eval Tool developed in this thesis is best suited for use by a company that is attempting to use the AMSDD to guide the development of its manufacturing system. The key to using the Eval Tool is to understand the tool's relationship to the AMSDD. When the Eval Tool is used to identify weaknesses in a company's manufacturing system, the company should refer back to the AMSDD to understand the interrelationships that affect the deficient areas. Efforts should then be applied to improve all of the practices that affect the categories that the Eval Tool identified as needing improvement. A company is unlikely to succeed at improving its performance if improvement attempts focus solely on the individual categories that score poorly.

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The past several years in graduate school have been a time of growth and development in my life, both professionally and personally. My time in the Production System Design Laboratory and in the Lean Aerospace Initiative have provided me with an amazing number of experiences with a wide range of manufacturing systems in an equally wide range of settings. I had always thought of manufacturing as some mysterious "black box." I had never really thought that I'd understand how a car or a plane could be built from raw materials – nevermind designing the entire manufacturing system, too.

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Chapter 1 Introduction

1.1 Motivation

This thesis addresses the need for companies in the aerospace industry to develop new manufacturing systems from a high-level *systems* perspective. Traditionally, the aerospace industry has been driven by high product performance requirements. This history has resulted in a strong product focus and subjugated many production issues to product concerns. For example, continuous design upgrades and changes may result in a product having the most modern capabilities available, but makes manufacturing very difficult. This thesis attempts to illustrate the attributes of a manufacturing system design that considers the product-oriented nature of the aerospace industry while addressing production issues from a high-level systems perspective.

The research program undertaken for this thesis was developed as a collaborative effort between the Lean Aerospace Initiative (LAI), and the Production System Design (PSD) Laboratory, both at MIT. The LAI has focused its research on identifying best practices from "lean" manufacturing that are applicable to the aerospace industry, as well as potential barriers to implementation. [Wang, 1999] The PSD Laboratory has pursued approaches to manufacturing system design based upon an Axiomatic Design methodology. [Suh, 1990; Cochran, 1994; Cochran and Dobbs, 2000b] A prior research effort to apply Axiomatic Design to the aerospace industry by the LAI and PSD Laboratory was presented in Andrew Wang's Master's Thesis [1999] on the *Design and Analysis of Production Systems in Aircraft Assembly*. In his thesis, Wang used an Axiomatic Design approach to develop a manufacturing system design decomposition[1] that describes the current design of military aircraft production systems. This research identified several barriers to implementing "lean" manufacturing practices and

[1] In this thesis, the term decomposition refers to a process in which objectives are broken down into sub-objectives. Satisfying all of a series of sub-objectives will ensure that the original objective is satisfied. The decomposition process can be iterated as many times as necessary until objectives and sub-objectives can be easily understood by the designer. In Axiomatic Design, decomposition refers to defining the Functional Requirements (FRs), i.e. objectives, of a system and the Design Parameters (DPs), i.e. means, for achieving the FRs.

contrasted the military manufacturing system against a Manufacturing System Design Decomposition (MSDD) approach.

1.2 The Manufacturing System Design Decomposition

The Manufacturing System Design Decomposition (MSDD), originally called the Production System Design Decomposition, was developed by the Production System Design Laboratory. [Carrus and Cochran, 1998; Suh et al, 1998; Cochran, 1999] The purpose of the MSDD is to "clarify the objectives, to design solutions, and to assist industry in developing better" manufacturing systems. [Cochran and Dobbs, 2000b, p. 359] The Manufacturing System Design Decomposition is the result of following an Axiomatic Design methodology. [Suh, 1990] The MSDD *decomposes* the top-level goal of a company into lower-level requirements and design solutions. This decomposition process results in a generalized manufacturing system design. The general manufacturing system design relationships represented by the MSDD are intended to apply to repetitive, discrete part manufacturing systems in a broad range of industries, rather than to a specific manufacturing system. The MSDD represents relationships that exist in any manufacturing system. These relationships affect production quality, throughput time, cost, and production investment.

It is hoped that the thinking represented by the MSDD will be used as an approach to help guide the design and development of many different types of repetitive, discrete part manufacturing systems. The MSDD should not be seen as an implementation methodology that can be followed step-by-step when designing a new manufacturing system. Designers should use the MSDD as a *lens* through which the overall manufacturing system design is observed. If an existing manufacturing system design does not closely correspond to the MSDD, comparison with the MSDD can help to identify solutions that will allow the system to better meet the objectives represented by the MSDD.

Although it was largely based upon research in the automotive industry, the MSDD was intended to apply to a broad range of industries repetitively producing discrete products. [Cochran, 1999] (As opposed to continuous manufacturing processes, such as oil refining, steel processing, etc.) When the MSDD was presented to the aerospace industry, many people expressed great interest in the MSDD and its implications for the industry. [Lean Aerospace Initiative, 1998b] The

MSDD was received as a possible new tool that could be used for developing future aerospace manufacturing systems. The MSDD was also viewed as a tool that could be used to understand the impact of military procurement policies on the design of aerospace manufacturing systems. The edict from the military leadership was to describe the activities and policies within the military that cause military contractors to not be "lean." [Lean Aerospace Initiative, 1998a]

While members of the aerospace industry believed that the MSDD approach was a valuable one, there was concern that a model based on design relationships apropos to the automotive industry and the consumer product manufacturing industry could not be applied to aerospace manufacturing. The research upon which this thesis is based is in response to the above concerns.

This thesis seeks to answer the above questions. To answer these questions, an Aerospace Manufacturing System Design Decomposition (AMSDD) is developed. The hypothesis is that the resulting AMSDD will be very similar to the original MSDD. This hypothesis assumes that the design relationships illustrated by the MSDD apply to a wide range of repetitive, discrete product manufacturing systems – including the aerospace industry. If the AMSDD and MSDD are very similar, this hypothesis will be proven.

After developing the AMSDD, this thesis revisits Andrew Wang's work to see how the AMSDD compares with the "as-is" decomposition developed by Wang [1999]. In addition, an Aerospace Manufacturing System Design Evaluation Tool is developed as a potential means for evaluating current manufacturing system designs and evaluating areas that need improvement. It is further proposed that this Evaluation Tool could be used to identify the impact of procurement policies on manufacturing system designs. By comparing evaluations of multiple military aerospace manufacturing systems, it may be possible to discern trends that result from military procurement policies.

1.3 Approach for Developing the Aerospace Manufacturing System Design Decomposition

The AMSDD was developed through extensive research at many aerospace manufacturing companies. The MSDD was used as the basis for the research and provided a framework for data collection. Over fifty structured interviews took place at aerospace manufacturing facilities producing products that included military and commercial aircraft, space launch vehicles, satellites, and electronic systems. In order to capture multiple perspectives, interviewees included multiple engineers and managers from each organization that was visited.

The interviews first familiarized participants with Axiomatic Design and the motivation for developing a manufacturing system design decomposition. Interviewees were then taken step-by-step through a detailed explanation of the MSDD. The participants were asked to suggest changes that would enable the MSDD to better illustrate the manufacturing system requirements present at each site. After collecting the data, the manufacturing system requirements and means that were found to be missing from the MSDD were integrated into the new AMSDD.

1.4 Chapter Overviews

Chapter 2 explains the motivation for developing the Manufacturing System Design Decomposition and describes the Axiomatic Design process used to develop the MSDD. A detailed description of the entire MSDD is presented to familiarize readers with the assumptions underlying the MSDD and to clarify the intentions of each Functional Requirement (FR) and Design Parameter (DP) selected.

Chapter 3 presents a compilation of the feedback obtained from industry members regarding the applicability of the MSDD to the aerospace industry. The feedback highlights concerns that are unique to the aerospace industry, describes which suggestions for improvements have been added to the AMSDD, and explains why.

Chapter 4 develops the new Aerospace Manufacturing System Design Decomposition while considering the issues presented in Chapter 3. The chapter focuses upon the FRs and DPs that have changed from the original MSDD.

Chapter 5 compares the AMSDD to the Military Manufacturing System Design Decomposition, developed by Wang [1999], to illustrate opportunities to improve military procurement policies. The chapter then presents the Aerospace Manufacturing System Design Evaluation Tool (Eval Tool) and explains how the Eval Tool can be used. The Eval Tool is used to evaluate the manufacturing system designs of three plants visited during development of the AMSDD. Analysis of the evaluation results is used to illustrate how the Eval Tool can be used to highlight strengths and weaknesses of manufacturing systems. This analysis is then used to develop possible links between the evaluated manufacturing system designs and government procurement policies.

Chapter 6 draws conclusions from the research results, and identifies areas for future research.

Chapter 2 The Manufacturing System Design Decomposition

2.1 Introduction

Designing a manufacturing system to achieve a set of strategic objectives involves making a series of decisions over time [Hayes and Wheelwright, 1979]. Manufacturing systems contain many variables with initially unknown interdependencies. Making design decisions in a way that supports a firm's high-level objectives requires an understanding of how detailed design issues affect the interactions among various components of a manufacturing system. [Cochran et al, 2000] These interactions must be made visible and understood by designers to help them develop a successful system implementation strategy. Successful implementation requires that designers understand that the manufacturing system consists of more than a series of processes designed to fabricate and assemble a product. The complete manufacturing system consists of the "arrangement and operation of machines, tools, material, people and information to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters." [Cochran and Dobbs, 2000a] Cochran et al [2000] define the process of manufacturing system design as:

> All aspects of creating and operating a manufacturing system. Creating the system includes equipment selection, physical arrangement of equipment, work design (manual and automatic), standardization, design of material and information flow etc. The result of the creating process is the factory as it looks in a snapshot of time. Operation includes all aspects that are necessary to run the created factory.

Problems often occur when companies try to implement tools from one manufacturing system design or partial solutions without first understanding how the solutions fit into a complete manufacturing system design. Many companies have tried unsuccessfully to implement aspects of the Toyota Production System (TPS) because they have confused the tools and practices of TPS with the system itself. [Spear and Bowen, 1999] For example, implementing a kanban system is not a guaranteed way to improve the operation of a manufacturing system. Shingo

[1989] describes kanban as a means for putting TPS into practice, but stresses that development of a kanban system flows naturally from the thinking implicit in TPS.

The Manufacturing System Design Decomposition, referred to in this thesis as the MSDD, provides a systematic method of identifying business objectives (Functional Requirements) and the means (Design Parameters) to achieve those objectives. [Cochran, 1999] The MSDD is intended for use as a conceptual tool that guides the thinking of manufacturing system designers, rather than as a step-by-step design methodology. The MSDD illustrates relationships that exist in every manufacturing system and affect production quality, throughput time, cost, and capital investment. The MSDD can be used to help designers understand how the decisions that they make impact a manufacturing system's ability to meet high-level business objectives. For this reason, the functional requirements (objectives) and design parameters (means) presented by the MSDD are generalized in order to apply to a wide range of manufacturing systems. [Kuest, 1999]

2.2 Axiomatic Design

The Manufacturing System Design Decomposition was developed by applying an Axiomatic Design methodology. Axiomatic Design defines design as the "creation of synthesized solutions in the form of products, processes, or systems that satisfy perceived needs through *mapping*" between Functional Requirements (FRs) and Design Parameters (DPs). [Suh, 1990] The two design axioms are the Independence Axiom and the Information Axiom. The Independence Axiom states that a good design must *maintain the independence of the functional requirements.* The Information Axiom requires *minimizing the information content of the design.* To accomplish independence of the Functional Requirements requires determining a physical design implementation (or solution), called a Design Parameter (DP), that affects only one Functional Requirement (FR). Independence also means that the definition and selection of the FRs must be independent.

Zigzagging

The first step in Axiomatic Design of manufacturing systems is defining the top level FRs for the manufacturing system being designed. Next, specific Design Parameters must be determined. This process is called zigzagging. The "zig" in zigzagging means translating Functional

Requirements to Design Parameters at the same level in the design hierarchy. If axiom 1 is observed, the definition of the FRs for the next level of the design decomposition can begin. "Zag" means going from the Design Parameters of a parent level to the Functional Requirements of the next level. It is not possible to decompose the functional hierarchy unless the FRs of the next level satisfy the context of the parent DP level. Figure 2.1 illustrates the process of zigzagging. It should be noted that this process is not linear and may require several iterations.

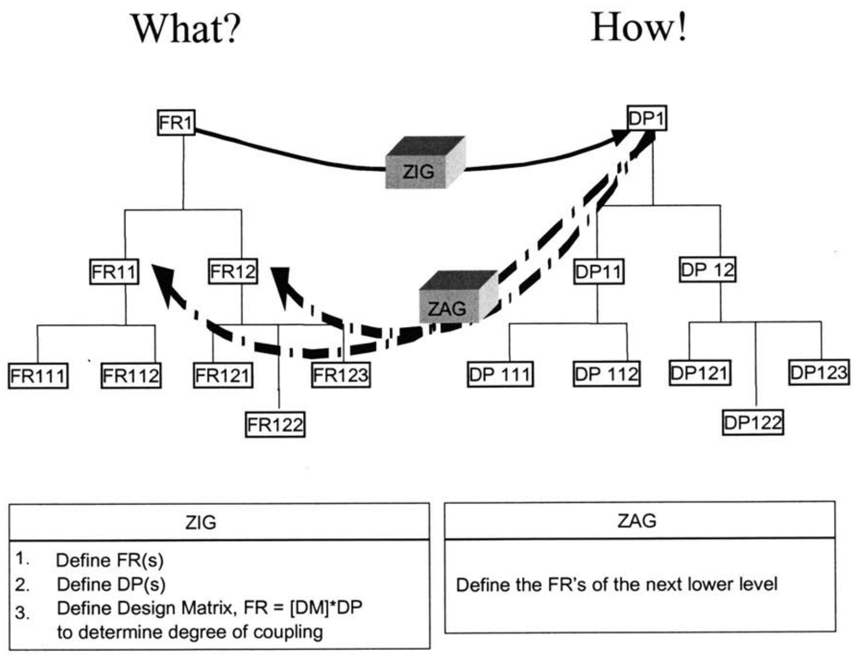


Figure 2.1 Zigzagging [Linck, 1996]

Design Matrices

To determine whether the first Axiom has been achieved, and whether decomposition to the next lower level can proceed, the relationship between the FRs and DPs must be expressed in terms of a design matrix. The design that constitutes the FR-DP relationships may be of three types: uncoupled, partially coupled, and coupled. Figure 2.2 illustrates the three types of design matrices. Further decomposition is not possible until the design relationship is shown to be uncoupled or partially coupled.

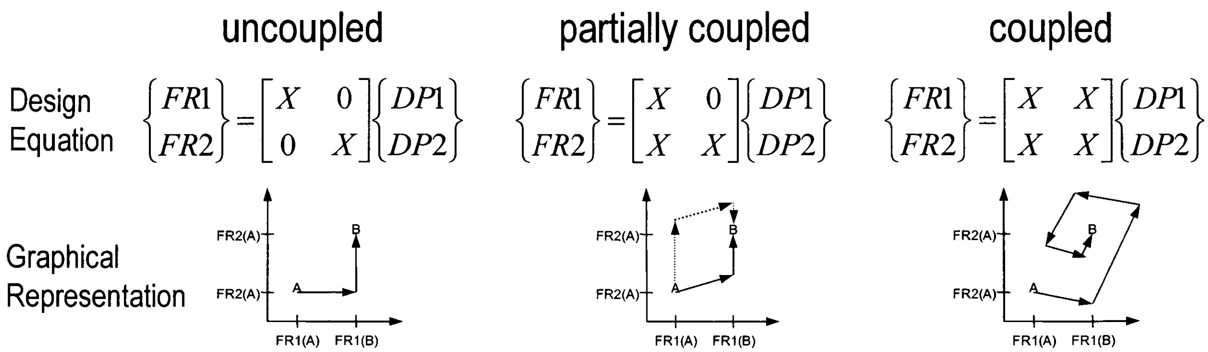


Figure 2.2: Design Matrices [Cochran, 1994; Wang, 1999]

An uncoupled design is represented by a diagonal matrix. X's represent the relationships between the FRs and DPs. An uncoupled design ensures that the chosen DPs independently impact the FRs. When implementing an uncoupled design, the DPs may be performed in any order. [Suh et al, 1998]

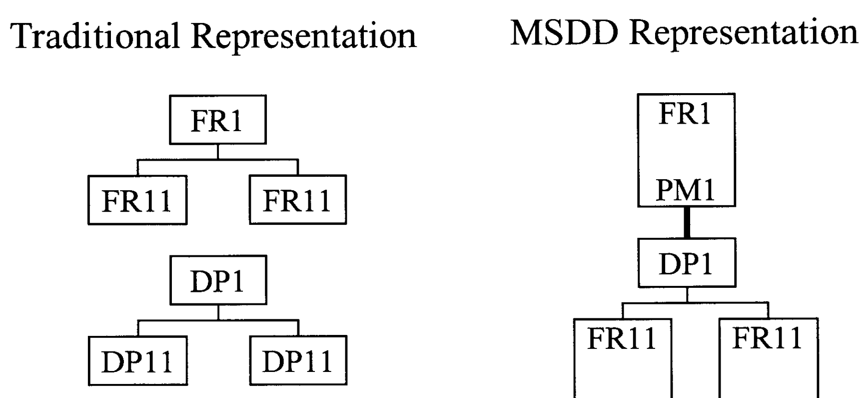
In a partially coupled design, one or more FRs are affected by more than one DP. A partially coupled design is represented by an upper or lower triangular matrix. A partially coupled design is path dependent. This dependency means that the order of DP implementation is critical. For example, when implementing a partially coupled design, the DPs should be implemented so that the DP that affects the most FRs is implemented first. In the partially coupled matrix, the order of DP implementation is DP1 then DP2. Independence is achieved by virtue of the implementation path.

A coupled design matrix does not maintain independence of the FRs.

Although Axiomatic Design indicates that in a partially coupled design DPs that affect the most FRs should be implemented first, this is not always possible. For example, in the top levels of the MSDD, shown in Figure 2.4, the relationship between FR11, FR12, FR13, and DP11, DP12, and DP13 is a partially coupled design. This partial coupling indicates that the order of implementation should be DP11, DP12, then DP13. In reality, it would not be possible to implement the DPs in this order, because one could not begin DP11, "Production to maximize customer satisfaction," before making an investment in the manufacturing system, DP13. Therefore, in manufacturing system design, the coupling indicates which DPs should be *considered* first. In the case of FR/DP11 through FR/DP13, a manufacturing system designer would first consider how to maximize customer satisfaction, then how to eliminate non-value adding sources of cost, and finally how to minimize long-term investment.

2.3 The Manufacturing System Design Decomposition

The MSDD uses a graphical representation of coupling between DPs and FRs, which varies slightly from the traditional Axiomatic Design representation, which uses design matrices. Figure 2.3 illustrates the traditional representation of an FR/DP pair and its decomposition into sub-FR/DPs.



$$\begin{Bmatrix} FR11 \\ FR12 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \end{Bmatrix}$$

Figure 2.3: Traditional and MSDD Representation of FRs and DPs

The traditional representation separates the FRs and the DPs into two separate structures and requires that design matrices be shown to illustrate the coupling between FRs and DPs. The MSDD representation groups each FR with the DP that satisfies it, connecting them with a dark line. Coupling is illustrated by a dashed arrow from a DP to an FR. The MSDD also includes performance measurements (PMs) that can be used to evaluate whether each FR has been achieved. Including PMs helps to make the MSDD a useful tool for guiding manufacturing system design, because the decomposition illustrates the manufacturing system objectives (FRs), the means of achieving the objectives (DPs), and a way to measure how well the objectives have been achieved (PMs).

The layout of the MSDD is arranged so that the DPs that affect the most FRs are on the left-hand side. This arrangement helps designers to understand which DPs, as a result of coupling, have the greatest impact on the FRs of the overall manufacturing system design as well as the FRs within a section of the MSDD. The arrangement is not meant to imply that FRs and DPs towards the right-hand side of the MSDD are less important than FRs and DPs on the left.

The MSDD presented in this thesis is MSDD version 5.1. A full decomposition of version 5.1 can be found in Appendix A. The Aerospace Manufacturing System Design Decomposition is based on MSDD v.5.1, but uses data collected from interviews using MSDD version 5.0. The MSDD version 5.0 can be found in Appendix B.

2.3.1 Upper-level FRs & DPs

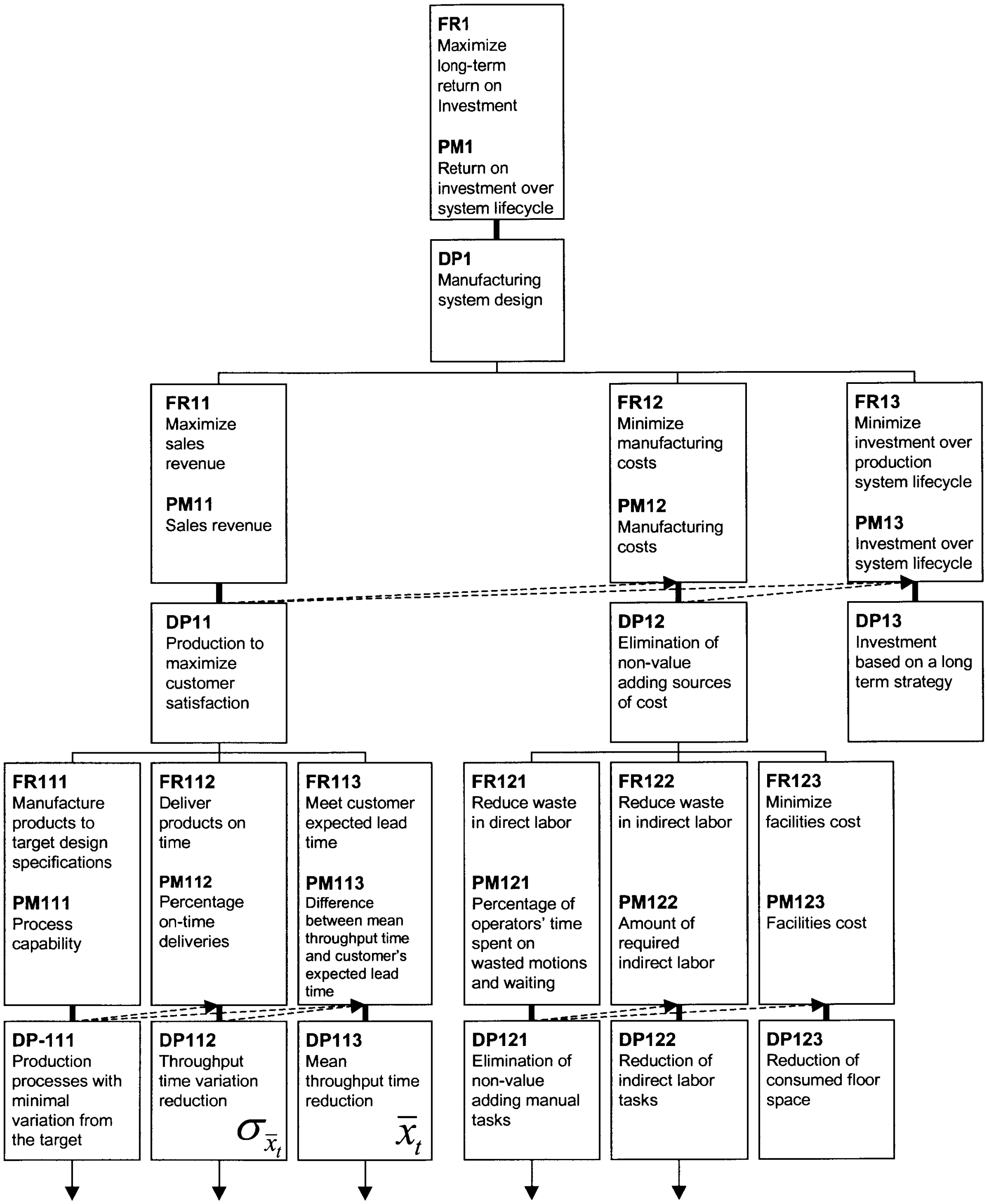


Figure 2.4: Top Three Levels of the MSDD (version 5.1)

The top-level functional requirement of the MSDD, FR1, is to "Maximize long-term Return on Investment." The phrase *long-term* indicates that short-term solutions that result in an artificially high return on investment (ROI) should not be selected. Drastically slashing investment for one quarter may temporarily make a company look like it has a high ROI, but the harmful effects of this decision will reduce the company's long-term ROI. Therefore, the top-level design parameter, DP1, is "Manufacturing system design." The selection of DP1 indicates that in order to maximize long-term ROI, it is important to *design* a manufacturing system, not let it evolve haphazardly over time. The performance measurement that indicates how well FR1 has been achieved is PM1, "Return on investment over system lifecycle." It should be noted that the MSDD addresses maximizing the long-term ROI of a company's manufacturing system. The ROI of product design, sales and marketing, and other functions within a company are not considered by this version of the MSDD.

The second level FRs were derived from the formula for ROI [Suh, et al, 1998]:

$$\text{ROI} = \frac{\text{Sales - Cost}}{\text{Investment}}$$

In order to maximize ROI, a company must fulfill FR11, "Maximize sales revenue," FR12, "Minimize manufacturing costs," and FR13, "Minimize investment over production system lifecycle." DP11, "Production to maximize customer satisfaction," indicates that, within a manufacturing system, the only way to increase sales revenue is to produce products that satisfy the customers. Other methods of increasing sales revenue, such as product design and marketing decisions are external to the manufacturing system and not addressed by the MSDD. DP12, "Elimination of non-value adding sources of cost," indicates that companies should eliminate any activities in the manufacturing system that do not add value to the final product. DP13, "Investment based on a long term strategy," specifies that companies should make investment decisions that will achieve the company's long-term objectives. These investment decisions may not appear to be the best choices if they are evaluated over a short period, but evaluating them over a long period should indicate that these decisions require the least investment for achieving a set of goals. The decomposition of FR/DP1 is a *partially coupled* design. DP11 affects FR11, FR12, FR13, and DP12 affects FR12 and FR13. This coupling indicates that production to maximize customer satisfaction affects a company's ability to minimize production costs and to minimize long-term investment. The coupling also indicates that eliminating non-value adding costs affects a company's ability to minimize its long-term investment requirements.

FR/DP11 are decomposed into three sub-FRs, FR111, FR112, and FR113. FR111 requires a company to "Manufacture products to target design specifications" and is satisfied by DP111, "Production processes with minimal variation from the target." FR112, "Deliver products on time," is satisfied by DP112, "Throughput time variation reduction." And FR113, "Meet customer expected lead time," is satisfied by DP113, "Mean throughput time reduction." These FRs and DPs indicate that the best way to *maximize sales revenue* by *maximizing customer satisfaction* is to produce high quality products in a reliable, short amount of time.

FR/DP12 is decomposed into FR121, FR122, and FR123. FR121, "reduce waste in direct labor," is satisfied by DP121, "Elimination of non-value adding manual tasks." This FR/DP pair indicates that manual labor is important to the manufacturing system and that workers should not be required to perform tasks that do not add value to the final product. FR122, "Reduce waste in indirect labor," is satisfied by DP122, "Reduction of indirect labor." The requirement to reduce indirect labor recognizes that the number of supervisory and management positions in a manufacturing system should be kept as low as possible, because these jobs do not directly add value to products. FR123, "Minimize facilities cost," is satisfied by DP123, "Reduction of consumed floor space." This FR/DP pair assumes that costs associated with facilities (electricity, heating, maintenance) should be kept as low as possible by efficiently utilizing facilities.

2.3.2 Quality

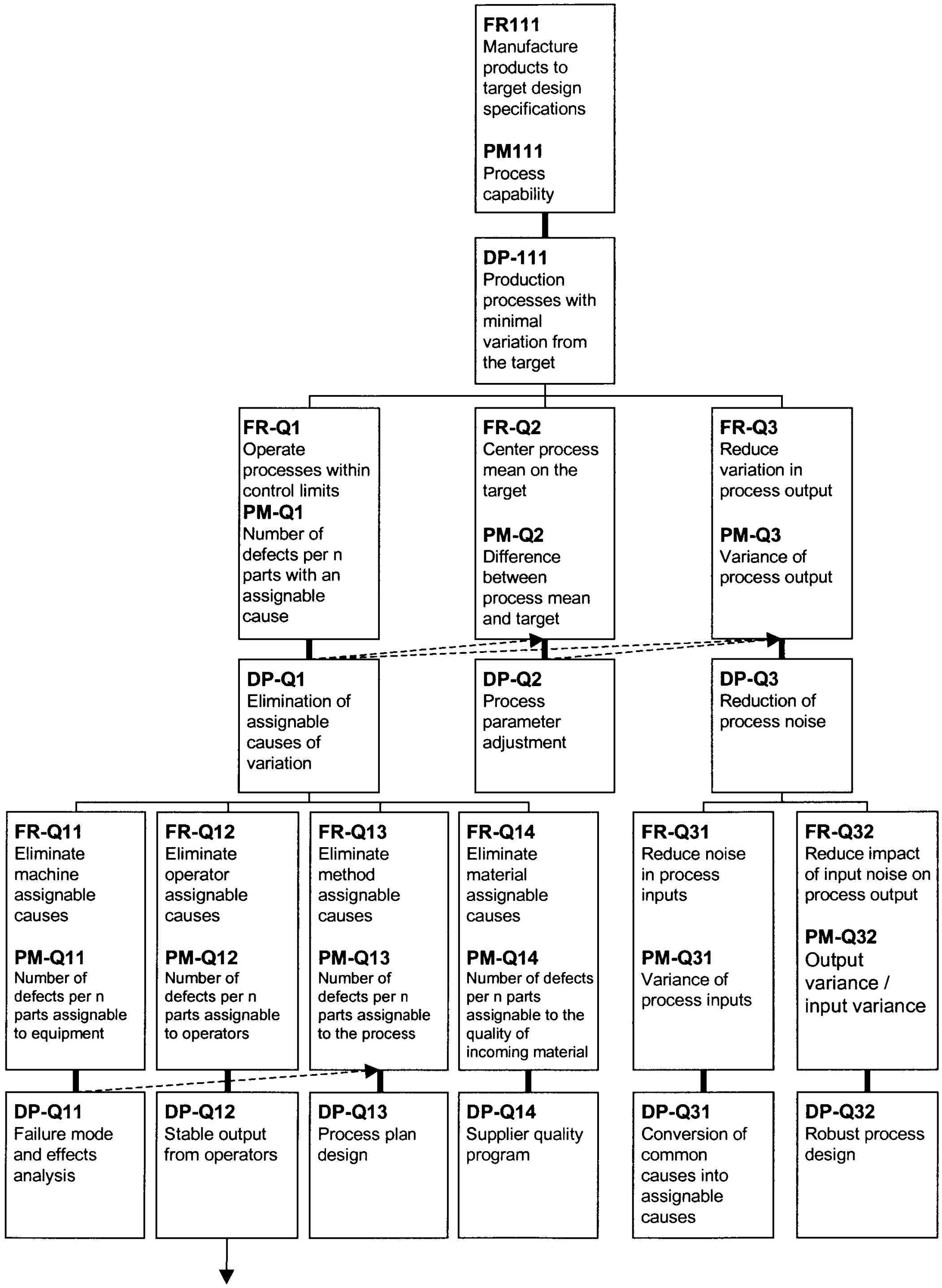


Figure 2.5: Quality Section of the MSDD (Level III through Level V)

FR/DP111 is decomposed into FR-Q1, FR-Q2, and FR-Q3. These three FRs indicate how companies can improve the quality output of their manufacturing systems. The concepts that are decomposed are based upon statistical process control (SPC) methods. [Chu, 2000; Montgomery, 1985] FR-Q1, "Operate processes within control limits," is satisfied by DP-Q1, "Elimination of assignable causes of variation." Assignable causes of variation are causes that can be identified. These causes should be traced down and eliminated in order keep processes within specified control limits. FR-Q2, "Center process mean on the target," is satisfied by DP-Q2, "Process parameter adjustment." If a process mean is not centered on the target, the probability that a defect will be created increases, as shown in Figure 2.6. Design of experiments helps guide the adjustment of process parameters to center the mean on the target. FR-Q3, "Reduce variation in process output," is satisfied by DP-Q3, "Reduction of process noise." Reducing the variation of a process output also decreases the probability that a defect will be created, as shown in Figure 2.6. Process noise reduction involves reducing the types of variation that a process receives as input as well as reducing the effect that input noise has on the output. Noise can be environmental, such as temperature, humidity and vibration, or noise can be variation in the quality of incoming materials and parts.

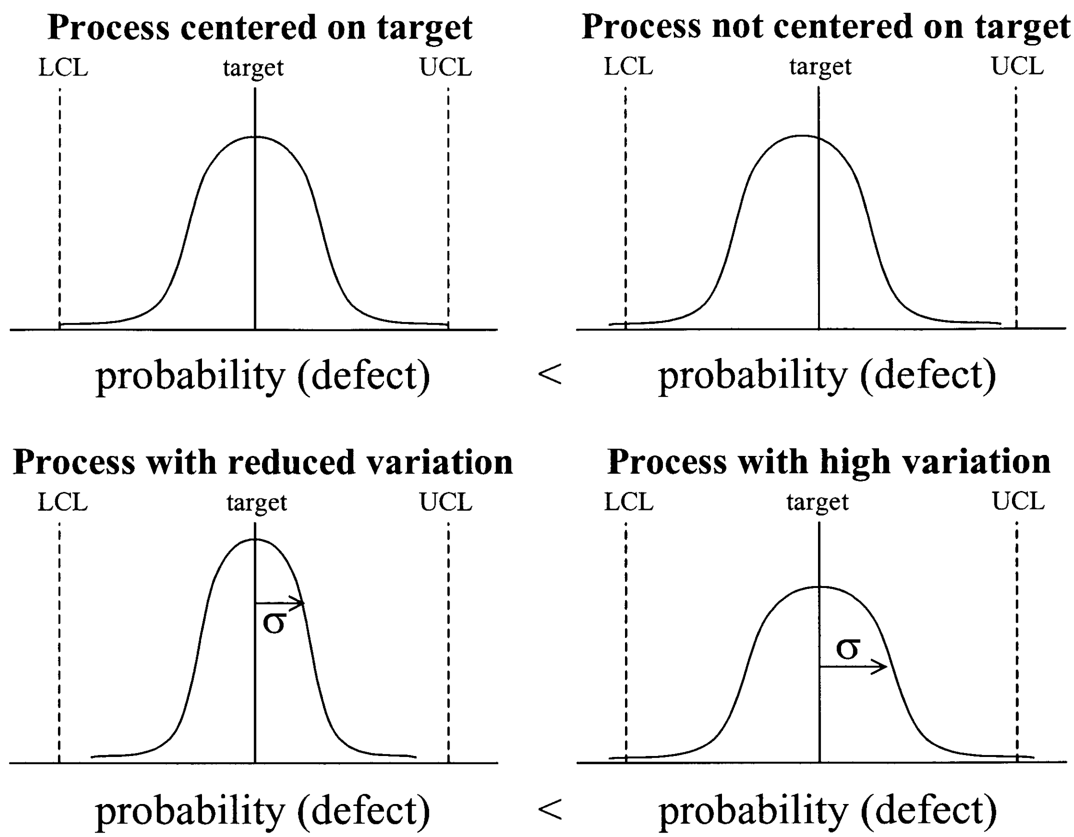


Figure 2.6: Effects of Centering and Reducing Variability of Manufacturing Processes

FR/DP-Q3 is decomposed into FR-Q31 and FR-Q32 in order to better illustrate how process variation can be reduced. FR-Q31, "Reduce noise in process inputs," is satisfied by DP-Q31, "Conversion of common causes into assignable causes." Once common causes of process noise have been converted into assignable causes, the causes can be eliminated using the methods decomposed from FR-Q1. FR-Q32, "Reduce impact of input noise on process output," is satisfied by DP-Q32, "Robust process design." Identifying and eliminating input noise is one way to reduce process variation, but it may never be possible to identify and eliminate all sources of noise. Making a process robust to input noise helps to ensure that processes are not disrupted by random or unavoidable sources of noise.

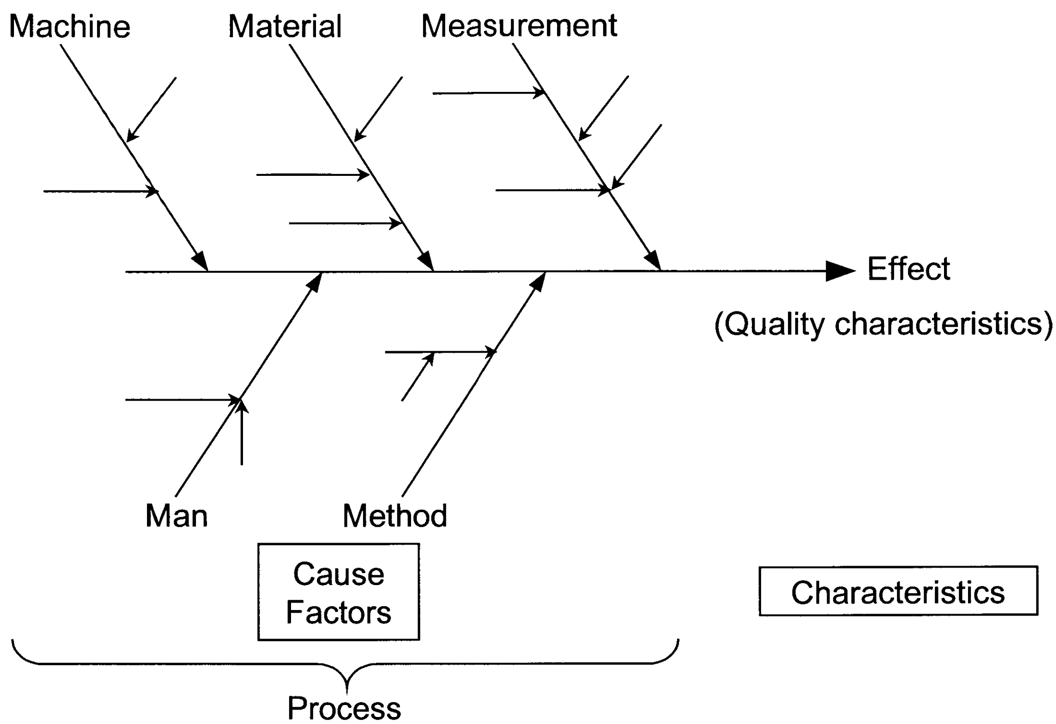


Figure 2.7: Ishikawa Fishbone Diagram [Ishikawa, 1985]

FR/DP-Q1 is decomposed into FR-Q11, FR-Q12, FR-Q13, and FR-Q14. This decomposition follows four of the branches of an Ishikawa fishbone diagram, such as the one shown in Figure 2.7. FR-Q11, "Eliminate machine assignable causes," is satisfied by DP-Q11, "Failure mode and effects analysis." By analyzing the failure modes and effects of machines, the machines can be redesigned or modified to prevent making bad parts. FR-Q12, "Eliminate operator assignable causes," is satisfied by DP-Q12, "Stable output from operators." Obtaining consistently high-quality output from workers is very important. Further decomposition of FR/DP-Q12 is shown in Figure 2.8.

FR-Q13, "Eliminate method assignable causes," is satisfied by DP-Q13, "Process plan design." The way that a process is planned can have a significant impact on quality. It may be much easier to perform some processes early in the fabrication or assembly stages of a product. For example, machining parts prior to a hardening process may significantly reduce machining costs. If the machined surfaces require tight tolerances, however, machining prior to heat treatment may not be a good choice due to distortion of the part during the heat treatment process. FR-Q14, "Eliminate material assignable causes," is satisfied by DP-Q14, "Supplier quality program." Incoming product quality has a direct impact on the output quality of a manufacturing system. It is not possible to produce good products if suppliers cannot reliably provide high-quality materials and components.

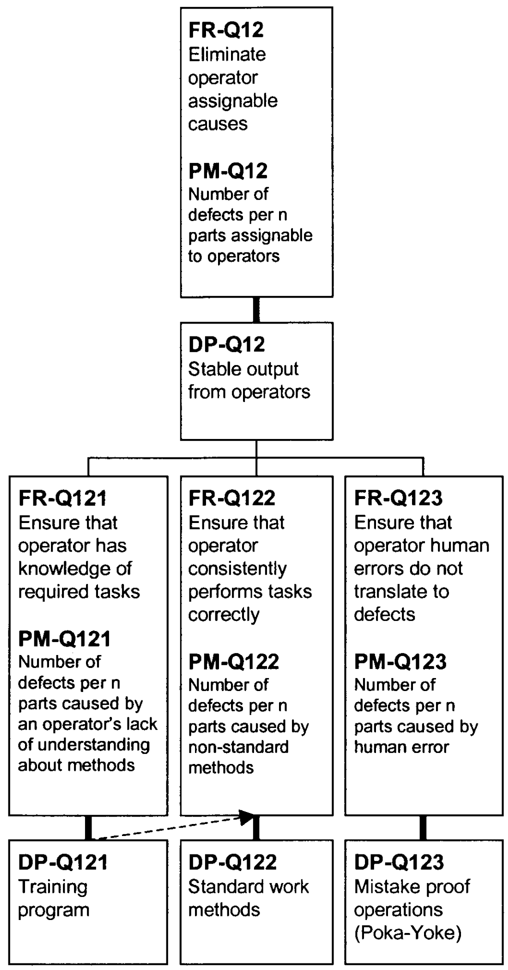


Figure 2.8: Quality Section of the MSDD (Level V and Level VI)

FR-Q12 is further decomposed into FR-Q121, FR-Q122, and FR-Q123. FR-Q121, "Ensure that operator has knowledge of required tasks," is satisfied by DP-Q121, "Training program." A training program is necessary to ensure that operators have more than just a working knowledge of their tasks. FR-Q122, "Ensure that operator consistently performs tasks correctly," is satisfied by DP-Q122, "Standard work methods." It is important that tasks are performed identically from one worker to the next. A lack of standardization increases the likelihood that workers will make mistakes. The ability of a company to standardize work is affected by the quality of its training program. This dependency is illustrated by the coupling between DP-Q121 and FR-Q122. FR-

Q123, "Ensure that operator human errors do not translate to defects," is satisfied by DP-Q123, "Mistake proof operations (Poka-Yoke)." Even with a good training program and standard work, mistakes may happen. Equipment should be designed to help operators by preventing them from making mistakes in the first place. Mistake proofing devices include fixtures that only allow a part to be inserted in the proper orientation and machines that will not start if they detect any irregularities in the product. [Monden, 1998; Ohno, 1988] Figure 2.9 shows an example of an operation before and after mistake-proofing. Without the mistake-proofing device, a part could be inserted into the fixture incorrectly. After mistake proofing, the part can only be inserted one way.

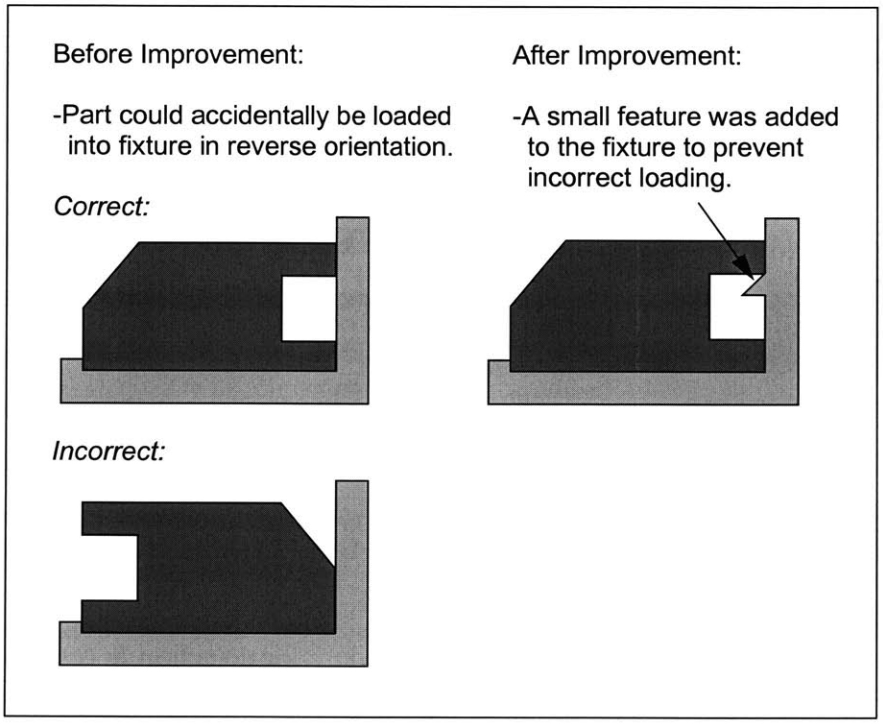


Figure 2.9: Mistake-Proofing Device [Charles, 1997]

2.3.3 Identifying and Resolving Problems

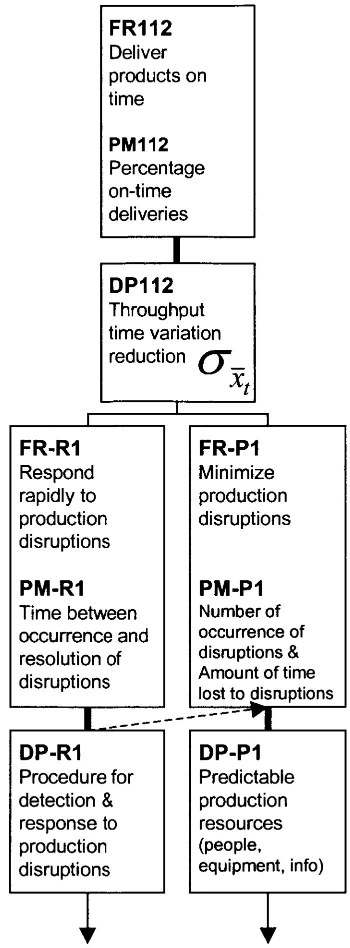


Figure 2.10: Decomposition of FR112 and DP112 (Level III and Level IV)

FR/DP112 is decomposed into two FRs, FR-R1 and FR-P1. FR-R1, "Respond rapidly to production disruptions," is satisfied by DP-R1, "Procedure for detection & response to production disruptions." The section of the MSDD that is decomposed from FR/DP-R1 is called *Identifying and Resolving Problems*. FR-P1, "Minimize production disruptions," is satisfied by DP-P1, "Predictable production resources (people, equipment, info)." The section of the MSDD that is decomposed from FR/DP-P1 is called *Predictable Output*.

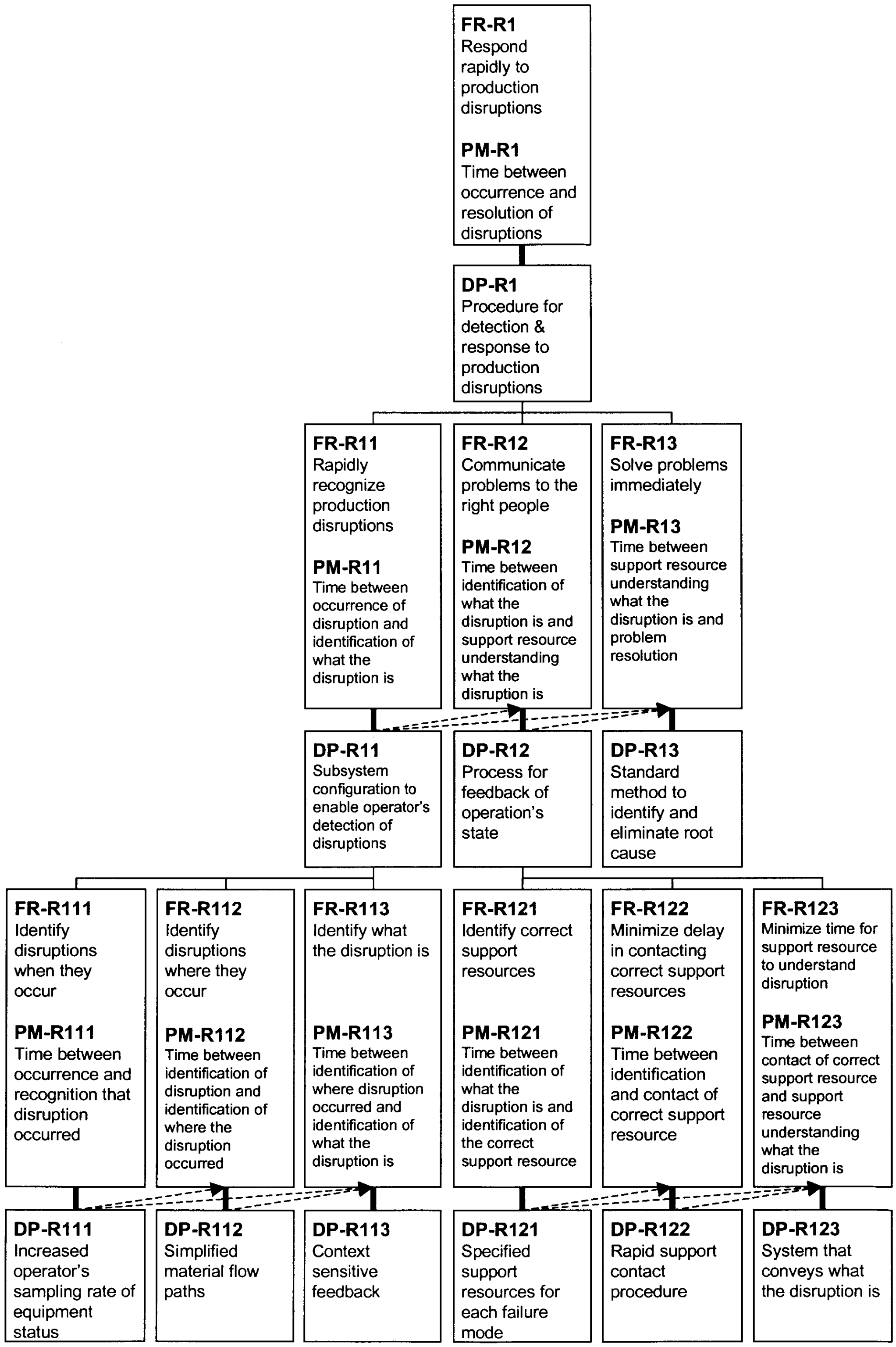


Figure 2.11: Identifying and Resolving Problems Section of the MSDD (Level IV through Level VI)

FR/DP-R1 is decomposed into FR-R11, FR-R12, and FR-R13. FR-R11, "Rapidly recognize production disruptions," is satisfied by DP-R11, "Subsystem configuration to enable operator's detection of disruptions." In order to quickly respond to production problems, operators must become aware of the problem as soon as it occurs. FR-R12, "Communicate problems to the right people," is satisfied by DP-R12, "Process for feedback of operation's state." Once an operator has become aware of a problem, he/she must be able to contact the people who can resolve the problem and tell them what the problem is. FR-R13, "Solve problems immediately," is satisfied by DP-R13, "Standard method to identify and eliminate root cause." Finally, the support resources must solve the problem quickly by identifying its root cause and eliminating the cause, so that the problem will not recur.

FR/DP-R11 is decomposed into FR-R111, FR-R112, and FR-R113. These FRs require that when there is a disruption, operators must determine what happened, where it happened, and when it happened. FR-R111, "Identify disruptions when they occur," is satisfied by DP-R111, "Increased operator sampling rate of equipment status." By frequently checking the status of equipment, operators will notice if a machine stops or is producing defective parts. Recognizing that a problem has occurred may take a long time in a factory where machines are started by an operator and then left untended for long periods of time. FR-R112, "Identify disruptions where they occur," is satisfied by DP-R112, "Simplified material flow." Complicated material flow paths make it difficult to identify the machine or process step at which a problem has occurred. Simple flow paths, such as those found within a manufacturing cell, make it easier to identify where a problem has occurred. Workers performing successive checks between processes help ensure that problems are identified before parts move to the next process. [Black, 1991] FR-R113, "Identify what the disruption is," is satisfied by DP-R113, "Context sensitive feedback." Equipment should provide operators with feedback that helps them identify the cause of the production disruption. This feedback can be as simple as a light that indicates what part of the machine is malfunctioning or as complex as a digital display that provides descriptive details of the problem.

FR/DP-R12 is decomposed into FR-R121, FR-R122, and FR-R123. These FRs address the need to get the right information to the right people as quickly as possible after a disruption has occurred. FR-R121, "Identify correct support resources," is satisfied by DP-R121, "Specified support resources for each failure mode." When the correct resources are not specified, an operator must waste his/her time tracking down the appropriate resources, further delaying problem resolution. FR-R122, "Minimize delay in contacting correct support resources," is satisfied by DP-R122, "Rapid support contact procedure." An *andon* board is one method of rapidly contacting support resources. [Ohno, 1988] When an operator has a problem, he/she flips a switch and illuminates a light on an andon board that is visible throughout the production area. This immediately brings the problem to the attention of supervisors and support resources. FR-R123, "Minimize time for support resource to understand disruption," is satisfied by DP-R123, "System that conveys what the disruption is." Conveying the nature of the problem to the support resource is important, so that the resource can arrive with the tools and parts that will be necessary to fix the problem. This communication prevents the support resource from making multiple trips to first identify the problem, then retrieve the necessary equipment, and finally to resolve the problem. It may be possible to use a single tool, such as an alpha-numeric pager system, to achieve both DP-R122 and DP-R123. Pagers can immediately contact support resources while simultaneously informing them of the nature of the problem.

2.3.4 Predictable Output

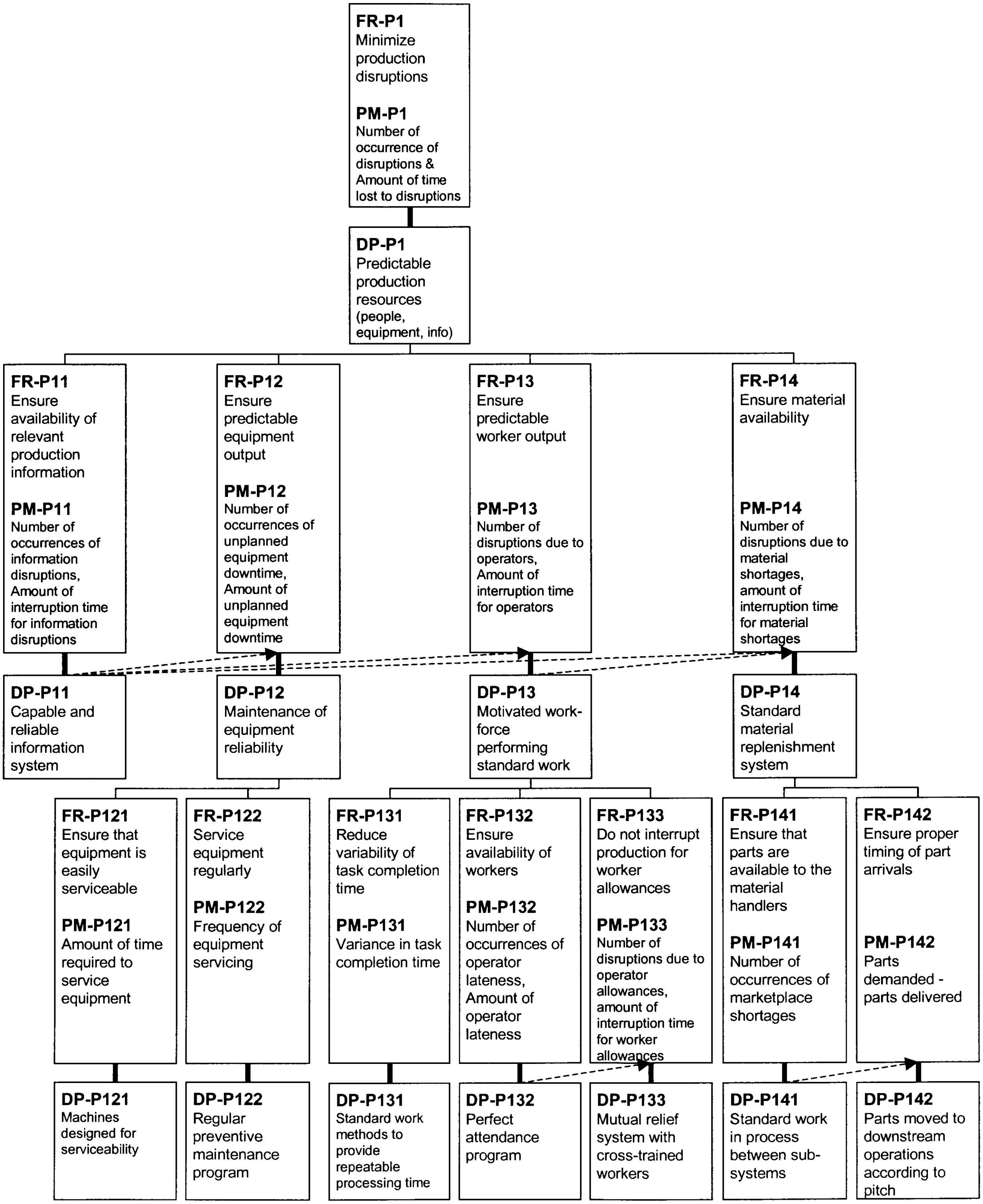


Figure 2.12: Predictable Output Section of the MSDD (Level IV through Level VI)

FR/DP-P1 is decomposed into FR-P11, FR-P12, FR-P13, and FR-P14. These FRs follow a decomposition similar to the branches of an Ishikawa fishbone diagram, except production information is considered in place of method. FR-P11, "Ensure availability of relevant production information," is satisfied by DP-P11, "Capable and reliable information system." Timely and relevant information within a manufacturing system is very important, because it affects the ability of equipment, operators, and the material handling system to fulfill their required tasks. This coupling is shown between DP-P11 and FR-P12, FR-P13, and FR-P14. Late or incorrect information can cause production delays, overproduction, and part shortages. FR-P12, "Ensure predictable equipment output," is satisfied by DP-P12, "Maintenance of equipment reliability." Without predictable equipment output, a manufacturing system must purchase extra equipment or build up inventory to ensure that parts are available when needed. FR-P13, "Ensure predictable worker output," is satisfied by DP-P13, "Motivated work-force performing standard work." Unpredictable worker output requires companies to hire extra workers to fill in for absentees and often results in large amounts of overtime work to make up for lost production time. FR-P14, "Ensure material availability," is satisfied by DP-P14, "Standard material replenishment system." If materials are not available when they are needed, a manufacturing system cannot operate. Non-standard material replenishment leads companies to store large amounts of inventory to ensure that parts are available.

FR/DP-P12 is decomposed into FR-P121 and FR-P122. FR-P121, "Ensure that equipment is easily serviceable," is satisfied by DP-P121, "Machines designed for serviceability." Designing equipment for ease of serviceability enables support resources to perform preventive maintenance on equipment without requiring a major overhaul that would take the equipment out of production for a long period of time. FR-P122, "Service equipment regularly," is satisfied by DP-P122, "Regular preventive maintenance program." Regular machine service helps prevent unplanned machine downtime by replacing worn components before they fail. Consumable parts and supplies, such as cutting tools, machining oils, and coolant, should also be changed and replenished regularly.

FR/DP-P13 is decomposed into FR-P131, FR-P132, and FR-P133. FR-P131, "Reduce variability of task completion time," is satisfied by DP-P131, "Standard work methods to provide repeatable processing time." Ensuring that all workers perform the same tasks in the same manner helps keep processing times consistent from one worker to the next. FR-P132, "Ensure availability of workers," is satisfied by DP-P132, "Perfect attendance program." High absenteeism within a company makes production output unpredictable, because it is difficult to know whether enough people will be present to produce the required demand for a day. FR-P133, "Do not interrupt production for worker allowances," is satisfied by DP-P133, "Mutual relief system with cross-trained workers." It is best to ensure that workers are present when needed, but production should not stop when a worker cannot come in or must temporarily step away from his/her task. Workers should be cross-trained, so that they can fill in for one another.

FR/DP-P14 is decomposed into FR-P141 and FR-P142. FR-P141, "Ensure that parts are available to the material handlers," is satisfied by DP-P141, "Standard work in process between sub-systems." A standard level of work in process (WIP) prevents slight variations in processing times or minor production disturbances from disrupting production throughout a factory. Standard WIP also draws attention to potential problems before they can impact downstream operations. If an operation is having trouble maintaining its standard WIP, this may be a signal that the operation needs to be redesigned or that something is preventing the operation from performing its tasks correctly. FR-P142, "Ensure proper timing of part arrivals," is satisfied by DP-P142, "Parts moved to downstream operations according to pitch." Pitch is equal to the number of products produced in a single setup multiplied by the takt time. Moving parts downstream according to pitch means that parts should be supplied to downstream stations at time intervals corresponding to the time between changeovers.

2.3.5 Delay Reduction

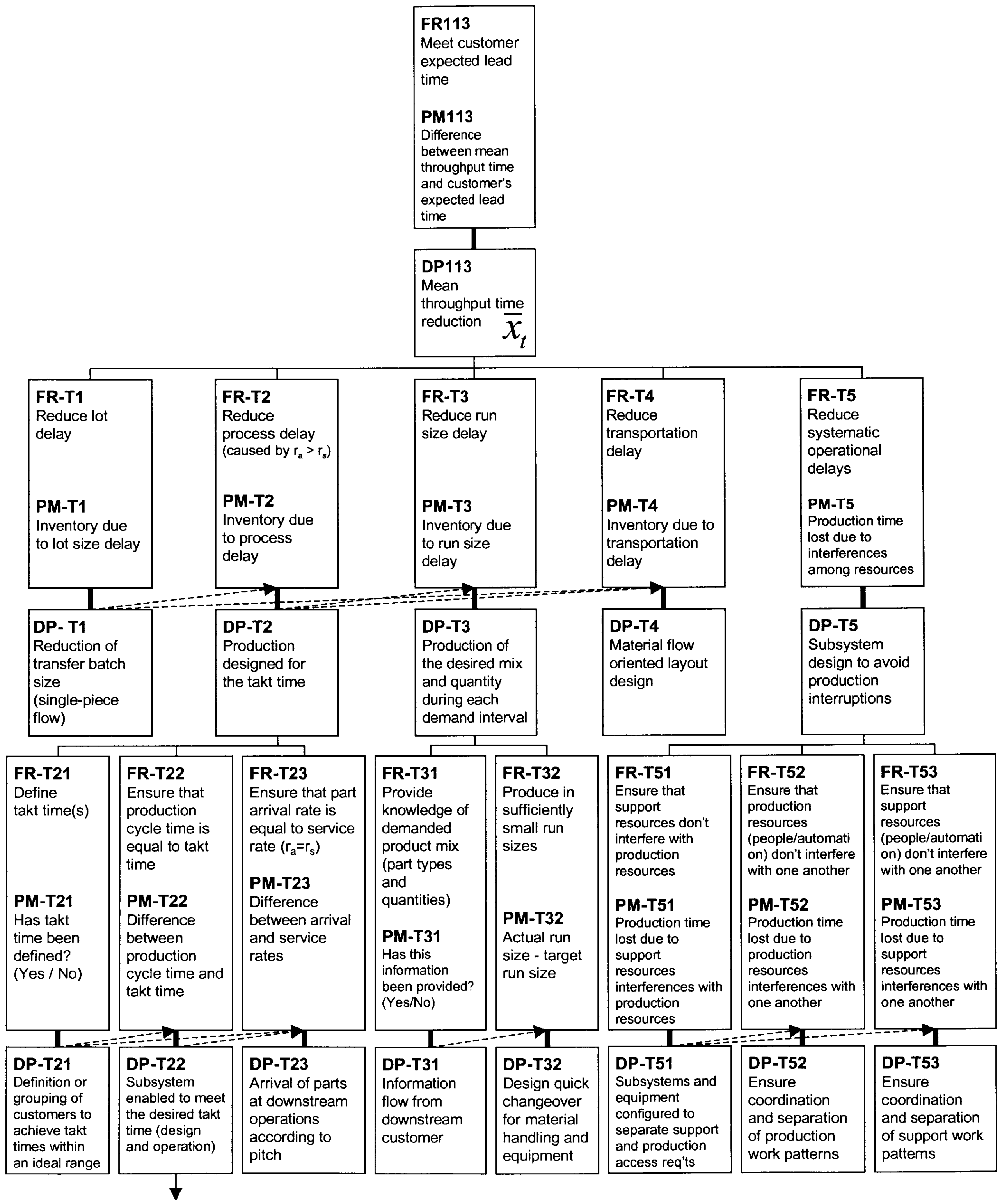


Figure 2.13: Delay Reduction Section of the MSDD (Level III through Level V)

FR/DP113 is decomposed into FR-T1, FR-T2, FR-T3, FR-T4, and FR-T5. These FRs address types of delay that occur within a manufacturing system and increase the mean throughput time. FR-T1, "Reduce lot delay," is satisfied by DP-T1, "Reduction of transfer batch size (single-piece flow)." Lot delay occurs when parts are transferred from one station to another in batches. The first part that is processed must wait for the last part in the batch to be processed before all parts are moved to the next process. Transferring parts between stations one-piece at a time eliminates lot delay. FR-T2, "Reduce process delay (caused by $r_a > r_s$)," is satisfied by DP-T2, "Production designed for takt time." Process delay occurs when the arrival rate of parts at a machine or station, r_a, is greater than the service rate, r_s, at which the machine or station can process parts. Designing production equipment and manual operations to operate at takt time eliminates process delay, and is called "balanced production." Figure 2.14 shows an example with two sets of processes. The first set of process is not balanced and has different cycle times at each station. The second set of processes is balanced and has the same cycle time at each station.

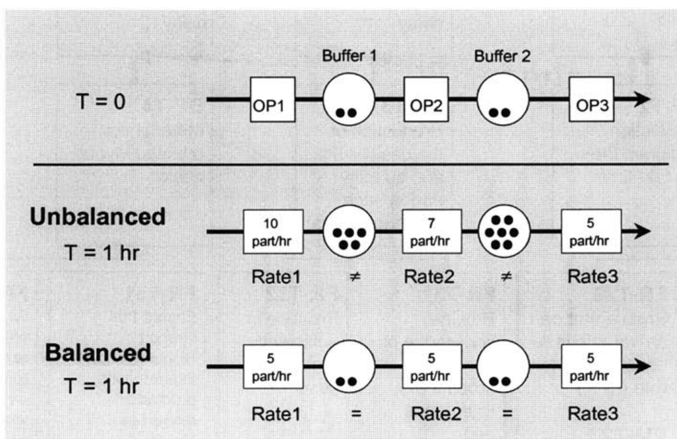


Figure 2.14: Balanced Production [Linck and Cochran, 1999]

FR-T3, "Reduce run size delay," is satisfied by DP-T3, "Production of the desired mix and quantity during each demand interval." The run size is the number of parts of one type that are produced between changeovers. Producing the same part for a long period of time requires that other parts, which are not being produced, must be supplied from inventory. Producing each type and quantity of part that is demanded within a specified time interval is called "level production." Level production reduces the amount of inventory that must be stored and reduces the delay between making and shipping a part, as shown in Figure 2.15. [Linck and Cochran, 1999]

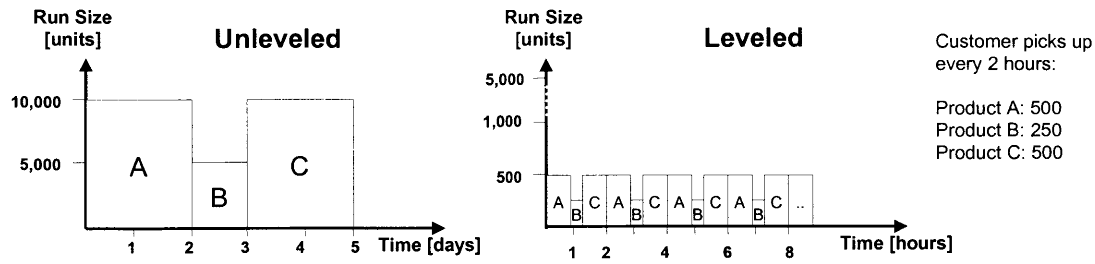


Figure 2.15: Level Production [Linck and Cochran, 1999]

FR-T4, "Reduce transportation delay," is satisfied by DP-T4, "Material flow oriented layout design." Transportation delay results from moving parts long distances between processing steps. Facilities and equipment should be laid out to minimize the distances that parts travel between processing steps. FR-T5, "Reduce systematic operational delays," is satisfied by DP-T5, "Subsystem design to avoid production interruptions." Systematic operational delays result from subsystems within the manufacturing system that interfere with the operation of other subsystems.

FR/DP-T2 is decomposed into FR-T21, FR-T22, and FR-T23. FR-T21, "Define takt time(s)," is satisfied by DP-T21, "Definition or grouping of customers to achieve takt times within an ideal range." Takt time is the pace of customer demand and is equal to the available production time in a day divided by the average customer demand (over a time interval).

$$\text{Takt Time} = \frac{\text{Production time available in a day}}{\text{Average customer demand (over a time interval)}}$$

Takt time can be measured in seconds for high-volume industries, such as consumer products, or weeks for lower volume industries, such as airplanes. Takt time is typically calculated for intervals of weeks or months for higher volume industries and for yearly intervals for lower volume industries. This practice prevents the takt time from changing more frequently than the manufacturing system can respond. The *ideal range* of takt times depends upon the type of industry and production volume. For high-volume industries that use manufacturing cells, customers should be defined so that takt times are greater than or equal to 30 seconds. Shorter takt times make it difficult for workers to perform more than one task within the takt time.

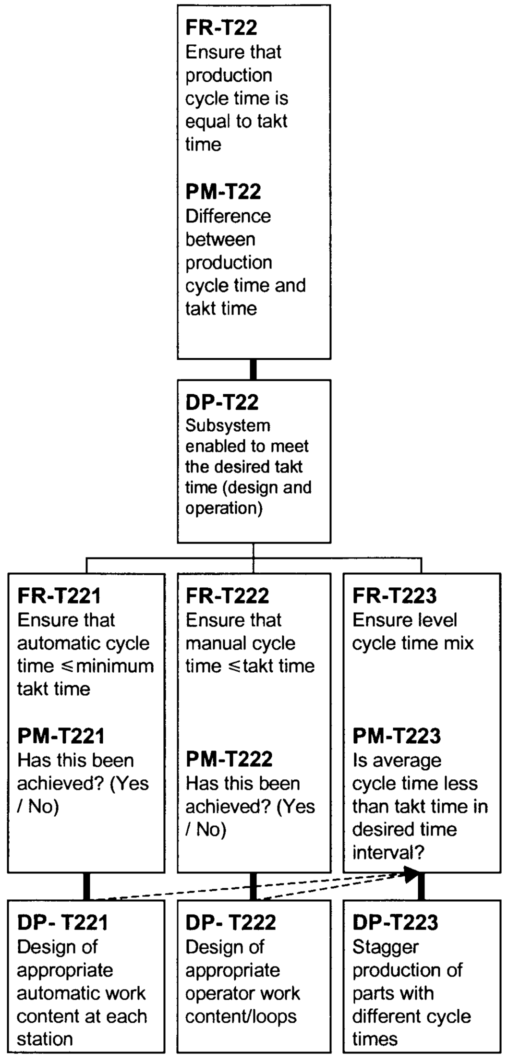


Figure 2.16: Delay Reduction Section of the MSDD (Level V and Level VI)

FR-T22, "Ensure that production cycle time equals takt time," is satisfied by DP-T22, "Subsystem enabled to meet the desired takt time (design and operation)." In order for the production cycle time to equal takt time, the sub-systems must first be designed to operate at takt time. FR/DP-T22 is further decomposed into FR-T221, FR-T222, and FR-T223, as shown in Figure 2.16. FR-T221 and FR-T222 require that the work content at every station be performed in less than or equal to takt time. FR-T221, "Ensure that automatic cycle time ≤ minimum takt time," is satisfied by DP-T221, "Design of appropriate automatic work content at each station." FR-T222, "Ensure that manual cycle time ≤ takt time," is satisfied by DP-T222, "Design of appropriate operator work content/loops." FR-T223, "Ensure level cycle time mix," is satisfied by DP-T223, "Stagger production of parts with different cycle times." If the cycle time for some part types exceeds the takt time, the parts should be sequenced so that the average cycle time is less than or equal to takt time. Figure 2.17 illustrates how production can be leveled by cycle time.

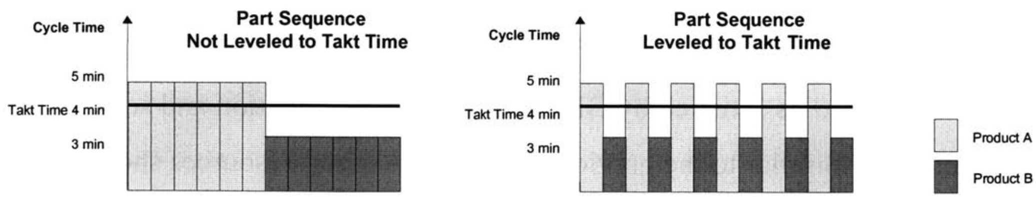


Figure 2.17: Level by Cycle Time [Linck and Cochran, 1999]

FR-T23, "Ensure that part arrival rate is equal to service rate ($r_a = r_s$)," is satisfied by DP-T23, "Arrival of parts at downstream operations according to pitch." As discussed for FR/DP-P142, pitch is equal to the number of products produced in a single setup multiplied by the takt time. Whereas in DP-P142 parts must be moved downstream according to pitch, for DP-T23 parts must arrive according to pitch. This ensures that parts arrive when they are needed, but not before they are needed. This arrival discipline prevents inventory from building up in the manufacturing system.

FR/DP-T3 is decomposed into FR-T31 and FR-T32. FR-T31, "Provide knowledge of demanded product mix (part types and quantities)," is satisfied by DP-T31, "Information flow from downstream customer." In order to produce the right mix and quantity of products, customer demand must be communicated to the manufacturing system. FR-T32, "Produce in sufficiently small run sizes," is satisfied by DP-T32, "Design quick changeover for material handling and equipment." In order to meet customer demand within a given time interval, it must be possible to changeover the machines frequently enough to produce all of the parts that are demanded.

FR/DP-T5 is decomposed into FR-T51, FR-T52, and FR-T53. FR-T51, "Ensure that support resources don't interfere with production resources," is satisfied by DP-T51, "Subsystems and equipment configured to separate support and production access requirements." Regular support activities, such as chip removal and refilling machine lubricants, should not cause people or machines to stop production. Equipment should be designed so that the production activity can proceed while the support activity is being performed. For example, machining chips should be fed to the rear of the machine where they can be collected and removed without interfering with the machine operator. FR-T52, "Ensure that production resources (people / automation) don't interfere with one another," is satisfied by DP-T52, "Ensure coordination and separation of production work patterns." Production resources should also not interfere with one another. For example, work patterns should be designed so that two operators do not require use of the same machine at the same time. FR-T53, "Ensure that support resources (people / automation) don't interfere with one another," is satisfied by DP-T53, "Ensure coordination and separation of support work patterns." Similar to the previous situations, support resources should not interfere with other support resources. For example, a material handler may not be able to replenish parts to an assembly cell if a worker performing preventive maintenance is blocking his/her access. The work patterns of the two workers should be better coordinated so that they will not get in each other's way.

2.3.6 Direct Labor

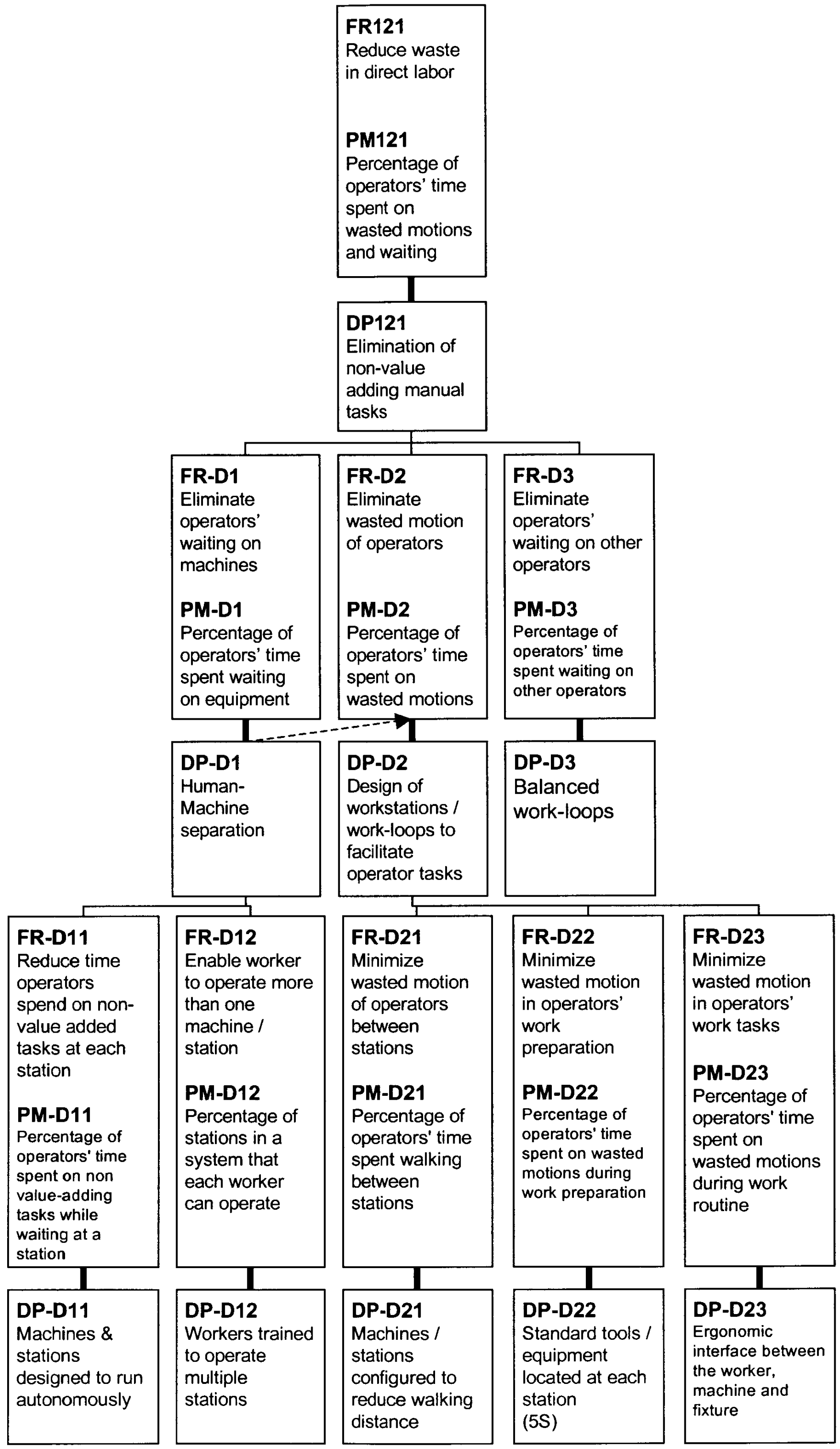


Figure 2.18: Direct Labor Section of the MSDD (Level III through Level V)

FR/DP-121 is decomposed into FR-D1, FR-D2, and FR-D3. FR-D1, "Eliminate operators' waiting on machines," is satisfied by DP-D1, "Human-Machine separation." Machine operators are not adding value to a product when they wait for machines to finish cycling. By separating workers from individual machines, workers can perform value-adding tasks to one part while another part is being processed in a machine. FR/DP-D1 is decomposed into FR-D11 and FR-D12. FR-D11, "Reduce time operators spend on non-value added tasks at each station," is satisfied by DP-D11, "Machines & stations designed to run autonomously." Autonomous machines do not require constant attention from the machine operator. The operator only needs to load a part, then begin the machine cycle. Autonomous machines allow operators to perform more than one task while a part is being processed. FR-D12, "Enable worker to operate more than one machine / station," is satisfied by DP-D12, "Workers trained to operate multiple stations." Once workers have been separated from individual machines, they should be trained to operate multiple machines.

FR-D2, "Eliminate wasted motion of operators," is satisfied by DP-D2, "Design of workstations / work-loops to facilitate operator tasks." Work stations and work patterns should be designed to minimize the non-value adding tasks required of workers. FR/DP-D2 is decomposed into FR-D21 and FR-D22. FR-D21, "Minimize wasted motion of operators between stations," is satisfied by DP-D21, "Machines / stations configured to reduce walking distance." Developing machines and stations with small profiles and locating them close together reduces wasted motion by decreasing the distance that workers must travel. [Gomez, 2000] FR-D22, "Minimize wasted motion in operators' work preparation," is satisfied by DP-D22, "Standard tools / equipment located at each station (5S)." By placing all of the tools that workers need at the locations where the tools are used, workers do not need to waste time collecting or finding tools before performing a task. FR-D23, "Minimize wasted motion in operators' work tasks," is satisfied by DP-D23, "Ergonomic interface between the worker, machine and fixture." Designing stations that minimize the distance that workers must reach and allow them to perform tasks comfortably will help workers to perform tasks more efficiently.

FR-D3, "Eliminate operators' waiting on other operators," is satisfied by DP-D3, "Balanced work-loops." Once workers have been separated from machines and perform multiple tasks, the work patterns must be balanced to ensure that workers will not have to wait on other workers.

Work content for each worker should be approximately equal, so that they all finish their set of tasks at the same time and can hand their part to the next worker.

2.3.7 Indirect Labor

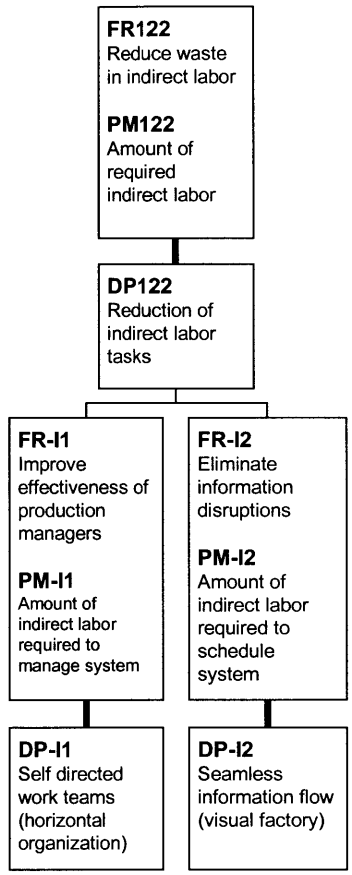


Figure 2.19: Indirect Labor Section of the MSDD (Level III and Level IV)

FR/DP122 is decomposed into FR-I1 and FR-I2. FR-I1, "Improve effectiveness of production managers," is satisfied by DP-I1, "Self directed work teams (horizontal organization)." Self directed work teams provide managers with more time to deal with difficult problems by empowering the teams to solve common problems without consulting management. FR-I2, "Eliminate information disruptions," is satisfied by DP-I2, "Seamless information flow (visual factory)." A visual information system allows workers and managers to quickly understand the status of production in a factory. Display panels can be used to indicate how many products have been produced and whether production is behind or ahead of customer demand. Specific locations for parts should be visually marked so that the correct part is placed in the correct spot.

Marking locations also allows people to quickly check if parts are present or not. [Monden, 1998] In addition to quickly communicating the status of production, a visual system allows production decisions to be made at lower levels within the company. Making decisions at lower levels speeds up the decision making process and allows workers to feel more in control of their own work.

Chapter 3 MSDD Feedback from the Aerospace Industry

3.1 Introduction

The Manufacturing System Design Decomposition (MSDD) was first presented to aerospace industry members at a Lean Aerospace Initiative (LAI) Implementation Workshop. [LAI, 1998] Andrew Wang's research into aircraft assembly illustrated how the MSDD could be used in an aerospace-specific setting [Wang, 1999]. Wang compared aerospace industry practices to the MSDD and developed a new military aircraft design decomposition to explain the differences between the MSDD approach and actual implementations found in industry. Wang used this comparison to illustrate how several military procurement policies impacted the design of aircraft manufacturing systems. Wang's work is revisited in Chapter 5.

Industry members were interested by the MSDD approach, but were not sure that it could be applied directly to the aerospace industry. In order to determine whether the MSDD could be used to design an aerospace manufacturing system, the LAI began looking for an opportunity to work with an industry member to design a new manufacturing system. When no opportunities arose, the research team decided to evaluate the applicability of the MSDD approach by obtaining feedback from industry members regarding the appropriateness of the MSDD's FRs and DPs to the issues faced by the aerospace industry. This research was expected to either validate the applicability of the existing MSDD or develop a new aerospace-specific MSDD.

In order to collect feedback from industry, a series of visits were arranged to multiple manufacturing sites of several aerospace companies. During these visits, meetings were held with engineers, managers, and occasionally production technicians. In these meetings, participants were familiarized with the Axiomatic Design approach and the motivation for developing a MSDD. Participants were then taken step-by-step through a detailed explanation of the MSDD. During and after this explanation, the participants were asked to suggest changes that would enable the MSDD to illustrate better the manufacturing system requirements present at each site.

This chapter reviews the MSDD feedback that was obtained from companies in the aerospace industry through a series of structured interviews. It should be noted that the MSDD used to collect this feedback was slightly different than the version presented in Chapter 2. The version presented to industry members was version 5.0. A complete copy of MSDD v.5.0 can be found in Appendix B. It should also be noted that most of the industry feedback did not focus on nor illustrate the differences between military and commercial manufacturing systems. This should not hinder the development of the Aerospace Manufacturing System Design Decomposition (AMSDD) however, because the AMSDD is meant to show a general manufacturing system design that represents the requirements of any aerospace manufacturing system. Therefore, differences between commercial and military manufacturing systems could be contrasted to identify procurement policies or perhaps commercial practices that positively/negatively affect manufacturing system design.

3.2 Upper-level FRs and DPs

3.2.1 Level I FR and DP

Industry comments concerning the appropriate FR1 for the AMSDD varied widely. Many people were not convinced that return on investment (ROI) was the appropriate top-level FR. When asked for alternatives, however, interviewees provided few well articulated suggestions. In the end, most people agreed that increasing ROI was an acceptable top-level FR. Alternative suggestions included return on net assets (RONA), and economic profit (EP). "Shareholder value" was mentioned frequently, but it was not initially clear how this would be linked to the design of the manufacturing system. A suggestion to investigate Economic Value Added (EVA™) was made at the LAI Plenary Session Manufacturing System Team meeting. EVA was relatively unknown to the team, but was suggested because it is frequently used by investors and was considered to hold potential for addressing the issue of shareholder value. EVA and its impact on the top level of the Aerospace MSDD will be discussed in detail in Chapter 4, Section 4.2.1.

3.2.2 Level II FRs and DPs

One of the sites believed that there was a missing FR and corresponding DP at the second level. This company focused primarily on the space sector and wanted additional guidance on ways to migrate their manufacturing system towards the commercialization of space. The company wanted to remove the "myth" that the space business is so unique that it cannot operate in a manner similar to other commercial industries. In particular, the site wanted to know how to move from what they considered a 1960's / 1970's mentality towards a modern way to address capacity needs in a systematic way. The suggestion that an FR/DP be developed to address "space commercialization" was not considered for the AMSDD, however. This FR would have been overly sector-specific, which does not fit with the goal of an AMSDD that applies throughout the aerospace industry.

Most sites agreed with FR11, "Maximize sales revenue," and its corresponding DP11, "Production to maximize customer satisfaction." An engineer at one site mentioned that historically, it had been the company's technical superiority, rather than cost effectiveness, that had attracted its customers. Customers would frequently present the company with a list of technical requirements, which the company would need to meet or exceed. Cost and schedule had been secondary issues, with the company's primary focus remaining on technical issues. The order of importance has now shifted more towards 1) schedule, 2) technical, and 3) cost, although this may change from customer to customer. Nonetheless, management was pushing for the company to improve its cost and schedule performance.

It was pointed out that the military has often been more concerned with product performance than cost. Many projects have been "cost-plus" programs, but this funding practice is now changing toward fixed-price programs when the technical risk has been removed. In the cost plus incentive fee programs, manufacturers are paid for all of their costs, plus a fixed fee. Cost-plus remains the predominant contracting method for projects with a high degree of technical risk, such as new product development programs. Industry members indicated that cost-plus funding is necessary for risky, large-scale projects, because privately funding a project that fails could bankrupt a company.

The coupling between DP11, "Production to maximize customer satisfaction," and FR12, "Minimize manufacturing costs," was also pointed out as being important for companies to consider. One company chooses to design all of its products to the highest specifications normally demanded by any customer (typically the military). This practice developed out of the belief that it would be more expensive to build products to varying standards for different customers. If a new customer asks for a product to be built to higher specifications than existing standards, the product will have increased production costs. These increased costs are due to the disruption that the non-standard work introduces to the manufacturing system and the increased cost associated with configuring equipment to achieve the higher specifications.

While it was generally agreed that reducing costs and eliminating non-value adding sources of cost is important, industry members had a number of concerns with FR12 and DP12 ranging from phrasing to the scope covered by the MSDD. Regarding the phrasing, one person commented that "minimize" may not be the best word, because some cost reductions may be detrimental to the overall manufacturing system. Several people mentioned that the subsequent decomposition of FR/DP12 at Level III needs to be broader, including material costs and supply chain management. Regarding the phrasing, the term "minimize" is maintained in the AMSDD. The intention is that minimization should be performed while considering overall system goals. Therefore, the AMSDD is not advocating drastic or detrimental cost reductions. Decomposition of FR/DP12 is now broader in the AMSDD than in the MSDD and is described in Chapter 4, Section 4.2.8

It was also pointed out that a number of non-value adding costs result from military requirements. Government oversight reviews are non-value adding. In cost-plus programs, however, the company gets paid for these reviews, so there is little incentive for the company to eliminate the reviews.

Most industry members commented that the MSDD needed more decomposition of FR/DP13. One comment was that this section doesn't address the investment that goes into design for manufacturing and design for assembly. Another comment was that many decisions in companies are based on financing, so the financial impacts of manufacturing decisions should be considered. FR/DP13 is now further decomposed by the AMSDD. Financing decisions, however, are not explicitly addressed by the AMSDD. It would be difficult to create a generalized finance model that applies throughout all sectors of the aerospace industry.

One meeting provided an interesting perspective on the actions taken by companies to ensure that the use of investment (i.e. assets) is maximized. An engineering manager mentioned that companies focus on keeping production facilities running around the clock to maximize the use of production assets. The focus is not on off-the-floor assets and improvements. For example, office buildings and equipment are only utilized for a small part of the day. This one-sided view of asset management brings about a couple of questions as to whether one practice makes more sense than the other and whether changes can or should be made to the less effective practice. This dilemma will not be discussed further in this thesis, but it is an interesting question that may deserve further research. The issue could be viewed as deciding whether three-shift operations should be selected for manufacturing systems in order to maximize the use of production assets and, if so, whether more off-the-floor personnel, such as designers and engineers, should work similar shifts to maximize the use of other assets.

3.2.3 Level III FRs and DPs

Many industry members commented on the lack of product design in the MSDD. The sections that are decomposed from FR/DP11 were specifically identified as the sections most lacking product design. Interviewees frequently commented that it is hard to look at the manufacturing system isolated from product design. One company said that product engineering was actually considered a part of the manufacturing system. In this company, the cycle time and lead time of engineering was factored into the overall manufacturing system. It should be noted that this company produced relatively customized products, so a significant amount of engineering was required for each new customer. Nonetheless, the role of product design in a manufacturing system was a frequent topic, so a new product design section has been added to the AMSDD.

Several people mentioned that the decomposition of FR/DP12 focused too much on labor, but ignored other sources of non-value adding costs. One of these areas is materials. One site frequently mentioned that aerospace companies have saturated the market for space qualified materials and products and therefore must pay a premium to acquire products and keep suppliers. This topic leads into the general area of supply-chain management. The same company was interested in seeing more details about negotiation and ways to drive down costs on vendor provided hardware. The AMSDD has broadened the decomposition of FR/DP12 and touches upon the need for supply-chain management.

Industry members mentioned that the cost of materials and a company's core competencies should be considered in the design phase. The idea was that companies should design products that do not require expensive or hard to procure parts. A number of people also mentioned that companies should try to keep manufacturing in-house for processes that they consider core competencies, but outsource other processes to reduce costs. In other words, tradeoffs used for make/buy decisions should be considered in the MSDD. A specific method for tradeoff analysis is not covered by the AMSDD. However, the new section on product design does address issues relating to material costs and component procurement.

Another comment was that FR123, "Minimize facilities cost," and DP123, "Reduction of consumed floor space," were too narrow. Additional overhead costs, such as supplies, tools, and environmental considerations should be considered in addition to floor space. As a result of these suggestions the AMSDD provides a broader treatment of overhead costs.

3.3 Lower Level FRs and DPs

3.3.1 Quality FRs and DPs

Industry members made a number of general comments regarding quality issues in the aerospace industry that did not relate directly to the FRs and DPs of the MSDD, but provide insight into typical industry concerns.

One comment was that manned space flight generated a lot of requirements that have carried over into the design of all space products. These requirements resulted from the fact that small defects and problems could have serious repercussions. It was suggested that the MSDD may not adequately address the severity of these concerns. Another suggestion was that the space sector requires a completely separate FR, such as "engineer for space applications." The reasoning behind this suggestion was that the environment in which space products must function is unique. Material selection becomes important, redundancy is an issue, and products must still function in the presence of partial failures. Space products are not serviceable, because (with very few exceptions) there is no way to recover and repair them after launch.

These suggestions that the MSDD does not address the severity of aerospace concerns and that a new FR specific to space applications be added are not within the scope of the MSDD or the new AMSDD. The MSDD cannot make the value judgements required for identifying and addressing the severity of issues external to the manufacturing system. Product safety and complexity issues are determined by product designers and mission planners. If these concerns are translated into production requirements, then the MSDD and AMSDD can help to ensure that the requirements are achieved.

Several people discussed issues relating to quality differences and how they relate to industries with different production volumes. Some believed that higher volume industries, such as the automobile industry, may not need to worry about quality as much because they could simply add a few more production runs to make up for defects. One industry member's perspective however, was that the automotive industry has moved to a culture where quality is a given. He suggested that the aerospace industry must make a similar cultural transition. An example of the lack of such a culture is that in general aviation, it is still accepted that one hour of flight is followed by one hour of maintenance. Another example is that avionics suppliers say that they can provide 85% product reliability, but why not 99.9%? The criticism was made that there shouldn't be such a low reliability, because the avionics are made of the same solid-state components used in a home stereo, which does have a high expected reliability.

A couple of people mentioned concerns about risk assessment and mitigation. It was suggested that an FR should be added to address this issue. Several people commented that some sort of inspection is needed to ensure the quality of products. Risk mitigation was proposed to address inspection as well as solving problems. The reasoning was that it is critical that there are zero defects for many aerospace products. This was claimed to be particularly true in the space sector, where it is often prohibitively expensive if not impossible to fix problems once a product has been launched. The AMSDD, however, does not attempt to address concerns for risk assessment and mitigation. These concerns should be identified by product designers and translated into production requirements.

A lack of quality feedback in the MSDD was mentioned several times by industry members. It was mentioned that at one site, inspectors look for problems that need to be reworked, but there is no feedback to the technicians who created the problem in the first place. Feedback was also mentioned in terms of transferring knowledge from production back into design to improve future products. People were uncertain how feedback was accomplished within the MSDD and whether it should be specified explicitly. The AMSDD addresses feedback concerns with a new section requiring Continuous Improvement. This section is described in Chapter 4, Section 4.2.2.

The comment was made that quality problems first need to be identified as issues (such as in the problem identification and resolution section). Some people believed that the coupling between FR111, FR112, DP111, and DP112s should indicate that the Quality section of the MSDD follows Identifying and Resolving Problems, rather than preceding it. These people questioned whether variability or quality issues had more of an impact on a system. The point was also made that it may not be possible to identify issues as quality issues until they cause variation within the manufacturing system. The author does not agree with these arguments however, and believes that the coupling is correct as it is currently illustrated. Improving production quality reduces the need to identify and resolve problems, because there are fewer problems. Identifying and resolving problems *after they have been created* does not change the fact that a defect has been made. It only prevents the defect from advancing through the system. For this reason, the coupling has been left unchanged.

Some people confused the "Quality" section of the MSDD with the Quality division within their companies. These comments were insightful, nonetheless, for understanding some of the specific aerospace industry concerns. A commercial aircraft manufacturer explained that everything from supplied parts to finished aircraft must be approved by the FAA. The job of the Quality system within this company was to ensure complete FAA compliance. In the event that an aircraft were to crash, the company would be required to prove that all parts of the plane had been through a quality assurance program.

Many people commented on the important role that design has on quality. It may be possible to produce a very high quality product with a given design, but the cost may be prohibitively high.

Several people pointed out that engineers will often call out specifications that are overly tight and hard to meet. These specs cause parts that would actually function fine to be scrapped. Nearly continuous design changes in the aerospace industry also have a negative impact on companies' ability to produce defect-free products. One site mentioned that experiments for design for manufacturability and design for assembly are lacking from the MSDD and are very important to getting the right quality output from the manufacturing system. A related comment was that physical modeling gives a better understanding of part produceability than CAD does. These comments indicate that the design process cannot be done in isolation from manufacturing. The new product design section of the AMSDD addresses many of these concerns in the context of the overall manufacturing system design.

The statement was made that product quality originates with product engineering. The point was that product designers must work to design stable manufacturing processes and design products so that they can be manufactured. Engineering should work with operators to determine the changes that need to be made to make products more manufacturable. At the same time, this interaction helps manufacturing to understand why some designs need to be done a certain way. It was suggested that "key characteristics" of products should be considered in the design of manufacturing processes. If features are so critical that they need to be measured (i.e. inspected), then the investment should be made to develop a system that prevents mistakes from ever occurring in the first place.

Several people noted that resolving quality problems requires additional work for military customers. The military requires a rigorous program to close process and test anomaly documents. Approval is required from the customer for each anomaly. In addition, for companies producing both military and commercial products, hardware and designs are frequently non-standard for military work.

Level IV

One manager said that it should be easy to achieve FR-Q1 by implementing DP-Q1, but that in practice it is not. He mentioned that processes are changed without telling anyone, materials are changed unexpectedly (by suppliers), or materials may become unavailable.

Companies generally agreed with FR/DP-Q2 and FR/DP-Q3. A comment was also made that very few aircraft companies have a good handle on process capabilities and that companies don't understand the impact of the capability of individual processes. This comment was supported by comments from other sectors in the aerospace industry. Some companies indicated that they desired to improve their process capabilities and wanted more guidance as to how to do so. Many assembly processes in the aerospace industry are manual and a good way was desired to measure and improve the capability of manual processes. It was also mentioned that it can be difficult to identify individual processes, because almost every feature of a part becomes a unique process. Due to the geometry of the part and physics of the process, process capability varies for each feature. Finally, when production rates are very low, it may take a long time to have a statistically significant sample to determine process capability.

Level V

One manager questioned how to evaluate the tradeoff between investing money to improve *tool quality* versus *operator quality*. He suggested that important factors in making this decision include how long a program will be around, what level of quality can be achieved with a tool versus operators alone, whether a tool is needed or helpful, and how simple tools need to be / how simple they can be.

Several groups questioned whether a new FR should be added to this level to the effect of "eliminate design assignable causes." The point was that there are many quality problems that result from product design decisions. Problems can be due to changes in an existing product design or because a product cannot easily be manufactured as it is currently designed. It was also mentioned that the MSDD does not address issues that arise when almost all products must be designed from scratch due to highly customized requirements. As mentioned previously, the new product design section of the AMSDD attempts to address these concerns.

Regarding FR/DP-Q11, one company discussed its decision to automate more processes to reduce variability and increase its capacity. Some processes cannot be automated, however, because older designs are incompatible with some of the new assembly equipment. Several companies mentioned that they desired further decomposition of FR/DP-Q11. The AMSDD does not provide further decomposition because the new product design section addresses several issues relating to equipment design/selection.

Comments about FR/DP-Q13 pertained much more to product design than specifically to the process plan design. Several people mentioned the need to work on design for manufacturability, explaining that products are often designed in ways that are difficult for technicians to meet the specifications. Some complaints were that designers are often time-constrained, so they quickly turn out a new design, rather than seeking to use existing components or create standard architectures. It would be easier for manufacturing to use existing stock products, but designers frequently specify new parts, different materials, different dimensions, or different tolerances. Again, the new AMSDD addresses many of these concerns in the new product design section.

FR/DP-Q14 were a major concern for every group in the aerospace industry. Each site had slightly different concerns and problems, but the quality of incoming material was a frequent issue. This problem was exacerbated at one site that had several thousand suppliers, many of which supplied similar or overlapping parts to different divisions. The quality of incoming material can fluctuate for a number of reasons. Sometimes, as was the case for several companies, suppliers will make a slight processing or material change that has an unintended result, yielding parts that do not meet customer requirements.

One engineer mentioned that parts spend a lot of time in rework. He said that the primary causes of this rework are 1) component failure and 2) design changes. Another person indicated that it is not necessarily the suppliers' fault when there are material problems. He said that 85% of material problems actually come from customers giving suppliers the wrong specifications in the first place.

Level VI

Concerns were raised by some people that the MSDD only addresses workers as parts of the manufacturing system and ignores other issues, such as home life, personal problems, etc.. The AMSDD does not attempt to provide significantly more detail on these issues. These issues are important, but are better addressed by social scientists within the human relations field.

Some people questioned whether a new FR and DP were needed to increase the amount of automation or to automate difficult processes. These people pointed out that there are some manual operations that cannot achieve the required Cpk or where automation would improve Cpk. The AMSDD does not attempt to specify the amount of automation that should be used or when a process should be automated. These decisions are left to product designers and manufacturing engineers, because they must be made on a case by case basis.

Another suggestion for a new FR and DP focused on personal responsibility and accountability for the quality of products from a factory. The intention was that people need to understand the customers' expectations for products and the company should build a culture that encourages individual responsibility throughout all levels of the organization. Parts of the industry are changing from a "do-check" system to ownership by operators. One manager suggested that people need to ask not only whether tasks get done, but if they're done correctly and then close the loop by following up on any problems. Again, the AMSDD does not attempt to address this issue, leaving it to the field of social sciences.

Industry members had a number of comments for FR/DP-Q121. Most companies had some type of certification process associated with their training program. One company mentioned that re-certification should be required, because as it currently stands people retain their certification indefinitely unless they are written up for a certain number of problems. The training programs and certification often seemed to be fairly general and not necessarily specific to the individual procedures that are required of technicians. This lack of detailed training results in non-standardized work. In some sectors it is difficult to standardize tasks, because from one product to the next the required tasks keep changing. In addition, the aerospace industry requires a significant amount of experience and on the job training before people can be entrusted to perform tasks on their own.

Regarding FR/DP-Q122, companies often said that they had a hard time standardizing work between operators. In order to standardize the performance of a specific fabrication procedure, one company filmed multiple operators performing an operation, then reviewed the tapes with all technicians and required them to perform it the same way. Another company that says it does not do well with standardization uses planning packages with a list of operations that must be performed, but lacks the specific order of operations or descriptions of how to perform the procedures.

Some companies pointed out that their current reward system and work ethic may slow the acceptance of standard work methods. At one company, technicians are individually evaluated for performance. If they can perform a task better than everyone else, they're rewarded for it. This leads to operators keeping their "tricks" and tips to themselves. Also, while some workers take pride in their work, there are always some who just do what is required for a paycheck. It was suggested that people need to be rewarded for bringing up problems and suggesting solutions.

An interesting point from one company was that workers have come to rely on inspectors to catch problems. There are three important problems with this situation, besides the fact that a mistake was created in the first place. First, inspectors themselves make mistakes and may overlook an error. Second, workers don't get immediate feedback about their errors. Finally, when an inspector finally does catch something, workers don't understand what's wrong, because they may have been doing the same thing for a long time.

Government regulations were pointed to as an obstacle for standardized work methods. One site said that the drawings used by technicians are not very descriptive, because the government requires drawings to be separated from the part dimensions and tolerances. Drawings are kept separate from these specifications and from the steps required to perform operations. This separation requires a significant amount of referencing and cross-referencing to assemble products.

While most companies agreed with the need to mistake-proof operations, many companies said they had difficulty actually doing so. Some companies were concerned that mistake-proofing fixtures don't always pay off if 1) products are frequently redesigned and the fixtures cannot be reused, 2) a very large number of fixtures would be required, or 3) production volumes are low. It was suggested that designers may be able to improve mistake-proofing by standardizing designs, but the designers are often pressed for time. Another concern was that with an older work force, some people may resist mistake-proofing devices, because they feel that they are not trusted to do a good job.

3.3.2 Identifying and Resolving Problems

Industry members generally agreed with the overall structure of this section of the MSDD. Some suggestions that are not specific to individual FR/DPs are discussed below, followed by more specific comments.

One company indicated that a lot of problems in the manufacturing system occurred because other problems were not identified early enough. Another company suggested that more emphasis should be placed upon being proactive and preventing problems before they happen. As mentioned in the Quality section, some people also said that the information generated by identifying and resolving problems should feedback into improving product quality. While proactive behavior by workers is beneficial to a manufacturing system, the AMSDD has not attempted to address this concern. The AMSDD does attempt to address quality feedback with a new section on continuous improvement.

Companies indicated that several problems hindered identifying and resolving problems. One of these problems is that many aerospace sectors are constantly pushing technological limits. Therefore, it is difficult to control the interactions between product design and manufacturing, because both designs and processes may be new. In addition, the government often pushes for product customization, rather than standardization. This customization may require unique processing techniques and parts that do not work with a company's regular methods of problem identification and resolution. Another problem is that some companies are spread out over long distances and many buildings. It can be difficult to get engineers at one location to deal with problems at another location.

Level IV

Many companies commented that good communication is critical to quickly respond to production disruptions. One site mentioned that it often had problems getting timely information about problems and changes because it was isolated from the main site where products were designed. Another site mentioned that people need to get involved and call attention to problems that they see. Multiple groups at this site use the same type of components. If one group discovers a problem with a batch of parts, that information should be transmitted to all other groups immediately. In practice however, it may take weeks or even months for the information to be communicated to everyone.

In contrast to FR-R1, one group suggested that a team shouldn't respond to problems with excessive speed. The point was that if a problem is taken care of too hastily it may be done poorly or incompletely. This company said that they use a very structured method of solving problems and that problems must be fully resolved before a product can be put into service.

Level V

One company said that they experienced problems satisfying FR/DP-R11, FR/DP-R12, and FR/DP-R13, because of a lack of standardization between groups. For example, one group would push defective parts aside while another group would do a full investigation of the parts. Similarly, communication between groups complicated problem resolution. Groups would sometimes provide incomplete information or they may deny responsibility for a problem. Another site pointed out that even when people know that something is wrong, people often don't want to stop production.

A different problem mentioned by a company is that the company has a good tracking system for some problems, but problem documentation is not always sufficient. The exact cause of problems and the corrective actions taken to resolve the problems are not always recorded. Some people do not want to spend time recording details about a problem after it has been resolved. A computer system used for tracking problems may be rigorous, but the human input may not be meaningful and well thought out.

One company working on a military product indicated that there is a large paperwork path through the steps of reporting, responding to, and correcting errors. For a previous product, they said that a standard repair model had been created and approved so that people could fix their own problems without external approval. This standardized repair system is not available on the current product, so a long approval process must take place before problems can be fixed. It was also mentioned that no two identical products ever come out of assembly.

Many people mentioned that they already use a standard method to identify and eliminate root causes, DP-R13. It was suggested that the aerospace industry may be particularly good at this as a result of its long military heritage. A couple of suggestions for improvement to the MSDD were made. The first suggestion was that engineers, both design and manufacturing, should be located on or near the manufacturing floor to speed the resolution of problems. It was also suggested that "trend analysis" be used in addition to a standard method of problem solving. The reason for trend analysis is that even if root-cause analysis is used it may be possible that the true root cause is not immediately identified. By keeping track of problems, so that trends can be discerned from the data, the true root cause of problems can be determined and eliminated. Both of these suggestions have been incorporated into the Identifying and Resolving Problems section of the AMSDD.

Level VI

Regarding the identification of disruptions where they occur, FR-R111 (now FR-R112 in MSDD v.5.1), it was suggested that inspection steps should be performed in logical places in the work sequence, so that problems can be caught when and where they occur. This suggestion was not implemented in the AMSDD because it requires specific product and process knowledge.

One company said that it has become more difficult to simplify material flow paths, DP-R111 (now DP-R112 in MSDD v.5.1), as the company has grown. They said that it was easier when parts were processed almost entirely in one area. Now, parts travel through multiple "centers of excellence" for their required processing. It was also noted that there are problems with parts getting lost as the parts travel throughout the company and it is almost impossible to identify where the parts are lost.

Another company indicated that simplifying flow paths is difficult for them because they use extremely large machines that are very difficult to move. Some machines rest on pilings that are driven down 70 feet into bedrock.

The question was raised as to whether DP-R111 (now DP-R112 in MSDD v.5.1) could be phrased more generally, so that it did not specifically address material flow paths. Other flow paths, such as information, should also be simplified to improve response time within a system. This suggestion was implemented in the AMSDD.

Most companies did not appear comfortable with their ability to identify disruptions when they occur, FR-R112 (now FR-R111 in MSDD v.5.1). Some people mentioned that manufacturing engineers monitor the output of workers, looking for problems. Other people said that workers rely too heavily upon planning to tell them when inspection of parts should take place. One company said that introducing self-inspection has helped, because the operators try to identify and fix their own errors before passing the work along. This company also admitted that there are limits to self-inspection and suggested that it is better for work to frequently be passed along to the next worker so that a fresh pair of eyes can find any mistakes. It is often difficult for people to find their own mistakes after they've worked on a part for too long.

There were a couple issues that industry members had with the wording of DP-R112 (now DP-R111 in MSDD v.5.1). The first was that it says to "increase" the operator's sampling rate. Increase could infer that checking 20% of parts as opposed to 10% is acceptable. In truth, the operator should check every part between each step, so that mistakes are caught immediately. This concern has been addressed in the AMSDD. The second problem was that the DP refers to equipment, rather than the product. Because many aerospace operations are manual, it was suggested that machine-specific references be reworded if possible. For this reason, the AMSDD has attempted to differentiate between FR/DPs that address only automated processes versus automated or manual processes.

Regarding DP-R113, "Context sensitive feedback," it was mentioned that not all groups have the expertise to provide specific information about problems.

Several people mentioned the need to identify correct support resources, FR-R121. A corrective action board was suggested as one possible way of implementing the DP-R121. People noted that workers often jump straight to the top of an organization, instead of working through lower-level resources who can address problems. It is also not infrequent for multiple people to be tasked with the same problem and each come up with a different solution.

Several companies mentioned different ways of implementing a rapid information transfer system, DP-R123. A comment was made that in the aerospace industry, support resources are typically people, not equipment. One way of contacting these people is with an automated pager and/or email system. If there is no response after a set period of time, the next level up is contacted. This continues until the problem has been resolved.

3.3.3 Predictable Output

For the most part, industry members agreed with this section of the MSDD and had only minor suggestions for changes. A couple general comments were related to knowledge transfer within the company. One site said that it was trying to create an integrated system with no isolated databases, so that information was available wherever it was needed within the company. Another site mentioned the importance of developing a critical path and precedence list for operations. This precedence system should be used for scheduling team members and the sequence of parts that need to be processed, so that the production schedule is met.

Level IV

There were no changes suggested to FR-P1 and DP-P1.

Level V

Regarding FR-P11, "Ensure availability of relevant production information," one company mentioned that they were setting up a visual information system to achieve this requirement. Another comment, which was discussed in the previous section, was that a capable information system is not sufficient unless the data in the system is useful. It was suggested that an FR/DP pair that addresses information integrity may be needed. Such an FR/DP pair has not been added, however, because it is unclear how this integrity would be assured within the manufacturing system design. Employee training is already addressed in the Quality section.

There were a couple comments on FR-P12 and DP-P12. The first was that people must understand how to use and setup equipment properly to ensure predictable output. One company experienced an electrostatic discharge problem in a circuit soldering operation, because non-grounded soldering tips were used for an application that required grounded tips. This incident would actually be addressed by the quality section of the MSDD, which discusses the need to give operators the proper training, select the appropriate equipment, and use mistake-proofing devices. The second comment was that FR-P12 and DP-P12 were insufficient as currently stated. It was suggested that an additional FR/DP pair should be added to address the need to ensure that tools and supplies are available when they are needed. This FR/DP has been added to the AMSDD.

There were many comments about FR-P14 and DP-P14. One company explained that many of the parts that it uses are specific to individual, highly-customized products. These products often require redesign for each customer, so many components cannot be ordered until the design has been finalized and moved to production. Some parts are "stock" parts, but the majority of parts are unique. A significant problem with these unique parts are that the lead time to procure them is often longer than the time available from when they are specified until they are needed. This requires parts to be bought "just in case" because they cannot be ordered just in time. In addition, some parts (particularly for military customers) require additional testing, radiation hardening, and may have a "freshness" date after which the parts cannot be used. In general, this company feels that most of its components cannot be considered "commodity" items.

A site that has a considerable number of fasteners that need to be stocked and replenished discussed how it controls supply. This company kits some fasteners, distributes some through vending machines, and stores others at their point of use. Use of the correct fastener is very important. If a technician drops a fastener on the floor, the fastener cannot be reused. This rule prevents the technician from accidentally picking up a different fastener that was on the floor and reduces the possibility that damaged fasteners are used.

Level VI

Many aerospace companies seemed to have trouble implementing standard work methods, DP-P131. One site said that operators are typically given components and diagrams, but not told the exact order of assembly, nor which tools to use for each step. A manager said that he was considering standardizing a process by having a few people do each process, rather than having everyone perform multiple processes. Some of the processes require high degrees of skill and can be performed better by some workers than others. Two problems with this approach are that 1) it reduces the cross-training of the workers and 2) it may be boring and monotonous, causing workers to lose focus and reduce the quality of their work. Government requirements were also cited as a hindrance to standardization, because the government requires some tests and processes that are not used for commercial products.

DP-P132 received significant criticism from industry members. Interviewees touched upon many aspects of human relations and indicated that a single FR/DP pair is insufficient for tackling this very complex issue. The overall message was that 1) it is virtually impossible to make workers come to work if they do not want to and 2) it requires more than a single incentive or motivational program to make workers want to work. As a result of this criticism, FR/DP-P132 has been rephrased more generally and specific concerns are left to the field of human relations and personnel management.

Using cross-trained workers to prevent production interruptions, DP-P133, received mixed reviews from the industry. Some sites indicated that they are working to better cross-train workers. One site said that cross-training can be difficult because some operations are very complex and can only be mastered by a small subset of workers. Another site mentioned that out-of-station work hinders workers' ability to cover for each other. Both sites mentioned that workers are often pulled away from the line for training and that their absence hinders production.

3.3.4 Delay Reduction

The Delay Reduction section of the MSDD was received well by some industry members who felt that it was pertinent to them as it was already structured. Other industry members felt that it addressed too many issues relating to high volume, mixed-model production that did not apply to them. One person was concerned that the variability of people within the production system had not been taken into account in this section. Specifically, since people in the aerospace industry often require higher expertise and may be difficult to find, he wondered if the variability of recruiting and retaining workers should be considered. If so, the question was whether they should be considered under throughput time variation or mean. Regarding the first concern, the AMSDD now differentiates FR/DP pairs that only apply to mixed-model production. The training issues covered in the Quality section should largely address the concern about variability of people within the production system. The AMSDD does not attempt to address frequent turnover rates, but employees should be properly trained for the tasks they are assigned.

Several concerns were raised that some common delays in the aerospace industry are not necessarily the result of the manufacturing system design. One cause of delay can occur when unexpected work is brought into the factory. This could be a product that is inserted into the middle of the factory for refitting or changes that are made to an unfinished product that interrupt the normal flow of production operations. Meeting government requirements (FAA, military, etc.) was also cited as a source of delay, because parts must pass through a series of inspections before they can be used. Restrictions are imposed upon the manufacturing system that products can only be built to a specified point, then the parts must wait for the customer to accept them.

One engineer believed that this would be the hardest section of the MSDD to implement in the aerospace industry, particularly in sheet metal fabrication. He said that it would require a very large capital investment to reduce setup times in order to eliminate the production of large batches. His reasoning was that stamped parts are inexpensive, but not having those parts is very expensive for the company. Furthermore, he suggested that inspection can be done more quickly in large batches, because if one part is good it is more likely that all of the parts are good. With sheet metal stampings, for example, if one part is good and it fits into a stack of other parts, the entire stack can be accepted as good.

Legacy products also hinder companies' ability to reduce delays. People are reluctant to redesign parts or components for the benefit of the overall manufacturing system. It is expensive to prove designs and get them accepted by customers. Companies often do not believe that they would recoup these costs with sales of the redesigned older product, so they continue to manufacture the known and accepted design. What manufacturers do not take into consideration is whether the overall system would recoup the costs. Redesigning the manufacturing system may result in lower overall costs for the company, even if some products individually cost more to produce.

Level IV

Some companies said that FR-T1 and DP-T1 are not applicable to them, because the company only produces one type of product. These responses varied between locations within companies, however. While assembly may have been continuously producing the same product, people in fabrication and sub-assembly areas often had to produce multiple components. Some of these areas tended to produce in small run sizes, even one at a time, while other areas ran large batches of products.

Companies identified several issues relating to FR/DP-T2 . One company said that producing to takt time was difficult, because customers demand products with what were effectively negative lead times. Finished goods are typically expected a couple months after the design has been finalized, but some parts can take six months or more to procure. The manufacturing system is left in a situation where it is always trying to catch up. Another source of process delay comes from test equipment. It is often difficult to finish environmental and performance tests within takt time. These tests require products to undergo long testing periods. If products do not meet the design requirements, changes must be made followed by another round of tests.

Some aerospace companies have transitioned to single-piece flow production in assembly. One company mentioned that they are working towards applying single minute exchange of die (SMED) techniques to apply single-piece flow to part fabrication. This company also uses a "bus schedule" for composite parts that must be autoclaved. Parts must arrive by a specified time each day or else wait until the next day to be processed. This method does not control the number of parts processed, but simplifies scheduling and limits the length of time that products must wait before being processed.

One company identified FR-T4, "Reduce transportation delay," as a serious need within its manufacturing system. The company processes parts at many different buildings across a large campus. Parts may be driven several miles when moving from one process to the next. This transportation increases the risk of parts being lost or damaged as well as adding transportation delays.

Level V

Industry members had different views on FR-T11 and DP-T11. One site that produced multiple product types in the same fabrication and assembly facility felt that its schedules change quickly and have very little stability. This site suggested that customers need to better understand their own requirements because constantly changing priorities and requirements makes scheduling within the factory very difficult. For this reason, the company also found it difficult to calculate their takt time, FR-T21. A different factory that produced only one type of product had a very different experience. The second site felt that its demand was very predictable, because its contracts are finalized years before full production begins.

Several sites said that they were working towards producing products in small run sizes, FR-T12. One of the sites said that it needed to produce in small run sizes because of the unique nature of its products. Problems obtaining quality parts was cited as the biggest obstacle to small run sizes at this company. Another company indicated that it is getting better at quick changeovers, but that it does not yet know how long changeovers actually take for some areas.

Most companies were comfortable with the concepts in FR/DP-T22 and FR/DP-T23. However, the term "pitch" was unknown to the majority of interviewees. It was suggested that a set of definitions be added to the MSDD to clarify concepts and terms with which people may not be familiar. These definitions have been added to the AMSDD and are described in Chapter 4, section 4.2.7.

Industry members had several comments regarding FR/DP-T51, FR/DP-T52, and FR/DP-T53. One company noted that the definition of "support" inferred by the MSDD is not the same as the definition used at some companies. This company used the term "support" to refer to everyone not working on the production floor, rather than maintenance, material supply, and specific resources that regularly interact with production workers. The term "support resources" has been added to the list of AMSDD definitions. Another comment was that DP-T52 could be misinterpreted as a suggestion to isolate workers. Finally, there were two suggestions for additional concepts that could be covered in this sub-section. The first suggestion was to consider how people or resources must wait for parts and information. The second suggestion was to include the planning, paperwork, and other tasks that production and support workers need to perform as part of their duties. The AMSDD incorporates these suggestions into a new FR/DP pair relating to information delay.

One site provided an example of problems that resulted from workers performing both production and support activities. Engineers at this site often take the best technicians from production to help them build prototypes of new products. This practice interferes with regular production, because the technicians are needed for their skills in the production area. These technicians would be valuable for helping to transition products from development into manufacturing if they could be counted upon to remain in production. Instead, the technicians are often busy helping to build the next prototype. It may be better to separate the responsibilities of these workers so that they can be counted on to work only in production or only in support for specified periods of time.

Level VI

Aerospace companies had varied responses to FR/DP-T221, FR/DP-T222, and FR/DP-T223. One company indicated that automated operations frequently could be accomplished in less than the takt time, but that it was more difficult to meet takt time with manual operations. Test operations were also considered difficult to keep within takt time, because when errors are discovered, they require reworking and retesting. As a result of the difficulties meeting takt time, one company said that it performs a lot of parallel processing. People at this company do not trust that everything will get completed if tasks are broken into smaller segments that allow each task to be accomplished within takt time. The current system is more like a "pig moving through a snake." People and resources are assigned to get one project done as quickly as possible, then move to the next critical project. This process is complicated by changing priorities that may result in one product being completed before it's due while an overdue project waits for completion.

Different sectors had different responses to DP-T223. One company said that they already stagger production of different products. Another site that produces only one product indicated that it's not possible for them to stagger production in assembly, although this may be possible in fabrication.

One company had trouble maintaining a standard level of work in process (WIP) between subsystems, DP-T231. People seemed more concerned with having the specific components needed for assembly than with maintaining a standard amount of WIP. Standard WIP is difficult because a large number of components were non-standard and had long lead-times. The company is trying to address this problem by using more common parts and consolidating part storage into a central store. Previously, every production area had its own storage area. One problem with the new setup however, is that specific programs still own the parts in central storage. This possession means that the parts cannot be used by other programs without first changing ownership. Each program also has less direct control over the storage and handling of its parts than when it maintained its own stores.

3.3.5 Direct Labor

Industry members had several comments about this section of the MSDD, but not many suggestions for changes. One general comment was that non-standard work throws a monkey wrench into the workings of a manufacturing system. Out-of-station work, late parts, rework, and other non-standard activities prevent people from adhering to efficient work patterns.

Level IV

Some people had trouble with FR/DP-D1, because they believed that it was not possible to separate operators from machines or because most processes in their factory were manual. In general, companies agreed with FR/DP-D2. A lot of companies indicated that they are focusing on ways to improve safety, training, and ergonomics. These companies have begun to look at the design of the entire workstation, rather than just jigs and fixtures.

It was suggested that another FR/DP pair should be added to address eliminating wasted processing. Some processing steps are not truly necessary, but are required because of the way that a manufacturing system is designed. For example, if parts of an assembly process are performed in two locations, a packaging operation between steps may be needed to protect against contamination. It may be possible to eliminate this operation, however, if the system layout was changed so that the parts were not transferred between locations. A new FR/DP pair has been added to the AMSDD to address these concerns.

Level V

There were several concerns about FR/DP-D11 and FR/DP-D12. One problem is that many machines are still manually operated, so they cannot be loaded and walked away from. Another concern is that the cost of designing and building autonomous equipment may counterbalance the increased labor productivity. A couple other problems stem from union rules. The union at one company does not want people to run more than one machine at a time. The union claims that running multiple machines places unfair demands on the workers. Union members also have job classifications that may restrict the types of tasks that workers can perform. One site worked with the union to prevent this problem by establishing a single job classification for all technicians at the site.

Several sites indicated that they have already begun implementing 5S programs, DP-D22. One site wanted to see a further decomposition of FR/DP-D22 to explain how stations should be setup for manual tasks versus automated tasks. Regarding FR-D23 and DP-D23, one site said that technicians perform different tasks from product to product, but agreed that it may be possible to setup a basic set of tools required for the majority of jobs.

3.3.6 Indirect Labor

Industry comments regarding Indirect Labor covered a wide range of topics. The phrase "indirect" seemed to be fairly nondescript and each person had his or her own interpretation of what indirect meant. One site said that the large amounts of paperwork required for managing people causes a large number of managers to spend their time just pushing paper. For this reason, outsourcing tasks was suggested as a way to reduce indirect labor costs. Another site suggested that indirect labor is a serious problem, because the impact of fringe benefits are rising more quickly than inflation or than direct labor efficiencies are improving.

Level IV

Most people agreed that self-directed work teams, DP-I1 are important. Some were concerned however, that there is a point past which self-directed work may reduce quality. It was suggested that there need to be checks and balances to ensure a stable quality output.

Several sites mentioned that they were working to develop visual factories to get the right information to the right people at the right time. Some people questioned whether Indirect Labor was the proper place for the visual factory. It was suggested that the visual factory benefits direct labor and contributes to 5S programs. As a result of other changes to the AMSDD, the concept of designing a "visual factory" has been moved to the Delay Reduction section which, through coupling, still affects Cost Reduction.

3.3.7 Other issues

Industry members brought up a number of issues that did not necessarily apply to a specific section of the MSDD. Some of these issues are general suggestions for improvements to the MSDD while other issues provide insight into situations within the aerospace industry.

Government / Military Issues

People at one site said that government requirements placed on contractors by Federal Acquisition Regulations (FARs) deter many capable suppliers from bidding for government contracts. These suppliers will not accept government work, because they do not want to deal with the invasive government oversight and hands on approach. It was suggested that this oversight is part of what leads to "$600 hammers," because the additional cost of overhead is tacked onto the price of the product.

Military programs were also criticized for the degree to which information transfer is restricted. Information can flow from other parts of a company into a classified program, but not out of the classified program. For example, if a batch of commonly used components is found to be defective on the commercial side, the government program will learn about the defect. If the same discovery is made on the government side however, the knowledge cannot flow out to the commercial side.

One engineer had a suggestion for how to use the MSDD to change military policies. His suggestion was that the MSDD be compared to the Department of Defense's Production Readiness Review (PRR). The PRR is used by the DoD to review the production readiness of a manufacturing system. He said that it is just a high-level checklist, but that it drives the design of companies' manufacturing systems. His hope was that by comparing the MSDD with the PRR, improvements could be recommended to the PRR process.

General Industry Issues

While some people commented specifically on the government's close oversight of projects, other people mentioned that this is common for the entire industry. It was suggested that the aerospace industry may have to interface directly with their customers more than other industries. Commercial and military customers alike often have to accept any exceptions to the original design specifications. Companies generally cannot make the decision to accept deviations on their own. Additionally, customers often want verification that specified processes were followed.

One plant manager explained that the manufacturing system at his plant had evolved over time. He said that the system is designed as though it had been extrapolated from a small engineering project into a company. The company had been successful due to its strength in engineering and new technology, rather than manufacturing expertise. The industry now needs to increase its manufacturing competence without sacrificing the engineering or technology. It is important to design the manufacturing system, rather than let it evolve. The plant manager suggested that the MSDD could be a useful tool for guiding the design of aerospace manufacturing systems, but that differences in characteristics between industries must be considered. In particular, he said that different industries have varying degrees of manufacturing repetition. In general, the automobile industry has highly repetitive processes, while the aerospace industry ranges from low to medium repetition. Demand is also much less predictable in the aerospace industry than in the auto industry and it is harder to make long-term demand predictions.

One company discussed a different accounting concept that they are using called "economic profit." In this system, profit is calculated as the operating earnings minus the cost of invested capital. The cost of invested capital is equal to the company's net assets multiplied by the cost of capital. This system often drives the company towards outsourcing. Outside suppliers do not need to perform the research and development that this company does, so the suppliers do not have to amortize these costs. The company feels that outsourcing allows them to concentrate their investments on core competencies and research and development that gives them an edge over their competitors. A cautionary statement from another company however, is that outsourcing takes time control away from a company and leaves the company dependent upon external capacity.

While many people pointed out the differences between aerospace manufacturing and other industries, some industry members were critical of this viewpoint. These people said that a large degree of internal chaos has been accepted by the aerospace industry as characteristic of the industry. They claimed that it is actually the way that the industry has gone about business that causes this chaos. For example, if design changes were incorporated in discrete blocks, rather than from one aircraft to the next, it would reduce some of this confusion. It was noted that frequent design changes are not solely the fault of the customer demanding the changes. The industry has also tended to make large promises that are hard to deliver.

The MSDD

A number of people wanted the MSDD to explicitly show how feedback is designed into a manufacturing system. These people wanted to know how different sections of the MSDD interrelate. They also wanted the MSDD to guide the development of feedback systems within manufacturing systems. A way to communicate manufacturing problems to a company's quality system and its design engineers was desired. The MSDD already indicates how different sections interrelate through coupling. Regarding feedback, a new Continuous Improvement section has been added to the AMSDD.

A number of people asked how the MSDD can be applied in practice. These people wanted a defined implementation methodology and pointed out that specific practices are often lacking. The MSDD however, is meant to be general and not so specific that it can only be applied to a single industry or even one factory. As for an implementation methodology, the MSDD is intended to guide the design of manufacturing systems as a conceptual tool, rather than as a step-by-step methodology.

One person asked how a company should address what he termed "surge capacity." Surge capacity is the ability to address and resolve problems without causing the entire manufacturing system to come to a standstill. Addressing "surge capacity" would likely be an individual consideration at a company that would depend on the expected degree of demand fluctuations. The MSDD attempts to portray a generalized manufacturing system design and would not specify excess capacity as a requirement. Excess capacity allows companies to be overly comfortable with problems that should be resolved. Therefore, companies should not seek to develop excess capacity, but should try to resolve problems to reduce the need for extra capacity.

Another person felt that the MSDD lacked details about how a company should be structured internally. One example he gave was whether maintenance workers are located in different parts of a machine shop or if they are centrally located. Another example was whether the company treats upstream processes as suppliers and downstream processes as customers. The MSDD does not attempt to address the organizational structure of a company, so that the MSDD can be applied to a wide range of industries.

One of the interviewees did not understand why takt time appears under the Delay Reduction section. He believed that takt time measures whether a manufacturing system will have a delay, but that takt time is not a means for reducing delays. The purpose of takt time is to set the pace of production. Work tasks should be divided into segments that can be accomplished within the takt time. While takt time does help to indicate if a set of operations is running too slow or too fast, it also helps prevent delays by balancing production throughout the factory. By both balancing demand and making future delays more visible, the takt time helps to eliminate delays by focusing improvements on specific processes where they are needed.

One company explained one reason why buy-off points between manufacturers and customers have been created in the aerospace industry. The way that contracts are written, customers can request design changes up to a certain point in the manufacturing process. If a product is delivered early, the company is responsible for fixing any design changes that would otherwise have been incorporated. Therefore, buy-off points in the manufacturing system protect manufacturers from being held responsible for changes after the product has been accepted by the customer.

Several people commented on the sequence and pace of production within the aerospace industry. One person commented that it is not always beneficial to level production within a takt time interval. For example, if an aircraft that has a 20 day takt time requires four engines, leveling production within the takt time interval would require that the first engine should be installed by day 5, the second by day 10, and so on until all engines had been installed by the end of day 20. Engines are expensive components and having the first engines installed wait for a long period of time incurs a significant capital holding cost. It was suggested that an economic analysis should be performed to help guide the production sequence within a time interval. If possible, more expensive components should be installed last. The bill of material (BOM) for a product should be sequenced so that it considers the economic value of the parts and how capital costs contribute to the overall manufacturing system cost.

Another person suggested that, because products have a higher value as they move through the value stream, it is beneficial to shrink later cycle times. The implication is that in the aerospace industry, due to inventory costs, it may not be desirable to have all manufacturing positions filled at a given time. It is true that it may not be desirable to have all positions filled at a given time, but these people are making an assumption that moving products according to takt time means that a product can only move from one position to another in a given period. Therefore, in order to move through multiple positions, people assume that a product must move faster than takt time. In truth, multiple positions can be combined into a processing step, so that parts are still moved according to takt time. The value to grouping positions according to takt time, even if the positions are physically separated, is that takt time sets the pace of production. If takt time is forgotten at the end of the production system, then the system must revert back to a schedule and output will not be as predictable. If takt time is maintained, then a product should continue to exit a set of positions at the specified time. If the product is not completed by the end of the takt time, efforts should be made to shrink the processing time of the positions so that takt time is met.

One manager suggested that a command and control network is missing from the MSDD. He also suggested that policy, or hoshin from the Japanese system, should be added. Hoshin planning is described as a policy deployment system that points an organization in the right direction to achieve its goals. [King, 1989] While hoshin planning may be a valuable tool for companies to use at an organizational level, the AMSDD does not attempt to address high-level business organization issues. Therefore, hoshin planning has not been added to the AMSDD. For the same reason that policy was not addressed, the AMSDD does not address the command and control issues. The AMSDD is not meant to prescribe the structure of an entire corporation. The AMSDD focuses on the organization of the manufacturing system and the interactions between manufacturing and other functions within the company.

A couple comments were made regarding employees and the manufacturing system. It was suggested that employee involvement and teamwork is lacking from the MSDD. It was further suggested that if a manufacturing system is working well, the operator will be the indicator. The AMSDD is not well suited for addressing employee involvement and teamwork, so these issues have not been incorporated.

A couple groups at one factory argued different viewpoints on the merits of using the MSDD to improve the design of manufacturing systems. The first group felt that because the manufacturing system usually accounts for less than 10 percent of costs incurred by a company, the manufacturing system should not be a high priority for improvement. Other problems, such as managing design changes, managing different product configurations, data management, and material planning were proposed as areas that incur high costs and need significant improvement. The second group argued that changes in the manufacturing system drive changes in the rest of the company, so it is important to work on manufacturing system changes and improvements.

Product Design

Many industry members suggested that the MSDD should explicitly address manufacturing issues relating to product design. There were only a few specific suggestions for what should be included, but the consensus was that product design plays a dynamic role in the design of aerospace manufacturing systems and should therefore be included in the MSDD. One particular suggestion was that there should be concurrency in design and manufacturing. Concurrent design allows product designers to consult with manufacturing engineers to ensure that the parts they are designing are manufacturable and can be produced at a reasonable cost. As a result of the many suggestions from industry members, product design has been added to the AMSDD and will be discussed in the next chapter.

3.4 Summary

The feedback from aerospace industry members provided many detailed insights into specific concerns and considerations for the operation of aerospace manufacturing systems. In general, the feedback indicated that the MSDD is a good model for describing many of the interactions and relationships within a manufacturing system. The feedback also made it clear that there were a couple of missing concepts that the aerospace industry considers very important. The first missing concept was product design. While only a few people specifically suggested that the MSDD should address product design, almost everyone interviewed at one time or another remarked that one or more sections of the MSDD was highly influenced by product design decisions. The second missing concept was a feedback system. Many industry members wanted the MSDD to indicate how lessons that are learned through the operation of a manufacturing system are used to improve the design of the manufacturing system.

Chapter 4 Aerospace Manufacturing System Design Decomposition

4.1 Introduction

This chapter addresses the issues raised by industry members regarding the applicability of the MSDD to the aerospace industry. As a result of the suggestions, a new Aerospace Manufacturing System Design Decomposition (AMSDD) is developed. The AMSDD is based upon the MSDD presented in Chapter 2. To address the importance of *feedback* and *product design* in the aerospace industry, the AMSDD has added two new sections called Continuous Improvement, and Product Development. In addition to these changes, some sections originally contained in the MSDD were modified or further decomposed to better address the industry concerns presented in Chapter 3. It is hoped that the new AMSDD will provide a valuable tool for the aerospace industry to use when designing future manufacturing systems.

4.2 Proposed Aerospace Manufacturing System Design Decomposition (AMSDD)

4.2.1 Top-level FRs and DPs

The AMSDD attempts to draw attention to some of the high-level decisions that a company must make when deciding whether to invest in manufacturing system design. A new top-level of decomposition was added, because discussions with industry members indicated that investment and financing strategies have a profound effect on the decision to design, operate and improve manufacturing systems. The AMSDD has seven levels of decomposition, so the levels start at "Level 0" as opposed to "Level 1." This numbering scheme is intended to facilitate comparisons between the AMSDD and the MSDD. A full version of the AMSDD can be found in Appendix C.

Shareholder Value

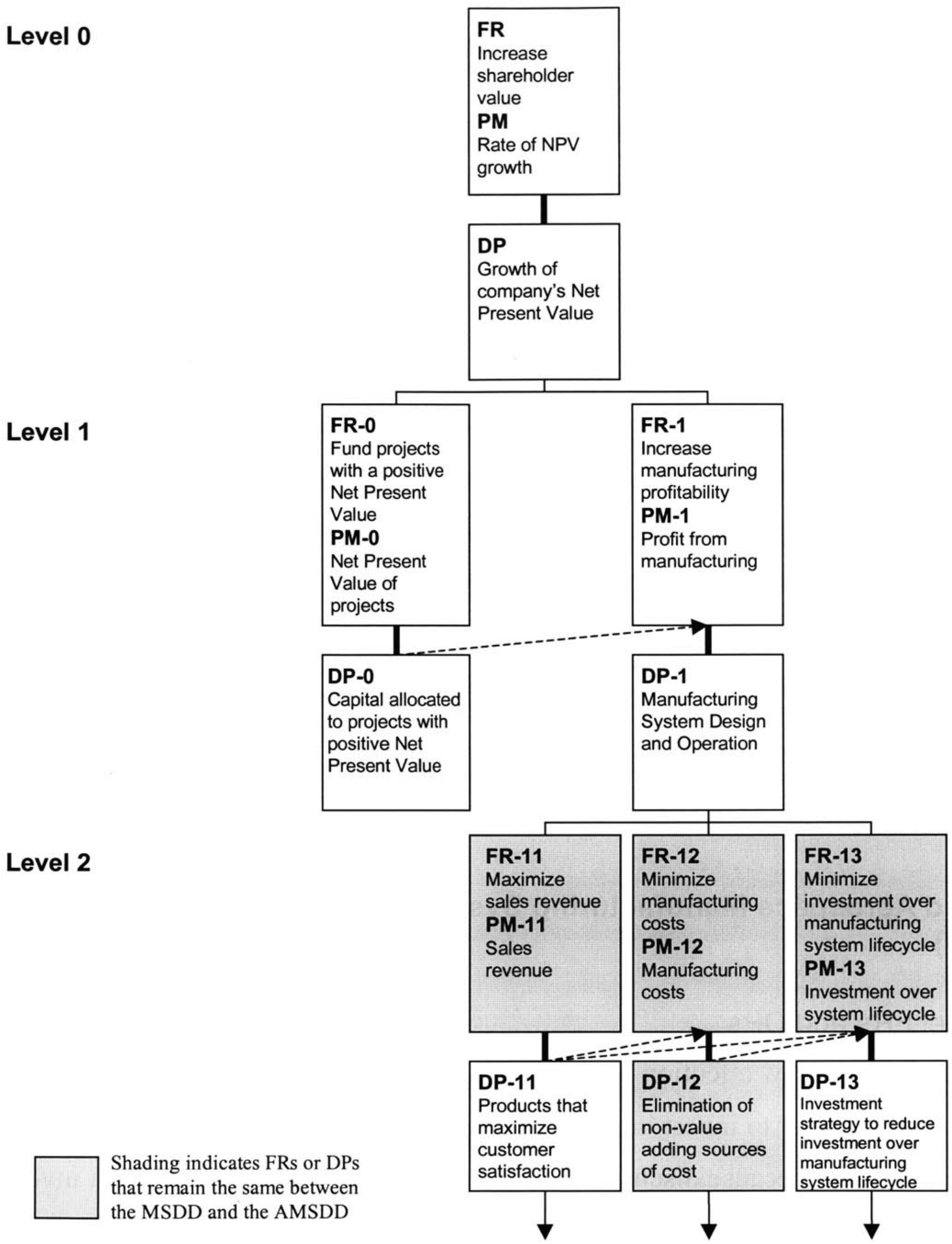


Figure 4.1: Top Levels of the AMSDD

As discussed in Chapter 3, EVA™ was suggested as a possible top-level functional requirement for the AMSDD. Shareholder value was also mentioned many times by industry members as a high-level corporate goal. A survey of 14 executive and middle level managers at aerospace companies found that all 14 managers believed that the stock market had a significant impact on their companies' top-level goals. [Fernandes, 2000] A problem with shareholder value however, was that it was uncertain how it could be evaluated as a top-level FR. Some investors use EVA as a way to evaluate stock values, so EVA was investigated as a possible surrogate for shareholder value.

According to Stern Stewart, the company that developed EVA, EVA is an estimate of a business's true economic profit. [Stuart, 1994] Economic profit is different from accounting profit, because economic profit considers a company's opportunity costs as well as actual costs. (See Appendix D for more information on opportunity cost.) Stern Stewart provides three specific ways that EVA differs from accounting profit:

- EVA is the residual income remaining after subtracting the cost of all the capital that has been employed to produce the operating profit.
- EVA is charged for capital at a rate that compensates investors for bearing the firm's explicit business risk.
- EVA adjusts reported accounting results to eliminate distortions encountered in measuring true economic performance.

A problem with using EVA in the AMSDD is EVA's customized nature. Stern Stewart does not advocate a single definition of EVA and even points out that it has identified 164 unique performance measurement issues that are considered differently and tailored to each company using EVA. Therefore, while EVA may be a good measurement by which individual companies guide their management decisions, it is not possible to create a single EVA model of the AMSDD that applies to multiple companies.

While a single EVA formulation cannot be used across companies, Stern Stuart draws an important link between EVA and Net Present Value (NPV)[2]. "The NPV of a project, strategy, or acquisition candidate … is by definition equal to the present value of the EVA it can be expected to generate in the future." [Stuart, p.74, 1994] Furthermore, Stern Stuart equates a company's shareholders' wealth with the company's NPV. (See Appendix D for more information on

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[2] NPV is used in place of EVA™ for most of this thesis because NPV is a commonly known concept and is not trademarked.

NPV.) This relationship is important because it indicates that NPV can be used to measure how well a company provides value to its shareholders.

After considering feedback from industry members and the relationship between EVA, shareholder wealth, and NPV, "Increase shareholder value" was selected as the top-level functional requirement of the AMSDD. The word *increase*, instead of maximize, was selected to indicate that companies should always try to provide shareholders with more value. The top-level design parameter achieves this FR through "Growth of [the] company's Net Present Value." The performance measurement, "Rate of NPV growth," measures how well the top-level FR has been satisfied.

The top-level FR/DP pair is decomposed into FR-0 and FR-1. FR-0 requires that companies only "Fund projects with a positive Net Present Value." FR-1 requires that companies "Increase manufacturing profitability." FR-0 follows logically from the top-level FR/DP pair, because exclusively funding projects with a positive NPV will increase a company's overall NPV, thus increasing shareholder value. FR-1 follows from decomposing the top-level FR/DP pair, because increasing the profitability of the manufacturing system increases the contribution of existing products to the overall corporate NPV. (Note: It would also be possible to have an FR-2, FR-3, and other functional requirements at this level of decomposition. In addition to improving the profitability of the manufacturing system, other FRs could address the profitability of product design, sales and marketing, and other business functions. A comprehensive corporate decomposition is beyond the scope of this thesis. This thesis focuses on decomposing the FRs and DPs that relate to aerospace *manufacturing*, so these other possibilities will not be pursued.)

In order to satisfy FR-0, DP-0 specifies "Capital allocated to projects with positive Net Present Value." If a project has a positive NPV, the amount of money returned to the company will be greater than the required investment and costs over the life of the project, where all funds are considered in present dollars. This FR/DP pair addresses investments in both new projects and improvements to existing systems. A concern was raised that this investment strategy will lead to sub-optimization. If a project's NPV is calculated correctly however, sub-optimization should not occur. The impact of a project on the entire manufacturing system should be considered.

Some projects, such as implementing a just-in-time material replenishment system, may not appear to have a positive NPV if the project is evaluated in only one part of a factory. When the entire factory is considered however, the NPV may prove to be positive. Therefore, using NPV analysis for investment decisions will encourage companies to take a high-level system view and avoid sub-optimization.

DP-1, "Manufacturing system design and operation," differs from the MSDD. The addition of "and operation" indicates that designing an effective manufacturing system is insufficient. The manufacturing system must also be operated as the designers intended. Even though the FR-1's from the AMSDD and the MSDD are different, their corresponding DP-1's remain very similar. This similarity indicates that once a company has decided to manufacture products, the only way to improve the performance of the manufacturing system is to design (and operate) the system in an efficient manner. Industry members generally agreed that the issues that must be considered when designing a manufacturing system are essentially the same, regardless of how the decision to manufacture was made. Therefore, even if there is disagreement about the top-level of the AMSDD, the AMSDD remains a valuable tool for identifying relationships that should be considered when designing a manufacturing system.

As in the MSDD, FR-1 and DP-1 are further decomposed into FR-11, FR-12, and FR-13. At the second level of the AMSDD, DP-11, FR-12, FR-13 and DP-13 were changed. DP-11 was changed from "Production to maximize customer satisfaction" to "Products that maximize customer satisfaction." The change reflects industry feedback that the MSDD did not address product design and its impact on manufacturing systems. The AMSDD attempts to address aspects of product design that have a direct impact on the manufacturing system. The Product Design section of the AMSDD results from further decomposition of FR-11 and DP-11, as shown in Figure 4.5.

DP-13 was changed from "Investment based on a long term strategy" to "Investment strategy to reduce investment over manufacturing system lifecycle." This change helps to better explain how FR-13 should be fulfilled. The original FR/DP-13 pair was criticized for being too vague and not being further decomposed. The new DP-13 indicates that manufacturing system design decisions should seek to reduce the overall investment that will be required for a manufacturing system. For example, this strategy may suggest a higher up-front investment for one project, but may indicate that it is better for another project to withhold a large investment until a future date when market demand will be better known. Further decomposition of this FR/DP pair is described in Section 4.2.9.

To illustrate how use of NPV in the AMSDD can influence manufacturing system design, a couple issues that arise in the aerospace industry will be considered in terms of an NPV analysis. The first issue is that several aerospace companies view manufacturing as a "necessary evil." These companies would prefer to focus their investments on research and development and outsource product manufacturing. An entirely hypothetical NPV analysis, shown in Figure 4.2 suggests how it may be a good idea for companies to retain a certain level of internal manufacturing capabilities. (Note: The benefits and drawbacks presented in the analysis would not all occur on the same time scale. This is part of the benefit of a NPV analysis. Some decisions that have a short-term benefit may result in a long-term disadvantage for a company.)

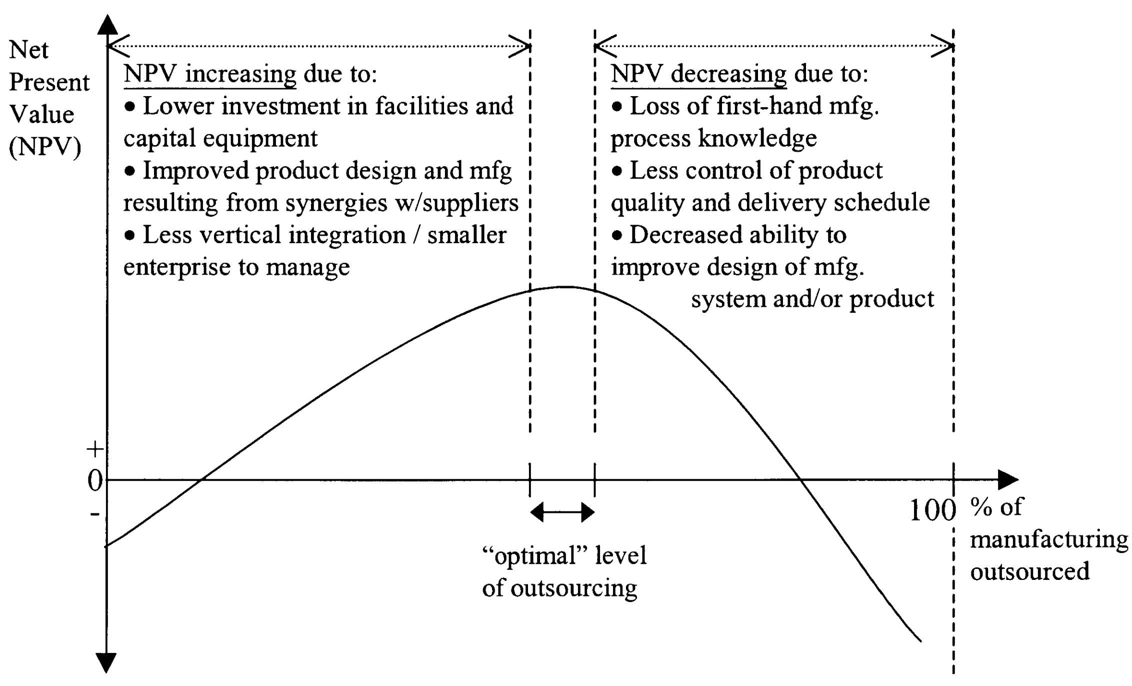

Figure 4.2: Hypothetical NPV Analysis of Decision to Outsource Manufacturing

If a company is completely vertically integrated, manufacturing everything from sub-components to the final product, the company may have a low NPV. The company may be able to make better use of capital that it has tied up in equipment by selling some equipment and investing the money to develop new products or new capabilities. Sharing knowledge with other companies, in order to purchase sub-components, may also increase the company's NPV. The company will gain access to a broader knowledge base that should benefit both companies. If the company outsources too much of its manufacturing capability however, it may lose some important advantages. When design engineers become removed from the manufacturing process, they may develop products that are more costly to manufacture than necessary. The engineers may not know the limits of the manufacturing system, or they may not realize that the system can perform even better than they believe. Outsourcing can also decrease the amount of control a company has over product quality and delivery, because the manufacturing facilities may not be close to the product designers.

The second issue that will be addressed in terms of an NPV analysis involves the decision to add capacity to a manufacturing system. People have commented that previous versions of the MSDD have not addressed how companies should decide to add manufacturing capacity. While it is not explicitly stated in the AMSDD, net present value analysis provides a valuable tool for guiding capacity planning decisions. Consider two examples. In the first example, a company with a discount rate of 12% is deciding whether it should build a new assembly cell to produce a product that will provide net revenue of $5 million per year for four years. The cost of a new assembly cell is $10 million. A cash flow diagram of the proposed project is found in Figure 4.3. Discounting the cash flows to present dollars, using the method found in Appendix D, indicates that the NPV of the proposed project is $5.2 million. The company should invest in the new assembly cell.

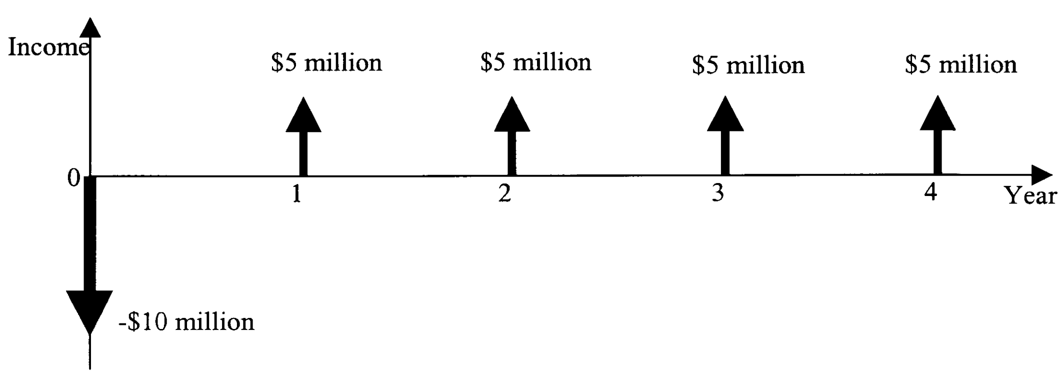

Figure 4.3: Cash Flow Diagram for Proposed Product

For the second example, assume that this same company is already manufacturing a product. Product sales have been better than originally expected, forcing the company to run three shifts of operation in a cell that was designed to run only two shifts. Three shifts of operations causes a couple of problems for the company. First, the cell does not receive as much preventive maintenance as desired. Second, using a third shift requires more material handlers and other support personnel than would be needed if production occurred only during the first or second shift. The total cost to the company of running a third shift is approximately $1.5 million per year. The revenue gained from meeting the increased demand is $3 million per year. The company must now decide whether to invest in a second cell for $5 million or continue running third shift operations. Demand for this product is expected to continue for another five years. Cash flow diagrams for the two choices are presented in Figure 4.4. Discounting the cash flows to present dollars, the NPV of building a new assembly cell is $5.8 million and the NPV of continuing the third shift is $5.4 million. Therefore, it would be best for the company to build a new cell to meet the increased demand.

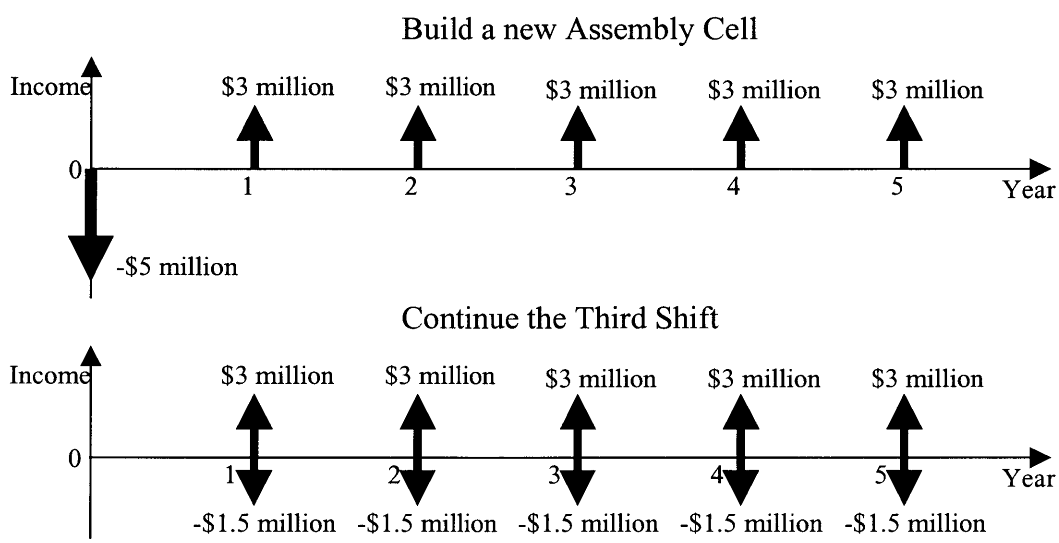

Figure 4.4: Cash Flow Diagram of New Assembly Cell vs. Third Shift Operations

Maximize Sales Revenue

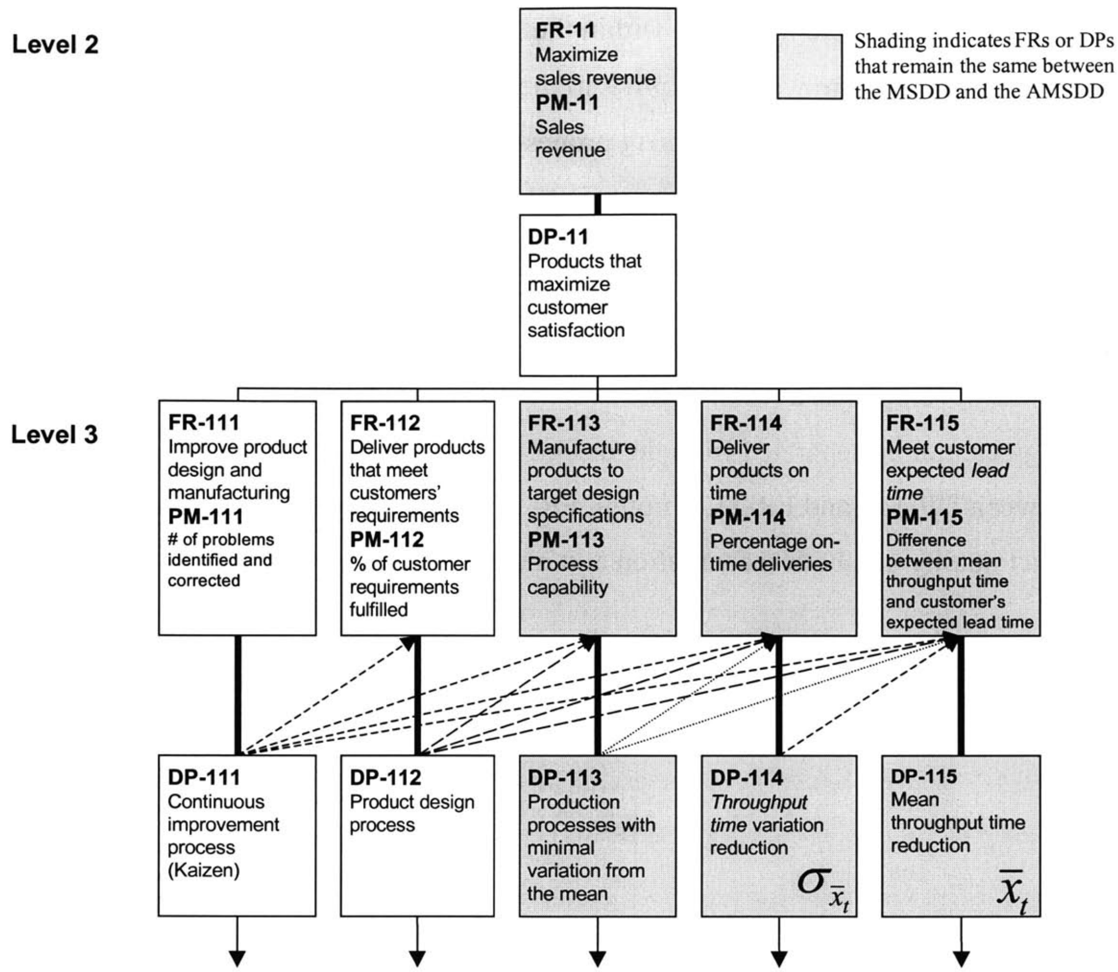

Figure 4.5: Decomposition of FR/DP-11 in the AMSDD

The decomposition of FR/DP-11 in the AMSDD, shown in Figure 4.5, is similar to the original MSDD, except two new FR/DP pairs have been added. The original FR/DP-111, FR/DP-112, and FR/DP-113 are now FR/DP-113, FR/DP-114, and FR/DP-115, respectively. The new FR-111, "Improve product design and manufacturing," is satisfied by DP-111, "Continuous improvement process." PM-111, "# of problems identified and corrected," measures the achievement of FR-111. The new FR-112, "Deliver products that meet customers' requirements," is satisfied by DP-112, "Product design process." PM-112, "% of customer requirements fulfilled," measures the achievement of FR-112. The decomposition of FR/DP-11 is partially coupled. DP-111 affects FR-111 through FR-115, DP-112 affects FR-112 through FR-115, DP-113 affects FR-113 through FR-115, and DP-114 affects both FR-114 and FR-115.

FR/DP-111 was developed in response to several questions by industry members regarding employee feedback and where it appears within the MSDD. It was determined that a feedback and improvement mechanism was not explicit in the MSDD, but that one should be present in the AMSDD. This continuous improvement process affects many aspects of a manufacturing system, as illustrated by the coupling between DP-111 and FR-111 through FR-115. It is because of this coupling and the profound effect that continuous improvement has on the entire manufacturing system that a separate branch has been added to the AMSDD.

FR/DP-112 was developed as a result of the overwhelming feedback from industry members that product design cannot be separated from the design of aerospace manufacturing systems. The coupling between DP-112 and FR-112 through FR-115 illustrates the impact that product design has on product quality and both the variation and mean of throughput time.

4.2.2 Continuous Improvement

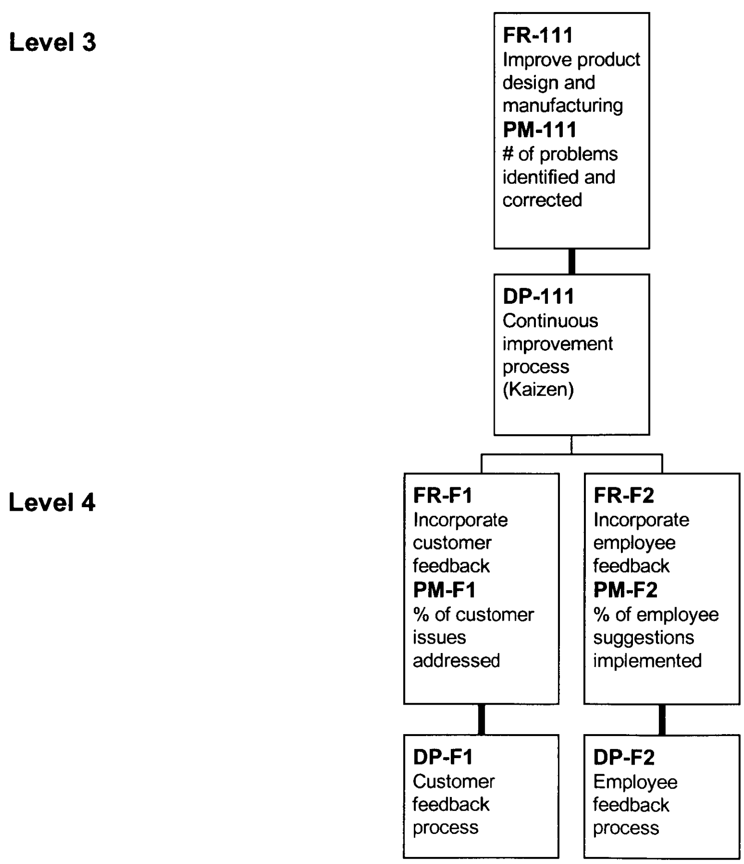

Figure 4.6: Continuous Improvement Section of the AMSDD

FR/DP-111 is decomposed into FR-F1 and FR-F2. FR-F1, "Incorporate customer feedback," is satisfied by implementing DP-F1, "Customer feedback process." PM-F1, "% of customer issues addressed," measures the achievement of FR-F1. This FR/DP pair indicates that it is important to seek and implement feedback from the actual users of a product. These users will often have important suggestions for how to make the product more valuable to themselves, thus improving future sales prospects. FR-F2, "Incorporate employee feedback," is satisfied by implementing DP-F1, "Employee feedback process." PM-F2, "% of employee suggestions implemented," measures the achievement of FR-F2. FR/DP-F2 recognizes that employees have detailed, yet often untapped, knowledge about many aspects of a product's design and manufacturing. It suggests that a formal mechanism or set of mechanisms should seek to capture this knowledge and gain feedback to improve products and the way that they are manufactured.

Initially, it may seem inappropriate to put Continuous Improvement at the far left of the AMSDD. The coupling between DP-111 and FR-111 through FR-115 indicates that this is correct from an Axiomatic Design standpoint, but one may argue that if a new manufacturing system is being designed it is not possible to begin with a continuous improvement process. As soon as a manufacturing system begins to take form however, improvements can begin. Customer feedback can be solicited before products are developed to ensure that the products will meet customer desires. Employee feedback can be obtained from employees at other sites, from employees involved in the system design process, and from the first people to begin working in the system.

4.2.3 Product Design

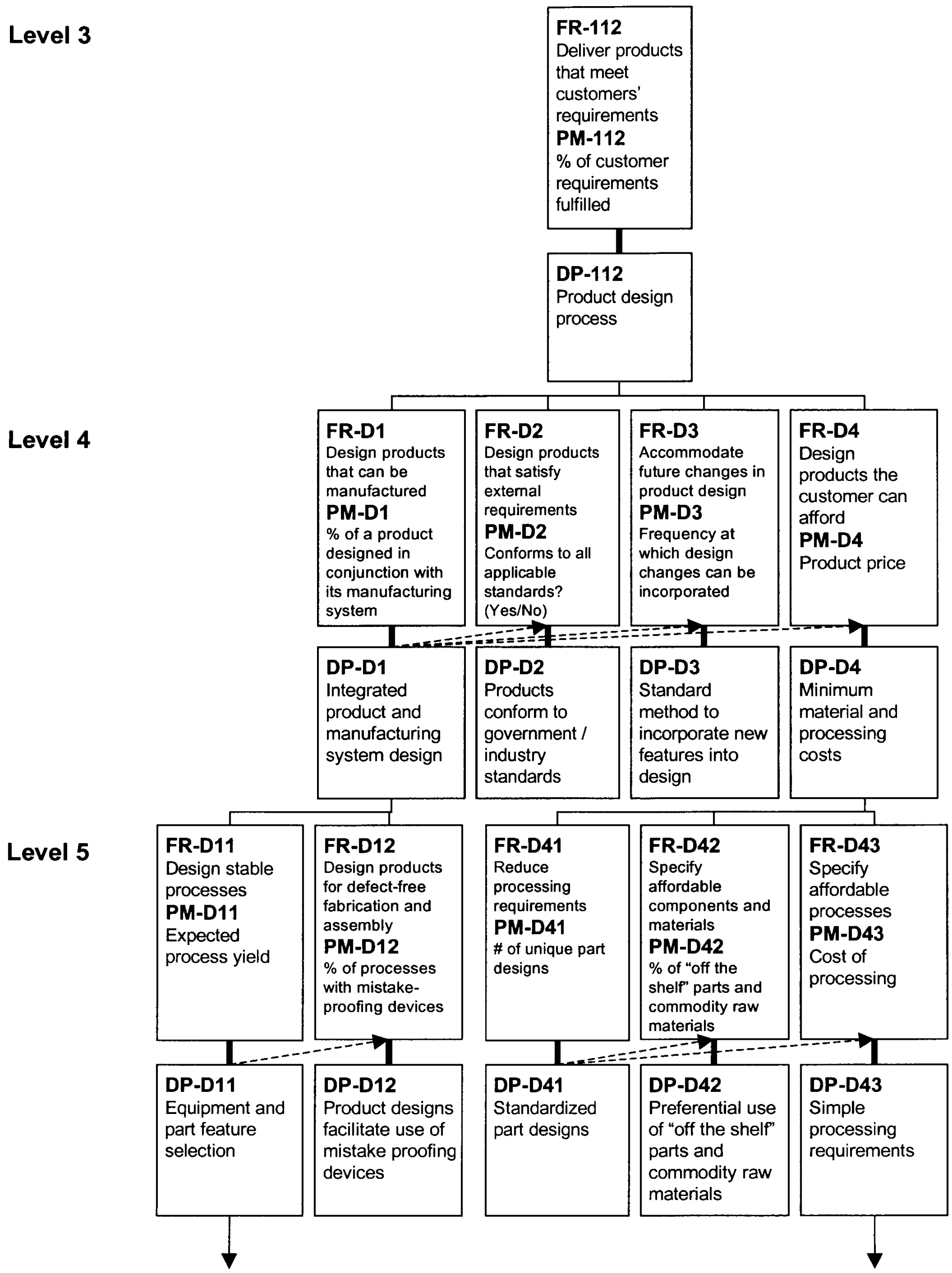

Figure 4.7: Product Design Section of the AMSDD

The product design section of the AMSDD addresses product design issues that affect manufacturing system design. The purpose of this section is to illustrate the interactions between product design and manufacturing, rather than to decompose the full product design process. A full product design decomposition is beyond the scope of this thesis.

FR-112, "Deliver products that meet customers' requirements," is decomposed into FR-D1, FR-D2, FR-D3, and FR-D4. FR-D1, "Design products that can be manufactured," is satisfied by DP-D1, "Integrated product and manufacturing system design." The success of achieving FR-D1 is measured by PM-D1, "% of a product designed in conjunction with its manufacturing system." FR/DP-D1 resulted from industry feedback that products must be manufacturable in order to meet customers' requirements. During visits to aerospace manufacturers, many manufacturing problems were attributed to product design. In order to design products that can be manufactured, the products should be designed concurrently with the manufacturing system and the equipment used to process the products. This design integration will ensure that the manufacturing engineers understand why products are designed the way that they are and why products must undergo specific processes. Integrated manufacturing system and product design also enables the design engineers to understand the manufacturing system's capabilities. Good interaction between manufacturing and design engineers enables the design and manufacture of products that meet the customer's requirements quickly and with little wasted costs.

FR-D2, "Design products that satisfy external requirements," is satisfied by DP-D2, "Products conform to government / industry standards." The achievement of FR-D2 is measured by PM-D2, "Conforms to all applicable standards? (Yes / No)." FR/DP-D2 resulted from industry feedback that products often have external requirements placed upon them that are not actually specified by the customer. These requirements can be FAA design requirements, military requirements, or even standards established within an industry. Designing products to meet these standards has consequences for product design that can impact design and operation of the manufacturing system.

FR-D3, "Accommodate future changes in product design," is satisfied by DP-D3, "Standard method to incorporate new features into design." The achievement of FR-D3 is measured by PM-D3, "Frequency at which design changes can be incorporated." One of the problems that appeared to be universal in the aerospace industry was the constant requirement to incorporate design changes into products already in production. It seemed that the design stage of the products was never entirely complete until the product was shipped to the customer and actually put in use. While it may be ideal to simply have zero design changes, this is not reasonable in any industry, and much less reasonable in the performance-oriented aerospace industry.

Therefore a mechanism should be created to facilitate these changes, so that the changes cause as little disruption to the manufacturing system as possible.

The method used for incorporating new design features should be standardized so that changes do not continuously disrupt production. One of the simplest ways to do this may be to allow changes only after a specified number of products have been built or after a predetermined time interval has passed. The changes that accumulate would all be incorporated into subsequent products. Additional changes would have to wait for the next set of products or the next time interval to be completed before the changes could be incorporated. This design change system is similar to the "block" system that was used for changing aircraft designs during World War II. The system could also operate in a similar manner to the automobile industry's practice of incorporating product changes by model year. A standardized system would allow the manufacturing system to operate with fewer disruptions between changes. Critical changes that would even require completed products to be retrofitted could perhaps be incorporated into the manufacturing system. This breach of standard practice should probably happen only if the impact of the changes on the entire manufacturing system would cost less than waiting for the current block to be completed and retrofitting the products immediately upon completion.

FR-D4, "Design products the customer can afford," is satisfied by DP-D4, "Minimum material and processing costs." The achievement of FR-D4 is measured by PM-D4, "Product price." Several people mentioned that product design has a significant impact on the final cost of the product. In order to keep products affordable, designers should try to keep the cost of materials and processes to a minimum.

Decomposition of FR/DP-D1 results in FR-D11 and FR-D12. FR-D11, "Design stable processes," is satisfied by DP-D11, "Equipment and part feature selection." The achievement of FR-D11 is measured by PM-D11, "Expected process yield." It is important for product designers to work with manufacturing engineers to ensure that the processes required to produce a part will be stable. Achieving this stability can be done by selecting the proper equipment for a design, designing parts so that they can be processed by existing equipment, or a combination of product design and equipment selection.

FR-D12, "Design products for defect-free fabrication and assembly," is accomplished by DP-D12, "Product designs facilitate use of mistake proofing devices." The achievement of FR-D12 is measured by PM-D12, "% of processes with mistake-proofing devices." FR-D12 requires that designers consider ways to ensure that the products can be manufactured with no defects. Some sectors of the aerospace industry produce many copies of a single product. This repetition makes it easier to design and use mistake-proofing devices. Mistake proofing can be more difficult for other sectors that have many unique part designs for different products. Designers should attempt to standardize parts or part features to enable the maximum use of mistake-proofing devices. These features could be as simple as directional indicators that tell assemblers which side of a part is "up." The features could also be common locating features that allow different products to fit into the same mistake-proofing device that guides technicians during a manual assembly or fabrication process.

FR/DP-D4 is further decomposed into FR-D41, FR-D42, and FR-D43. FR-D41, "Reduce processing requirements," is satisfied by DP-D41, "Standardized part designs." The achievement of FR-D41 is measured by PM-D41, "# of unique part designs." Using common component designs across multiple products, or for similar functions within a product, reduces the number of different processes that must be performed within a manufacturing system. For example, instead of using thousands of different fastener types and sizes on an airframe, designers could create a small list of fasteners that would be used to guide their specifications. This standardization would reduce the variety of holes that had to be fabricated, reduce the number of fastener types that had to be stocked, and reduce the possibility of drilling the wrong hole or using the wrong fastener. Another example would be selecting a single microprocessor design for use in multiple control systems, instead of designing unique microprocessors for each system. The processor may be considered too costly, or it may have unused or unnecessary capabilities if considered in the context of only one system. When used across several systems however, the single processor may require less investment in design. One design might also cost less because of volume discounts from purchasing larger quantities of the single processor, as opposed to small quantities of multiple processors.

FR-D42, "Specify affordable components and materials," is satisfied by DP-D42, "Preferential use of 'Off the shelf' parts and commodity raw materials." The achievement of FR-D42 is measured by PM-D42, "% of 'off the shelf' parts and raw materials." When designing products, designers should try to specify parts and materials that are affordable. Industry members commented that it is sometimes easier or faster for a designer to specify parts or materials that are very expensive or hard to obtain, but that this practice creates problems in manufacturing. Designers should consider the impact of their decisions on the final product cost. In order to keep costs to a minimum, commonly available or "off the shelf" parts should be used when possible.

FR-D43, "Specify affordable processes," is satisfied by DP-D43, "Simple processing requirements." The achievement of FR-P43 is measured by PM-D43, "Cost of processing." Designers must not only consider what parts and materials they specify, but what processes must be performed on the parts. If a part requires days of expensive processing, alternative designs and/or processing solutions should be considered. Whenever possible, parts should be processed on simple equipment that does not require a significant investment.

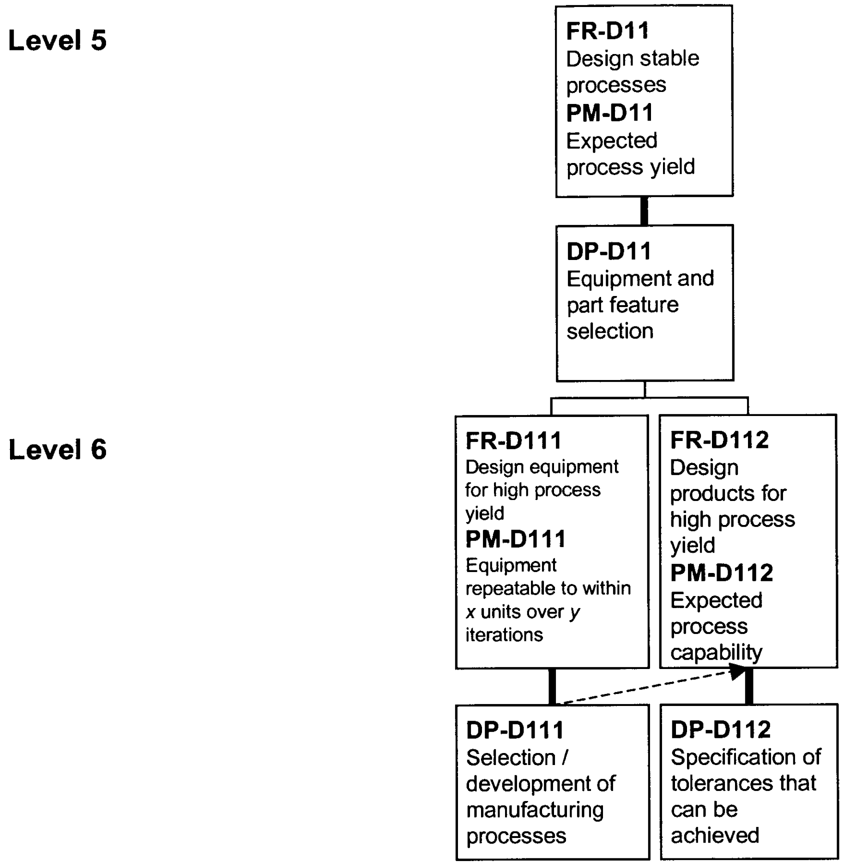

Figure 4.8: Product Design Section of the AMSDD (Design Stable Processes)

FR/DP-D11 is further decomposed into FR-D111 and FR-D112, as shown in Figure 4.8. FR-D111, "Design equipment for high process yield," is satisfied by DP-D111, "Selection / development of manufacturing processes." The achievement of FR-D111 is measured by PM-D111, "Equipment repeatable to within *x* units over *y* iterations." When selecting or designing processing equipment, it is important that the equipment can produce parts with a high process yield. It may be possible to achieve a high yield with existing processes, or by designing new processes.

FR-D112, "Design products for high process yield," is satisfied by DP-D112, "Specification of tolerances that can be achieved." The achievement of FR-D112 is measured by PM-D112, "Expected process capability." Designing and selecting processes to ensure a high process yield is not sufficient. New manufacturing processes can provide designers with a wider range of processing options and may allow new designs that had previously not been feasible. However, designing products that are expected to have a high process yield is important. Designers should ensure that the available manufacturing processes can achieve the specified tolerances. Specifying tolerances that are excessively tight may require inspecting and sorting parts to identify which ones can be used.

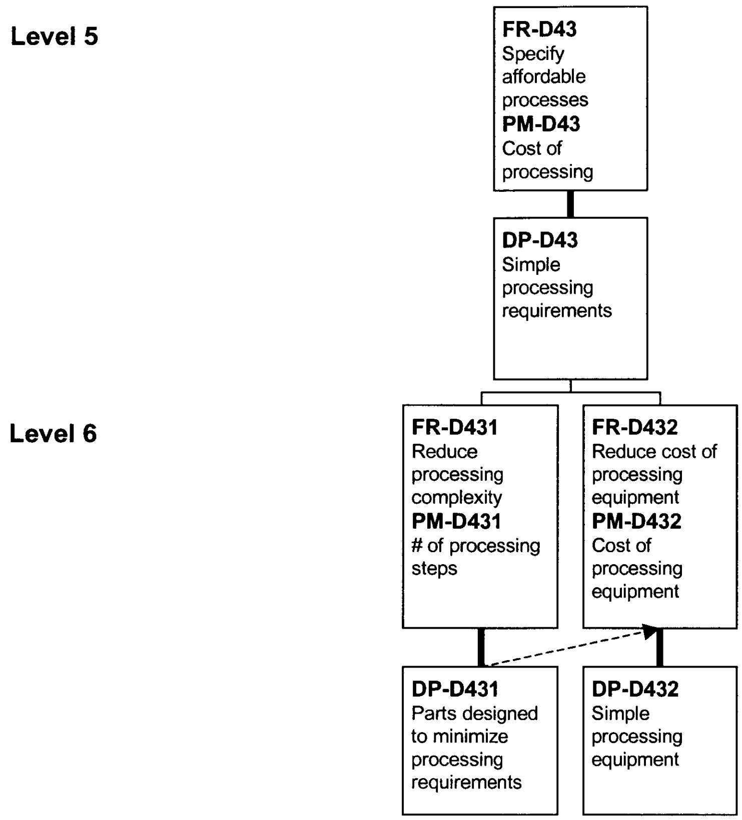

Figure 4.9: Product Design Section of the AMSDD (Affordable Processes)

FR/DP-D43 is further decomposed into FR-D431 and FR-D432, as shown in Figure 4.9. FR-D431, "Reduce processing complexity," is satisfied by DP-D431, "Parts designed to minimize processing requirements." The achievement of FR-D431 is measured by PM-D431, "# of processing steps." In order to reduce the complexity of processing, designers may choose to combine several parts into one. This compound part may require fewer total processing steps and therefore less total processing. On the other hand, creating an overly complex part may require significantly more processing, so it may be better to break the design into several smaller segments.

FR-D432, "Reduce cost of processing equipment," is satisfied by DP-D432, "Simple processing equipment." The achievement of FR-D432 is measured by PM-D432, "Cost of processing equipment." When designing products and the equipment, with which they will be fabricated and assembled, designers should try to reduce costs by reducing the equipment complexity. Instead of using one expensive, customized piece of equipment to fabricate a part, it may be possible to use several inexpensive, commonly available machines. An added benefit of this design strategy is that using inexpensive, commonly available machines increases the probability that the machines can be retooled and reused. If the product design changes or a specific product is not successful, it is likely that the simple machines will be easier to retool for other products.

4.2.4 Quality

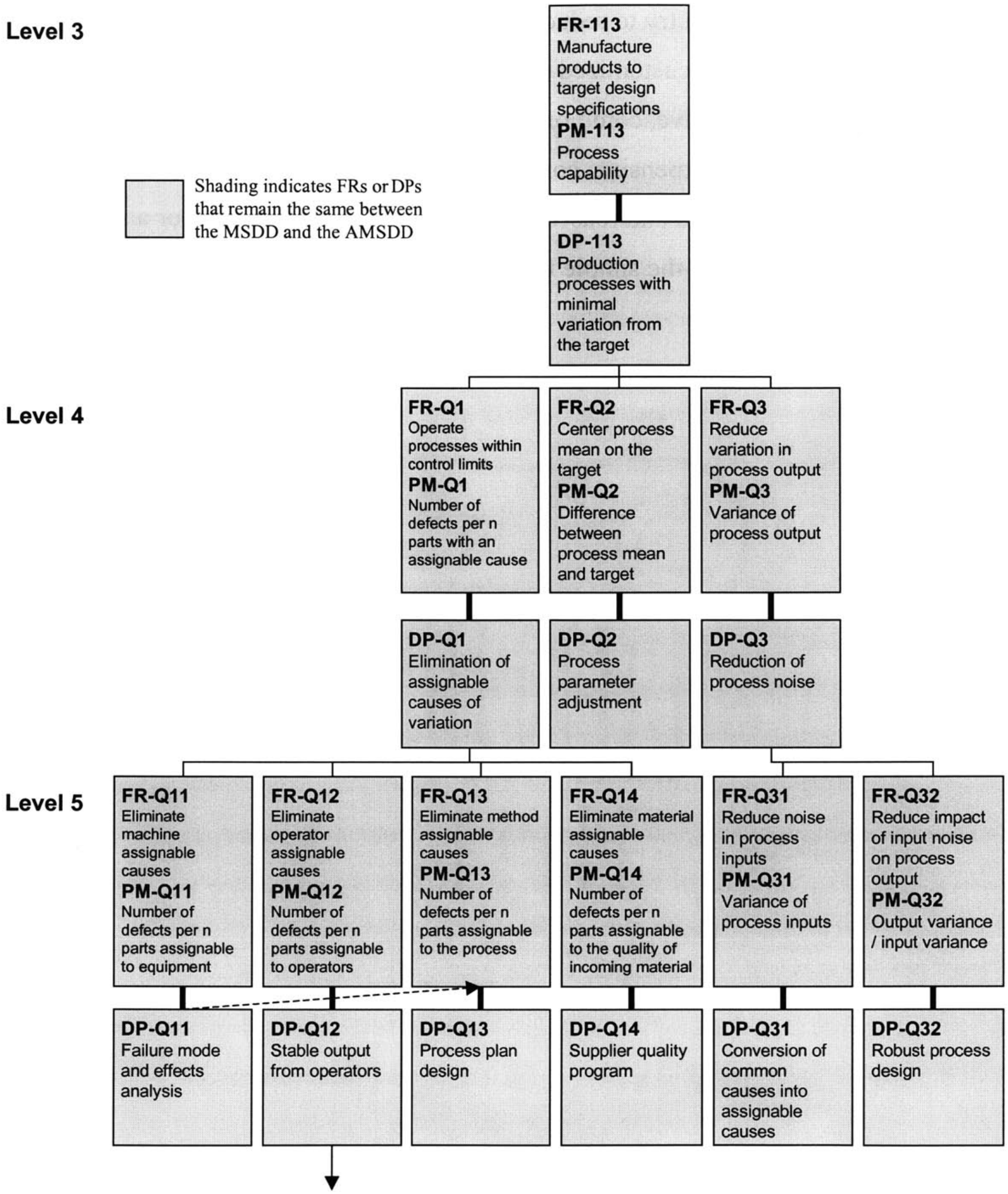

Figure 4.10: Quality Section of the AMSDD

The majority of industry members' comments about the Quality section of the MSDD indicated that they agreed with the section as it was presented to them. Only one minor change was made to the Quality section of the AMSDD when compared to the MSDD version 5.1. DP-Q121, shown below in Figure 4.11, was changed from "Training program" to "Training & certification program." This change resulted from comments that the aerospace industry requires its technicians to have a high degree of skill and knowledge. Most workers receive formal training, on the job training (OJT), and are certified to perform certain tasks. The new DP-Q121 indicates that it is not enough to simply train workers. The workers must demonstrate that they are qualified to perform the tasks required of them.

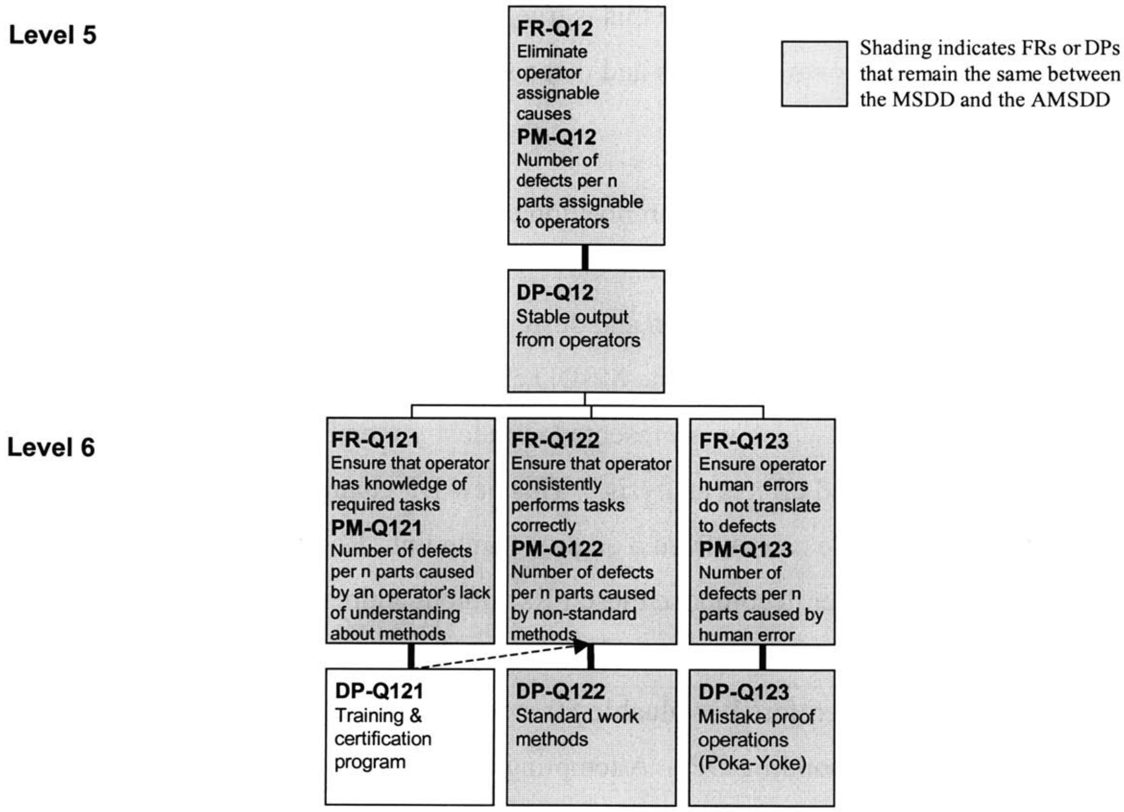

Figure 4.11: Quality Section of the AMSDD (Operator Assignable Causes)

A number of additional suggestions were received from industry members, but not added to the AMSDD. These suggestions and the reasons for not incorporating them will be discussed briefly. Several people at one site suggested including risk management and risk mitigation in the AMSDD. Risk management and mitigation appear to apply more to product design and operation than to manufacturing system design. The risks mentioned by the interviewees focused around the unexpected failure of a mission critical system and the need for redundant systems. It is likely that such issues, which are critical to a product successfully achieving its mission, will require tighter manufacturing tolerances. Product designers, not the manufacturing system, determine these tolerances. The AMSDD addresses some product design issues, but focuses on how these issues impact manufacturing. Risk assessment and risk mitigation appear to be issues that should be addressed primarily by product designers. These issues will indirectly impact manufacturing system design, but they should not be specifically addressed by the AMSDD.

Regarding FR-Q1, FR-Q2, and FR-Q3, a couple of people commented that a process must be defined before it can be stabilized. While this is true, it is assumed that manufacturing companies can define their own processes and that a specific FR/DP pair is not needed to address the issue.

Several people wanted to see further decomposition of FR-Q11, FR-Q13, and FR-Q14. There are two reasons not to further decompose FR-Q11. First, the new product design section addresses issues that relate to the selection and design of equipment for a manufacturing system. The second reason is that version 5.1 of the MSDD changed DP-Q11 from "Selection/ maintenance of equipment," which was presented to industry members in version 5.0 of the MSDD, to "Failure mode and effects analysis." This new DP change better explains how to eliminate machine assignable causes from a quality standpoint. Regarding FR-Q13 and FR-Q14, it would be difficult to further decompose these FRs without addressing the specific needs of a process or company. Decomposition at this level would be highly affected by unique situations at each company. It may therefore be valuable for a company to perform its own decomposition of these FRs and the corresponding DPs. Attempting further decomposition of FR-Q13 and FR-Q14 in the general AMSDD model, however, is not possible.

4.2.5 Identifying and Resolving Problems

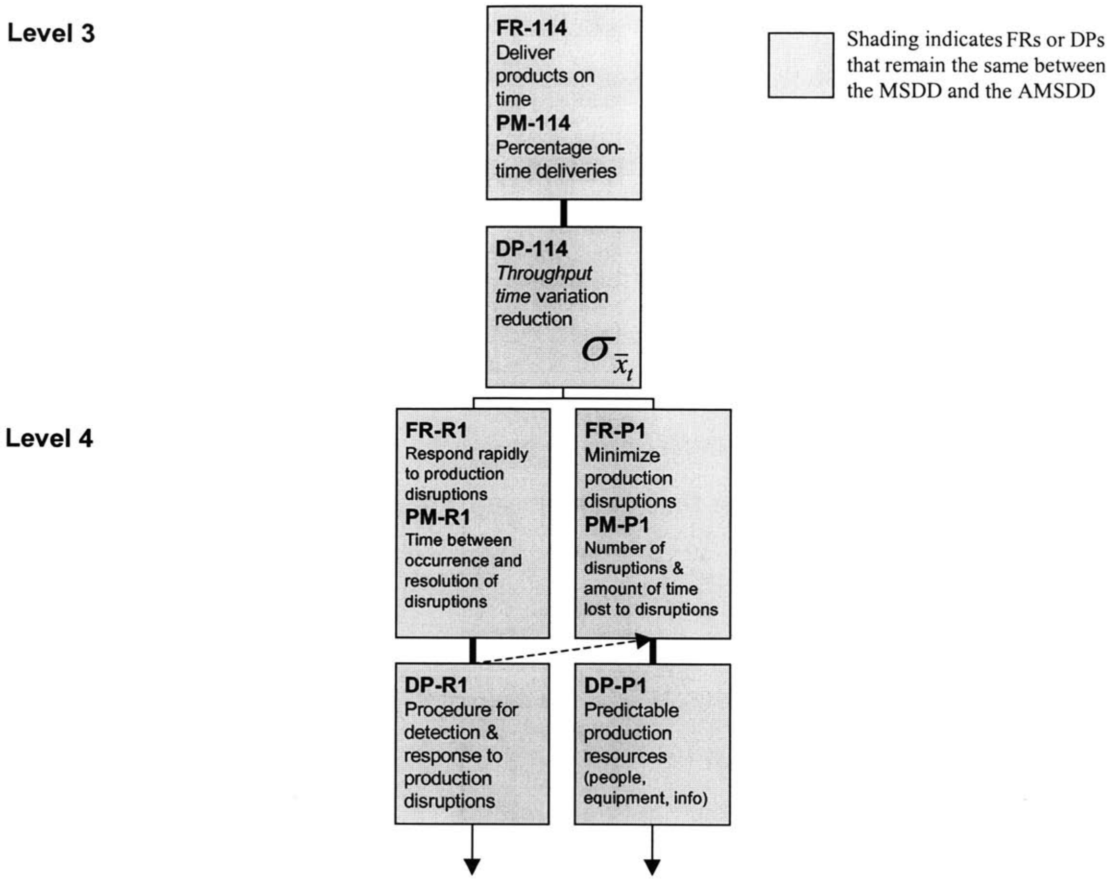

Figure 4.12: Decomposition of FR-114 and DP-114

The Identifying and Resolving Problems section of the MSDD was generally well received by the aerospace industry. The majority of suggested changes were incorporated into the AMSDD and are presented below. With the exception of the numbering and minor rephrasing of PM-P1, FR/DP-114 and its decomposition into FR-R1 and FR-P1 are the same as in the MSDD, version 5.1. PM-P1 was slightly rephrased from "Number of occurrence of disruptions & Amount of time lost to disruptions" to "Number of disruptions & amount of time lost to disruptions."

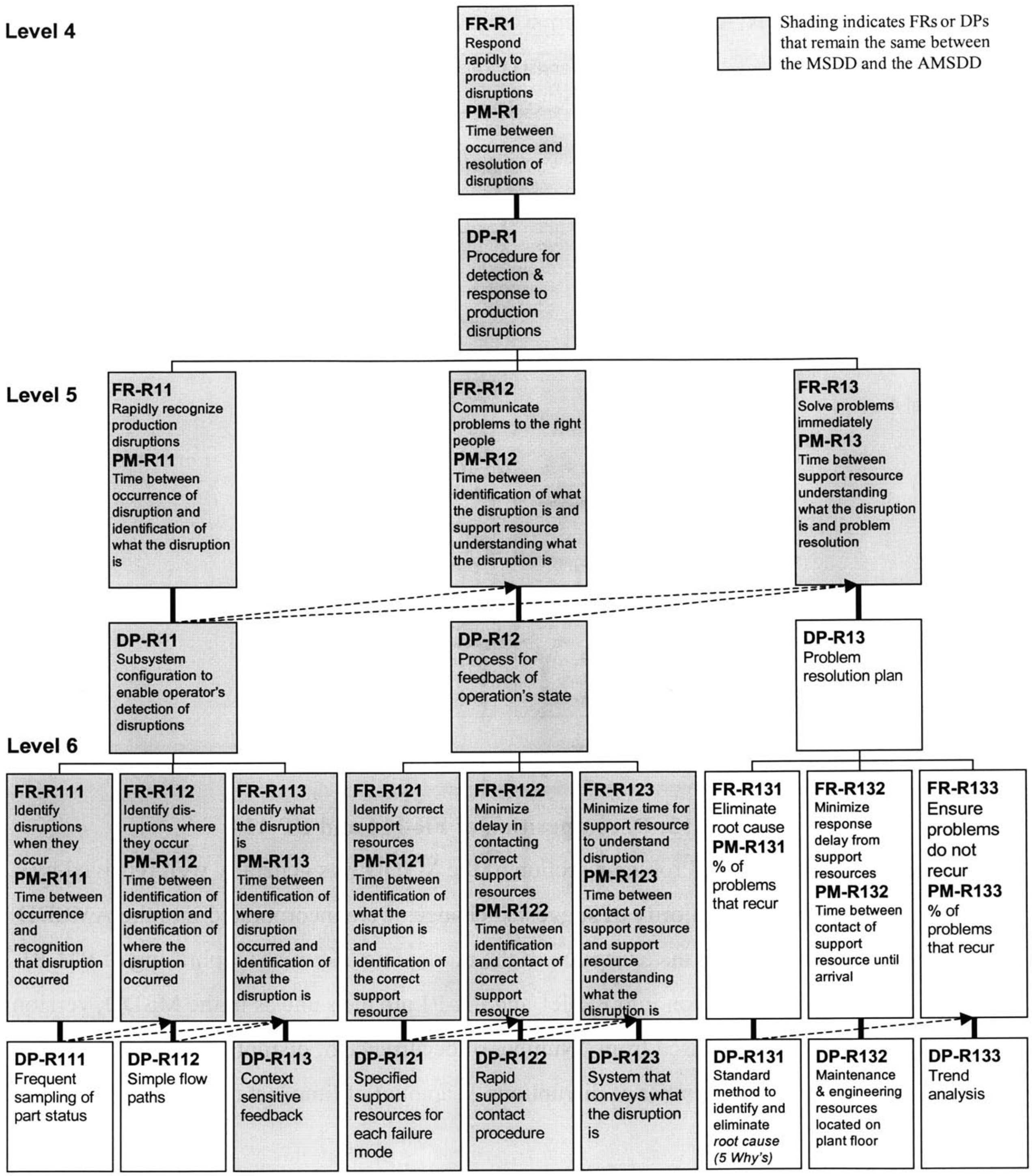

Figure 4.13: Identifying and Resolving Problems Section of the AMSDD

Following the suggestion of several industry members, DP-R111 was changed from "Increased operator sampling rate of equipment status" to "Frequent sampling of part status." Several people objected to making the DP specific to *equipment*. If an operation is manual, there is no equipment to monitor, only the part that is being worked on. Another problem was that *increased* could mean checking 20 percent of parts as opposed to only 10 percent. Neither of these sampling rates is sufficient. Frequent sampling of part status indicates that workers should regularly check the progress of parts to ensure that the parts are being processed correctly. The new DP-R111 does not differentiate between whether the operations being performed are manual or automated. One suggestion from an industry member for incorporating this DP into a manufacturing system is *consecutive inspection*. Consecutive inspection is essentially the same concept as *successive checks*, discussed in Chapter 2. In consecutive inspection, parts are frequently handed from one worker to the next. Each worker inspects the part to ensure the previous work was performed correctly before beginning his/her task. This practice prevents mistakes from going unnoticed, which is more likely if one worker keeps the same part for a long time. While the worker may still frequently check the part for errors, a worker is less likely to find an error that he/she made than one that someone else made. Frequently passing a part by a fresh pair of eyes improves the probability that errors will be caught quickly.

Another implemented suggestion was that DP-R112 should be changed from "Simplified material flow paths" to "Simple flow paths." The first reason for this change was that the DP does not need to be *material* specific. The flow of *information* in a manufacturing system, for example, should also be simplified. The second reason was that *simplified* is inappropriate, because it assumes that a flow path already exists. A company may be creating new paths, either in a new or existing manufacturing system. New paths should be designed to be as simple as possible.

Several companies suggested that FR/DP-R13 should be further decomposed to provide more information on how to solve problems immediately. FR-R13 was not changed, but DP-R13 has been changed from "Standard method to identify and eliminate root cause" to "Problem resolution plan." The new DP-R13 suggests that there should be further decomposition of the FR/DP pair. FR/DP-R13 is now decomposed into FR-R131, FR-R132, and FR-R133. FR-R131, "Eliminate root cause," is satisfied by DP-R131, "Standard method to identify and eliminate root cause (*5 Why's*)." PM-R131, "% of problems that recur," measures the achievement of FR-R131. DP-R131 had been DP-R13 in the MSDD. Eliminating the root cause of a problem is important for ensuring that the problem will not recur. Treating the symptoms of a problem is only a temporary solution and will lead to more problems in the future. A standard method, such as the "5 Why's" should be used to identify root causes. [Ohno, 1988] Standardization helps prevent misdiagnoses due to variations in problem solving methods.

FR-R132, "Minimize response delay from support resources," is satisfied by DP-R132, "Maintenance & engineering resources located on plant floor." PM-R132, "Time between contact of support resource until arrival," measures the achievement of FR-R132. It is important to have the required support resources able to arrive and begin fixing problems as soon as the problem has been identified. In order to minimize the response time, maintenance crews and manufacturing engineers should be located on the floor of the manufacturing plant. Repairs should not be delayed because engineers or repair crews need to travel from another building or site.

FR-R133, "Ensure problems do not recur," is satisfied by DP-R133, "Trend analysis." PM-R133, "% of problems that recur more than once," measures the achievement of FR-R133. Although eliminating the root cause of a problem should prevent the problem from recurring, it is possible that the root cause was misdiagnosed or that more than one cause of the problem existed. When problems occur, they should be recorded and compared against other problems that have occurred. Analyzing trends in problems allows companies to determine if there is a hidden cause to a series of problems. By identifying all problem sources, the problem can be resolved for good.

4.2.6 Predictable Output

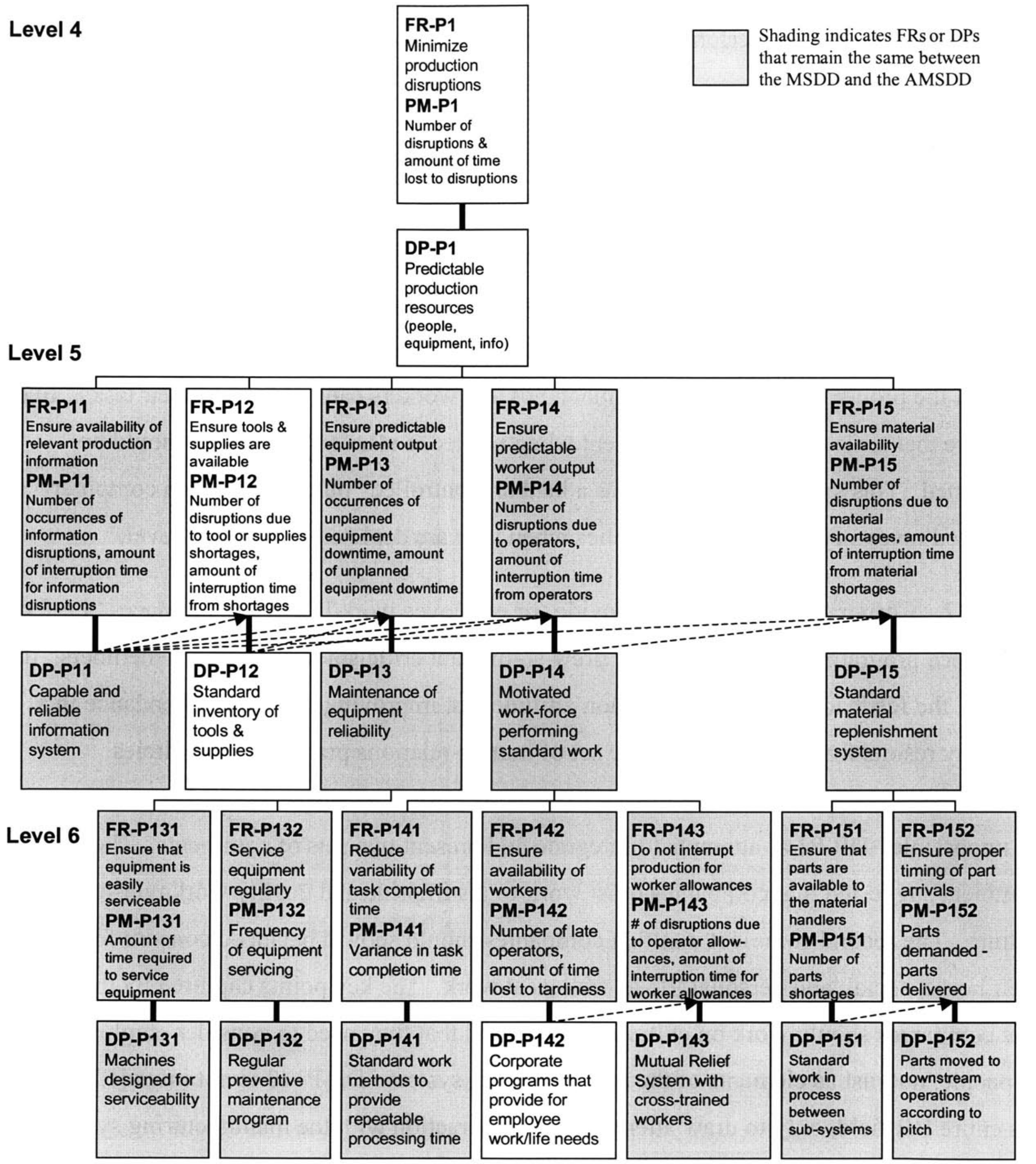

Figure 4.14: Predictable Output Section of the AMSDD

The Predictable Output section of the MSDD underwent a couple changes between version 5.0, which was presented to industry members, and version 5.1, presented in Chapter 2 of this paper. The changes addressed two suggestions from industry members. The suggestions were to further decompose FR-P14, "Ensure predictable equipment output," and FR-P15, "Ensure material availability." Aside from these suggestions, only one new FR/DP pair was added to this section of the AMSDD. Several performance measurements were slightly rephrased and one DP was changed.

The new addition to this section is FR/DP-P12. The Predictable Output section of the MSDD discusses information, machines, worker output, and material, but does not consider tools and supplies. FR-P12, "Ensure tools & supplies are available," is satisfied by DP-P12, "Standard inventory of tools & supplies." PM-P12, "Number of disruptions due to tool or supplies shortages, amount of interruption time from shortages," measures the achievement of FR-P12. Without the proper tools and supplies, machines and workers cannot achieve their tasks. In order to ensure that tools & supplies are present when needed, a standard inventory should be maintained. This system may operate as a kanban-controlled "pull" system or a computer controlled inventory that reorders supplies when they are depleted to a certain level.

DP-P142, "Corporate programs that provide for employee work/life needs," replaces "Perfect attendance program." The original DP drew significant criticism from industry members. In general, the feedback reflected a common attitude that improving employee attendance in a company results from a comprehensive set of human-relations practices and policies. Developing a single DP that encompasses the many intricacies of successful HR practices would be impossible. DP-P142 attempts to integrate and present two sets of comments. The first comment suggested that companies must work to instill pride and quality workmanship into their culture. The second comment was that companies should show a balanced concern for people in their home, social, and personal life as well as at work. The key points captured by the DP are that companies should work on culture-building and that they need to consider employees' needs as people, not just as elements of the manufacturing system. DP-P142 is not intended to address the entire HR field, only to draw attention to its interaction with the manufacturing system. Additional suggestions, such as stabilizing the workforce to minimize frequently hiring and laying off workers are not covered in the AMSDD.

In addition to the above issues that should most likely be best addressed by the HR group in a company, some issues were raised that may belong in the AMSDD, but how to add them is not clear at this time. One issue involves the need for *employee involvement* and *teaming*. Getting employees involved in their work and fostering a team environment is important. Teams are discussed briefly under the Cost Reduction section, but the details of team building and the interaction of teams with the manufacturing system are not developed. Another issue involves *recording/capturing employee knowledge*. Industry members said that tapping the knowledge of experienced workers is very important, because it allows companies to document techniques and practices that best achieve processing requirements. Having techniques recorded also allows multiple workers to perform a given task, instead of limiting the task to one specialist, who keeps the knowledge to him/herself. The problem with obtaining this knowledge is that employees may feel that their job is safer if they keep this information to themselves. If they share the skills that make them valuable to a company, they fear that they could be more easily replaced. This is a complicated subject and is coupled with HR issues. These issues may be a valuable area of research for future versions of the AMSDD, but this thesis does not propose FRs and DPs to address these issues in the context of manufacturing system design.

4.2.7 Delay Reduction

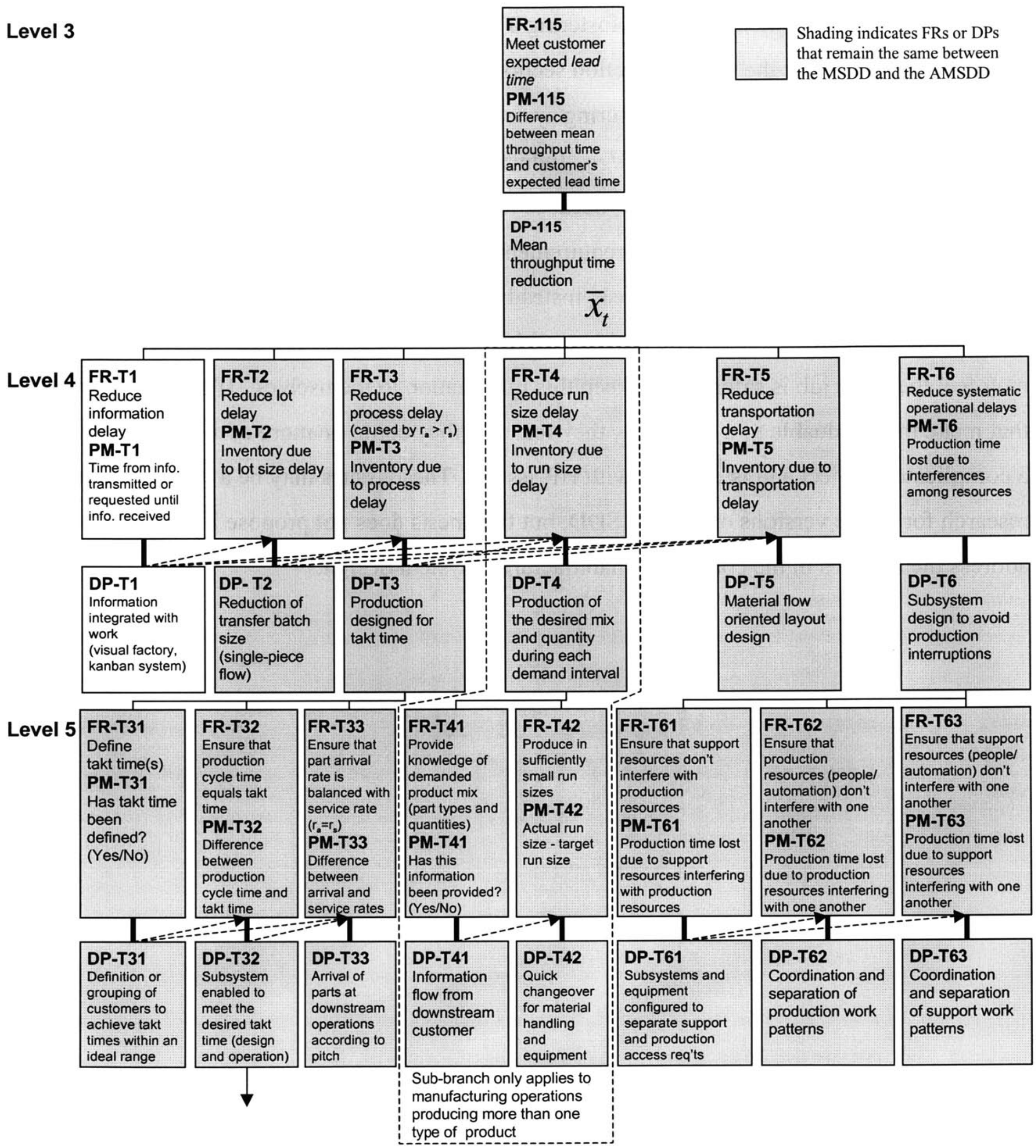

Figure 4.15: Delay Reduction Section of the AMSDD

The Delay Reduction section of the AMSDD has only one significant change when compared to the MSDD. At the suggestion of an industry member, FR/DP-T1 was added to address information delays in the manufacturing system. FR-T1, "Reduce information delay," is satisfied by DP-T1, "Information integrated with work (visual factory, kanban system)." PM-T1, "Time from info. transmitted or requested until info. received," measures the achievement of FR-T1. DP-T1 indicates that information delays can be reduced or eliminated by using the work that is being performed in the factory as a means to communicate information throughout the factory. Kanban cards that are transferred with a product can be used to signal upstream processes to replenish parts when the parts are removed. Visual controls can also be used to communicate the status of a product. One site that was visited used a moving assembly line with locations marked on the floor. These locations quickly communicated the status of a product to people at the plant.

Several industry members commented that the FR/DP pairs that addressed producing multiple product types did not apply to their manufacturing system, because the manufacturing system only produced a single product. While this statement was true for some of the assembly operations, it is likely that all companies had to deal with producing multiple part types in their fabrication facilities. To address this concern, the AMSDD identifies FR/DP-T323 and the subsection decomposed from FR/DP-T4 as applying only to manufacturing operations producing more than one type of product. This identification is denoted in the AMSDD by drawing a dotted line around these sections and shading the area, as shown in Figure 4.15 and Figure 4.16.

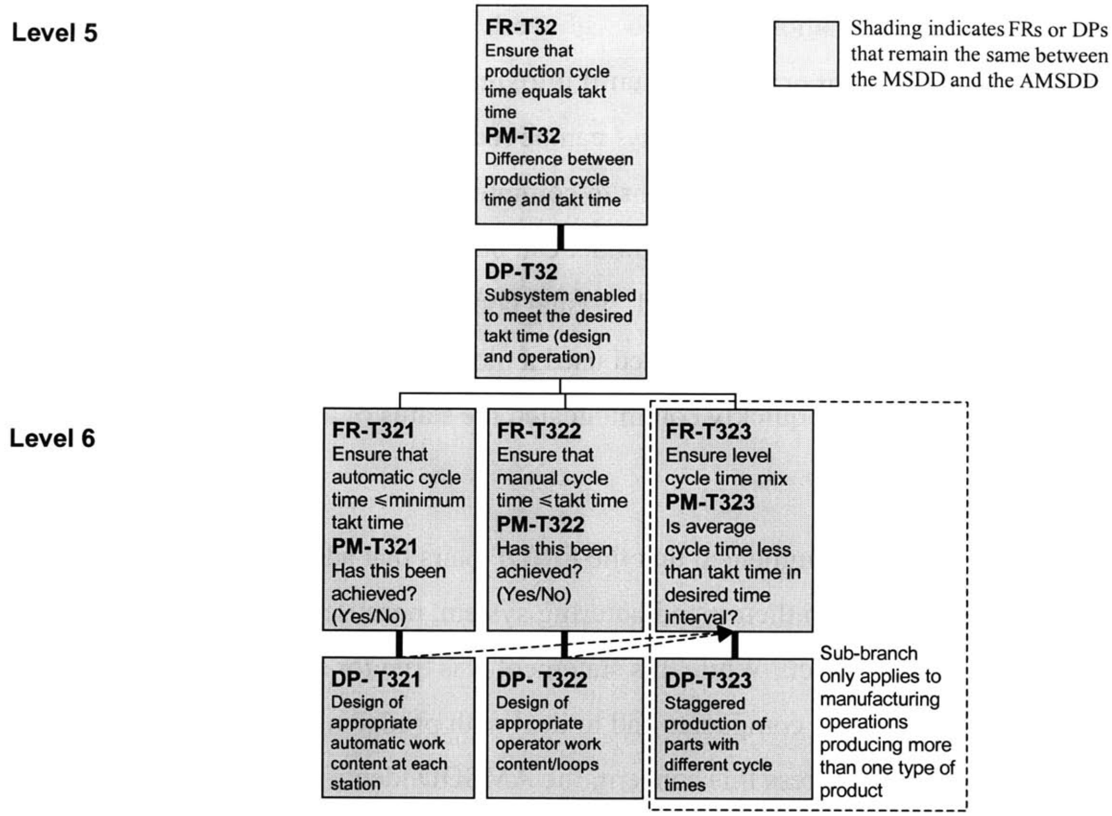

Figure 4.16: Delay Reduction Section of the AMSDD (Cycle Time Equals Takt Time)

Many industry members remarked that some terms used in the MSDD are non-intuitive. "Run size" and "pitch" were two frequently unknown terms. In order to make the AMSDD more useful as a stand-alone tool, a definitions section has been added to the decomposition. Figure 4.17 shows the definitions included in the AMSDD.

Definitions

Arrival rate (r_a): Rate at which an upstream operation supplies parts to the next station downstream

Autonomous: Automated so that an operator does not need to monitor during the process

Pitch: The takt time multiplied by the run size

Production resources: Any operator, technician, or equipment that directly adds value to a product

Run size: The # of one type of part produced between machine setups

Service rate (r_s): Rate at which a downstream operation processing incoming parts

Support resources: Any person or equipment in a manufacturing system that facilitates production resources, so that the production resource can perform its value-adding tasks

Takt time: $$\frac{\text{Production time available in a day (or week, month, etc.)}}{\text{Average customer demand (over a time interval)}}$$

Figure 4.17: AMSDD Definitions

Some industry members wanted FR/DP-T51 and FR/DP-T53 to be rephrased without using the term *support resources*. These people considered support resources to be all off-the-floor employees at a company. This definition of a support resource does not correspond with the intention of the FR/DPs in the MSDD and the AMSDD. Instead of rephrasing these FR/DPs, a definition of *support resources* has been added to the AMSDD definitions.

4.2.8 Cost Reduction

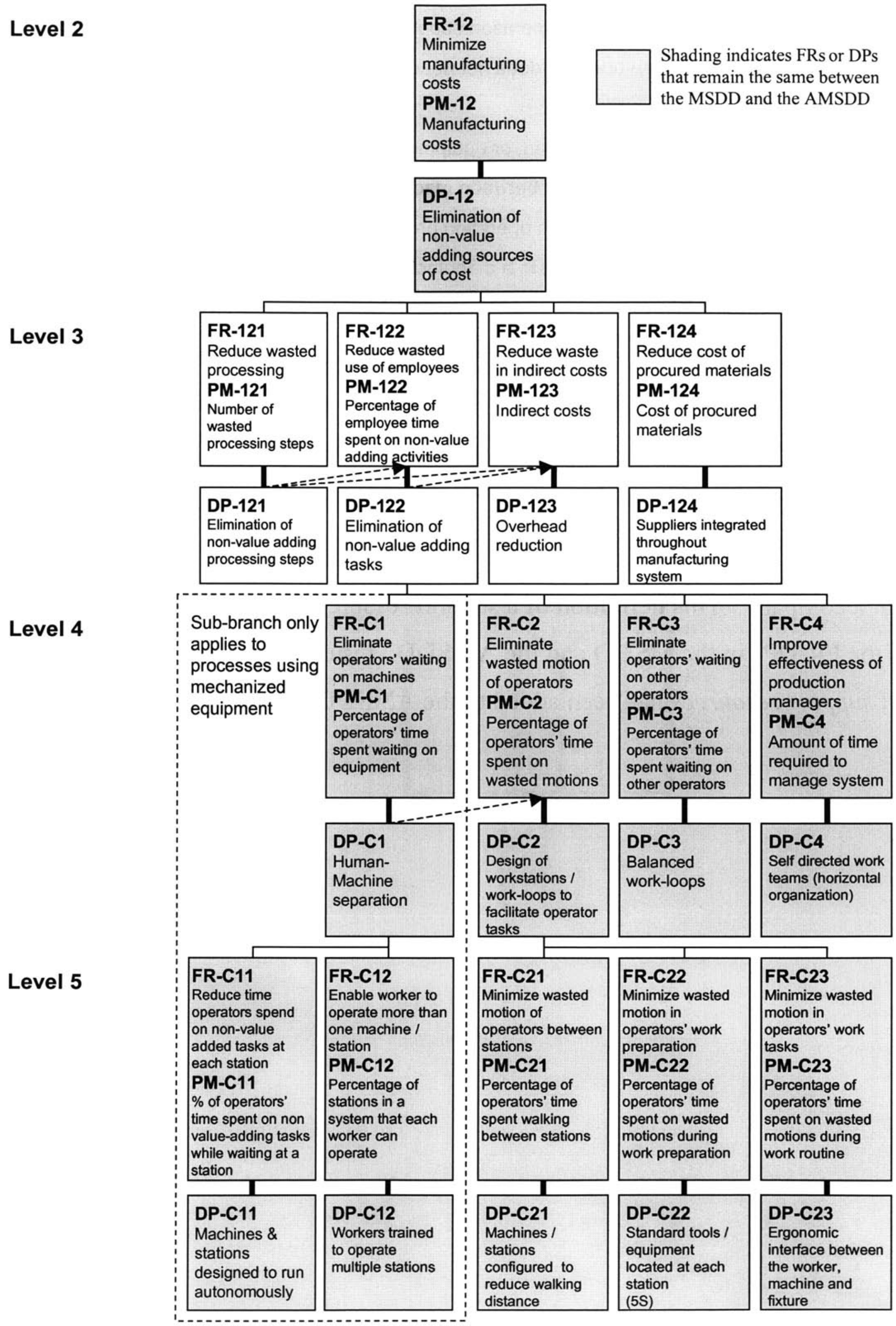

Figure 4.18: Cost Reduction Section of the AMSDD

The decomposition of FR/DP-12 has been changed significantly for the AMSDD. Most of the FRs and DPs remain the same as in the MSDD, but the organization has changed. There is no longer a distinction between direct and indirect labor. It was decided that non-value added tasks should be eliminated for all workers, whether direct or indirect, so the distinction was unnecessary. The Cost Reduction section also distinguishes FR/DP pairs that apply specifically to automated processes. This differentiation resulted from feedback that the MSDD assumed that most processes are automated, to which many industry members took exception. Another change is that the former FR-I2, "Eliminate information disruptions," was eliminated because of the new FR-T1, "Reduce information delay," from the Delay Reduction section of the AMSDD.

FR/DP-12 is decomposed into FR-121, FR-122, FR-123, and FR-124. When decomposing FR/DP-12, two concepts were considered. The first was how to reduce cost by eliminating waste from the manufacturing system. The second was how to reduce the cost of necessary activities within the manufacturing system. The "seven wastes" of the Toyota Production System are [Ohno, 1988]:

Overproduction	Producing too much, too early
Inventory	Semi-finished parts between operations
Transportation	Moving parts
Processing	Unnecessary processing steps
Making Defects	Parts need rework or are scrap
Motion	Unnecessary worker movements
Waiting	Workers waiting for machines or parts

The sections of the AMSDD that are decomposed from FR/DP-11 address the wastes of overproduction, inventory, transportation, making defects and partially address motion and waiting. FR-121 addresses processing waste and FR-122 further addresses the wastes of motion and waiting.

FR-121, "Reduce wasted processing," is satisfied by DP-121, "Elimination of non-value adding processing steps." PM-121, "Number of wasted processing steps," measures the achievement of FR-121. An example of wasted processing from the aerospace industry was a packaging operation performed between processing steps. One company sealed sub-components in plastic bags to allow the parts to be transported between locations where work was performed. The packaging step prevented contamination of the parts, but this step could be eliminated if the plant redesigned the operation so that the entire operation was completed in one location.

FR-122, "Reduce wasted use of employees," is satisfied by DP-122, "Elimination of non-value adding tasks." PM-122, "Percentage of employee time spent on non-value adding activities," measures achievement of FR-122. Previous versions of the decomposition have differentiated between direct and indirect labor. These terms do not seem to be helpful in the aerospace industry (and perhaps not in other industries, either.) Direct, in the aerospace industry, typically refers to items that can be charged to a program. Indirect typically refers to anything "above the floor." The terms *direct* and *indirect* also may sound like a distinction between hourly and salaried workers. The new FR-122 covers all employees and indicates that they all should be used efficiently. To prevent wasting employees' efforts, tasks that do not add value to the final product should be eliminated. Decomposition of FR/DP-122 is the same as in the MSDD, with the addition of FR/DP-C4, which had been under the Indirect Labor section.

FR-123, "Reduce waste in indirect costs," is achieved by DP-123, "Overhead reduction." PM-123, "Indirect costs," measures the achievement of FR-123. Suggestions for this FR/DP pair came from industry comments that there are many costs that hinder manufacturing systems and should be reduced. These "indirect costs" are typically charged to overhead. Activity Based Costing may be one way to identify overhead costs and improvement opportunities, but FR/DP-123 will not be further decomposed in this thesis. Using Activity Based Costing may be a valuable area for future AMSDD research efforts. Further decomposition of FR/DP-123 was not pursued, because of differences in overhead structures between companies.

FR-124, "Reduce cost of procured materials," is satisfied by DP-124, "Suppliers integrated throughout manufacturing system." PM-124, "Cost of procured materials," measures the achievement of FR-124. Reducing the cost of parts and materials that are purchased reduces the cost of production. Many industry members wanted to see a decomposition of supply-chain management in order to better understand cost reduction. People suggested that companies should increase their leverage over suppliers and find ways to drive down prices. Instead of examining specific methods of price reduction, the AMSDD specifies integrating suppliers throughout the manufacturing system. Decomposing supply-chain management under the cost section would draw too much attention to one concern, cost reduction, when the focus should be on integrating suppliers throughout the manufacturing system. The best supply chains are the most highly integrated ones. Suppliers should be integrated into the product design and development process, the earlier the better. There should be a seamless integration of design teams, with no organizational boundaries between companies.[3]

[3] DP-124 was developed based on a discussion about Supply Chain Management with Kirk Bozdogan, MIT Research Lead for the LAI Supplier Relations Focus Team.

4.2.9 Investment[4]

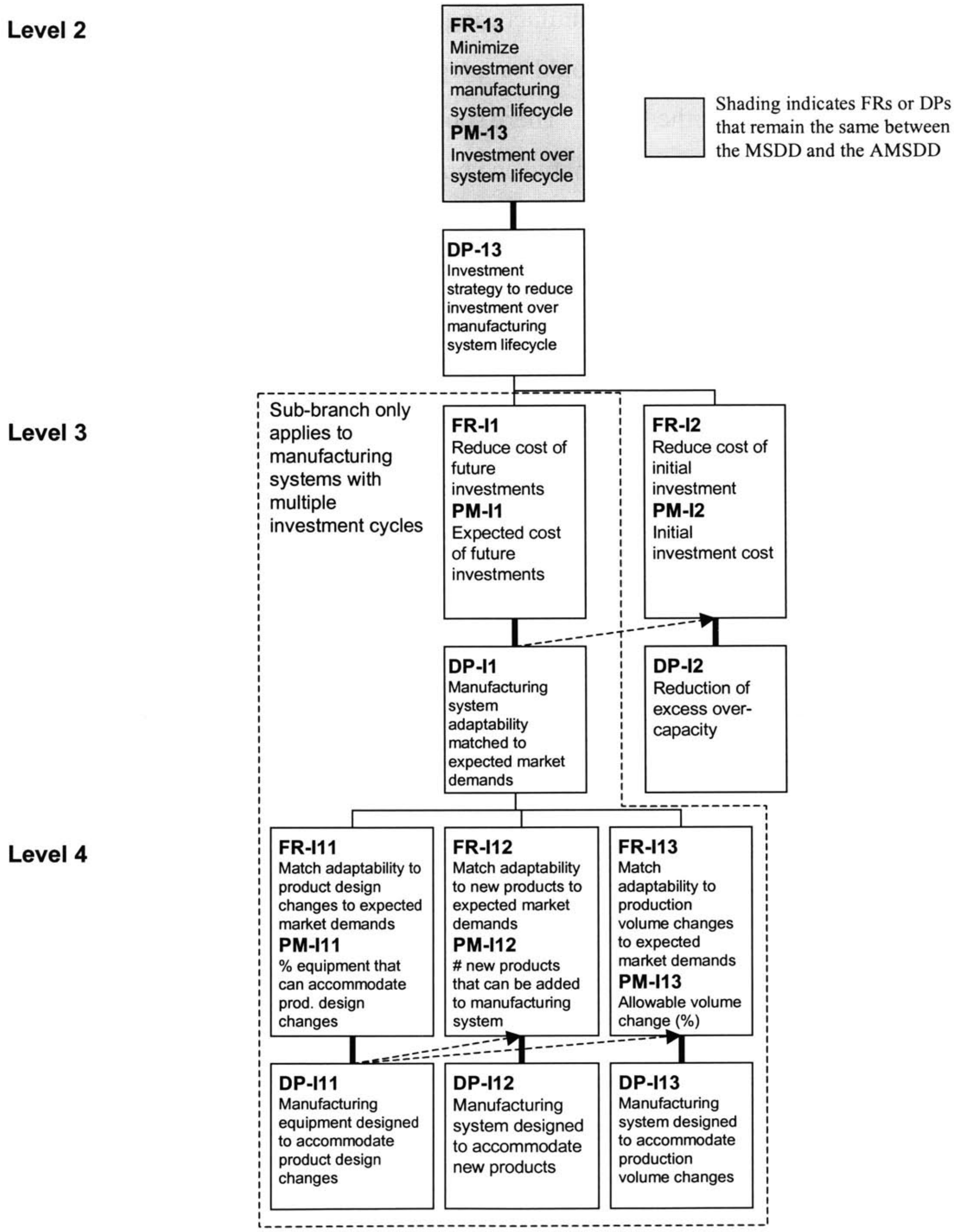

Figure 4.19: Investment Section of the AMSDD

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[4] Decomposition of the Investment section of the AMSDD was based upon work performed by Andreas Szentivanyi and Prof. David Cochran in the PSD Laboratory at MIT. [Cochran, Eversheim, Sesterhenn, Sventivanyi, 2000]

This section is entirely new for the AMSDD. In the MSDD, there was no further decomposition of FR/DP-13. Industry feedback strongly suggested that the AMSDD should provide further decomposition. Therefore, FR/DP-13 is now decomposed into FR-I1 and FR-I2, as shown in Figure 4.19. FR-I1, "Reduce cost of future investments," is satisfied by DP-I1, "Manufacturing system adaptability matched to expected market demands." The achievement of FR-I1 can be measured by PM-I1, "Expected cost of future investments." As noted by the shaded area in Figure 4.19, FR/DP-I1 and their sub-FRs only apply to manufacturing systems with multiple investment cycles. This distinction is made to indicate that there will be a different investment strategy for manufacturing systems that are funded with only a single, up-front investment. Some small-scale military programs, such as an order to fabricate a set of spare parts, may fall into this category. Most manufacturing systems, however, will involve multiple investment cycles. In order to reduce the cost of future investments, it is important to design the manufacturing system so that it can best respond to the production levels and types of demands that are expected to be placed upon the system.

FR-I2, "Reduce cost of initial investment," is satisfied by DP-I2, "Reduction of excess overcapacity." Achievement of FR-I2 is measured by PM-I2, "Initial investment cost." In order to keep investment in a new manufacturing system low, the system designers should strive not to purchase too much capacity up-front. The achievement of FR-I2 is coupled with DP-I1. This indicates that matching the adaptability of a manufacturing system to expected demand affects the ability to reduce the initial investment. For example, if a manufacturing system is being designed for a fast growth product, it may not be possible to minimize the initial investment. By investing in only enough tooling and equipment for initial demand, future investments may be higher than necessary, because increased capacity will require the existing manufacturing system to be redesigned and reconfigured.

FR/DP-I1 is decomposed into FR-I11, FR-I12, and FR-I13. FR-I11, "Match adaptability to product design changes to expected market demands," is satisfied by DP-I11, "Manufacturing equipment designed to accommodate product design changes." Achievement of FR-I11 is measured by PM-I11, "% equipment that can accommodate prod. design changes." In a manufacturing system that expects to have frequent design changes, it will be important to design the equipment to easily process new product designs. This flexibility may require purchasing more expensive equipment, but will be less expensive in the long-term than purchasing specialized equipment that cannot handle multiple product varieties. In a system that does not expect many product design changes however, paying for high flexibility may be a wasted investment.

FR-I12, "Match adaptability to new products to expected market demands," is satisfied by DP-I12, "Manufacturing system designed to accommodate new products." Achievement of FR-I12 is measured by PM-I12, "# new products that can be added to manufacturing system." The ability of a manufacturing system to introduce new products is affected by DP-I11, as illustrated by the coupling shown in Figure 4.19. In order to adapt to new product designs it is necessary, but not sufficient, to have equipment that can accommodate the expected range of product changes. In addition, the manufacturing system must be able to change. New product designs may require additional processes or different processing sequences. If a manufacturing system expects frequent changes, it should be possible to rearrange the system quickly to react to market demands.

FR-I13, "Match adaptability to production volume changes to expected market demands," is satisfied by DP-I13, "Manufacturing system designed to accommodate production volume changes." Achievement of FR-I13 is measured by PM-I13, "Allowable volume change (%)." If a company expects to have relatively stable production volumes for the life of a product, it is unlikely that the company will benefit from a manufacturing system that can quickly change capacity. On the other hand, if production volumes are uncertain or highly variable, a company may want to design a manufacturing system that allows capacity to be added and removed in discrete units. Manufacturing cells are one way that companies can quickly add capacity. A series of cells, designed to operate at the same takt time, fabricates and assembles the components required for a product or family of products. As demand increases, one or more sets of linked manufacturing cells can be added. This strategy allows the addition of capacity in a way that does not require complicated sharing and scheduling of existing processing equipment.

4.3 Summary

This chapter has presented a new Aerospace Manufacturing System Design Decomposition (AMSDD). The AMSDD is based upon the MSDD and incorporates the feedback collected from industry members that was presented in Chapter 3. The major differences between the AMSDD and the MSDD are the addition of an additional upper-level of decomposition, the addition of the Continuous Improvement and the Product Design sections, and further decomposition of the Investment section. The new topmost level of the AMSDD uses a net present value (NPV) analysis to illustrate how manufacturing system design fits into a company's goal to increase shareholder value. The Continuous Improvement section illustrates how feedback from customers and within a manufacturing system has a significant effect upon the overall manufacturing system design. The Product Design section helps to illustrate the interactions between product design and manufacturing system design that must be considered when developing a new product and its manufacturing system. Finally, the newly decomposed Investment section provides additional insight into the factors that must be considered by a company when choosing how to invest in a manufacturing system.

A summary table of the FRs and DPs contained in the AMSDD is presented in Appendix F.

Chapter 5 Use of the AMSDD to Support Military Procurement Programs

5.1 Introduction

This chapter will illustrate how the Aerospace Manufacturing System Design Decomposition (AMSDD) can be used by companies and the military to improve the design of aerospace manufacturing systems. The goal is to show that by using the AMSDD to guide the design of manufacturing systems, the overall system design will better satisfy the needs of the military as well as the manufacturing company. A comparison of the AMSDD with the Military Aircraft Manufacturing System Design Decomposition demonstrates how the AMSDD would lead to a different system design than currently exists. An Aerospace Manufacturing System Design Evaluation Tool is then developed to help evaluate the designs of existing manufacturing systems. Finally, the evaluation tool is used to evaluate three manufacturing systems and suggest how procurement policies may have influenced theses systems' designs.

5.2 Review of the Military Aircraft Manufacturing System Design Decomposition[5]

In his Master's thesis, Andrew Wang developed a Military Aircraft Manufacturing System Design Decomposition. [Wang, 1999] This decomposition presented an "as-is" look at the design of military aircraft programs. This approach is different from both the MSDD and the new AMSDD, which attempts to portray an *ideal* manufacturing system design. This section presents Wang's decomposition, the reasoning behind its development, and compares the Military Aircraft Manufacturing System Design Decomposition to the AMSDD. The Military Aircraft Manufacturing System Design Decomposition is shown in Figure 5.1.

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[5] The information on military procurement policies and the Military Aircraft Manufacturing System Design Decomposition, presented in this section, were adapted from the internal LAI document "A Production System Design Decomposition for the Aerospace Industry." [Wang et al, 1999] The material in the report was originally from Andrew Wang's Master's thesis "Design and Analysis of Production Systems in Aircraft Assembly." [Wang, 1999]

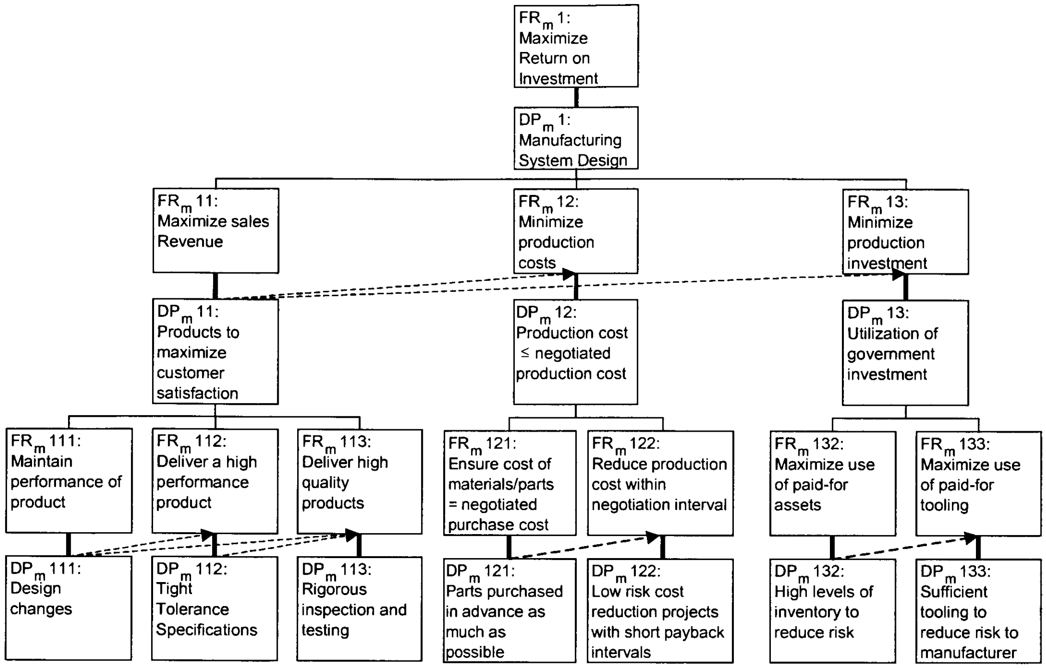

Figure 5.1: Military Aircraft Manufacturing System Design Decomposition [Wang, 1999]

5.2.1 Special Factors in Military Aircraft Programs[6]

Product Performance and Quality

To ensure that the United States' armed forces have a tactical advantage over their opponents, military aircraft are designed to possess the most advanced capabilities available. The product design and development teams take an aggressive approach to design a product with the most impressive specifications possible. In fact, in programs with long development times, technology that has not yet been achieved will be incorporated into the design based upon expectations that it will be mature when required. Although this approach makes products more difficult to build, it ensures that the aircraft will meet aggressive service requirements.

After the product development process, when the units are being used in service, changes are often requested to improve performance. Changes also occur to incorporate new technology. These changes were a common problem during World War II [Zeitlin, 1995] when combat experiences demanded many changes which disturbed the regular manufacturing process. A

[6] This sub-section copied directly from the internal LAI document "A Production System Design Decomposition for the Aerospace Industry." [Wang et al, 1999]

balance was eventually sought so that the planes would be kept as competitive as possible without debilitating the manufacturing process. Engineering changes were incorporated after each production block (50 – 500 units). At the Willow Run plant, these changes made more than half of the jigs and fixtures obsolete [Vogt, 1999].

In addition to product performance, quality is another requirement. Reliability in military aircraft is a critical factor since product failures may result in loss of life or failure of a mission. To ensure that the products are of the highest quality, 100% inspection is used, involving inspectors from manufacturing and even from the government. In addition, any quality issues (non-conformances) that may compromise structural integrity are fully analyzed by engineering and reworked accordingly. These non-conformances must often go through an approval cycle by the government as well.

Production Investment

The proposition of going through the design and development process of a military aircraft, purchasing all the tooling, materials, parts, and hiring all the employees necessary is a daunting and risky one for any manufacturer. To lessen these problems, the government becomes what may be viewed as the prime contractor. The government sets the requirements for what is needed and then pays for the development of those aircraft. Traditionally, these contracts have been cost-plus programs during design. When production is being ramped up, the government also pays for all the tooling and test equipment necessary up-front. One of the reasons for this is the bidding process for contracts. Even before production begins, an estimate of the investment cost is required before the project is approved. With an accepted proposal, the manufacturer is then expected to build all the tools necessary at the estimated investment cost. Although this practice allows manufacturers the resources to proceed with development and manufacturing of the aircraft, it may inadvertently motivate inefficient practices such as developing and building tooling where it may be unnecessary, and acquiring equipment and material too soon.

Cost Negotiations

Once production begins, the aircraft are typically ordered and built in lots. The price per aircraft for subsequent lots is negotiated based on the current actual manufacturing costs and the trend in cost reduction. It is expected that the costs will decrease for each subsequent lot of aircraft. The government has access to all the cost data so that a fair price can be set for the next lot. Although this strategy decreases the cost of each lot to the government, it may not decrease the long-term production cost. As manufacturers try to decrease their risk, they will try to ensure that the projected costs are attainable. To ensure that the cost of parts and materials is known, high-risk parts (long lead time, high cost items) are ordered well in advance so that those costs are posted as actual costs prior to negotiation. If the parts were ordered after negotiation, there is a risk that the price will be higher than what was allocated to obtain them.

Because cost savings do not result in profit but lowered cost to the customer [Harris, 1999], the approach to cost reduction will be more conservative. High risk, high payback projects are not attractive because any savings are passed on to the customer, but the manufacturer is responsible for cost overruns. This situation promotes low risk, low payback cost reduction projects to be implemented. Cost based pricing constrains investment recovery. In annual procurements, a cost reduction investment may not be made unless it is paid back within the negotiated period. This practice deters potentially worthy projects across multiple procurement periods from being implemented.

5.2.2 Military Aircraft Manufacturing System Design Decomposition vs. the AMSDD

The Military Manufacturing System Design Decomposition begins with the top-level FR of FR_m1, "Maximize return on investment," while the AMSDD begins with the top-level FR "Increase shareholder value." The military decomposition does not consider how a company made the decision to manufacture products and therefore begins decomposition with the assumption that this decision has already been made. The AMSDD makes the decision to pursue a project more explicit, decomposing the top-level FR and its corresponding DP into FR-0, "Fund projects with a positive Net Present Value" and FR-1 "Increase manufacturing profitability." If DP-0, "Capital allocated to projects with positive Net Present Value" indicates that a company should invest in a manufacturing system, then comparison between the two decompositions can continue with FR_m1 and FR-1. Both decompositions satisfy FR_m1 and FR-1 in a similar manner. The military manufacturing system design decomposition specifies DP_m1, "Manufacturing System Design" and the AMSDD specifies DP-1 "Manufacturing System Design and Operation." Figure 5.2 shows the top levels of the two decompositions.

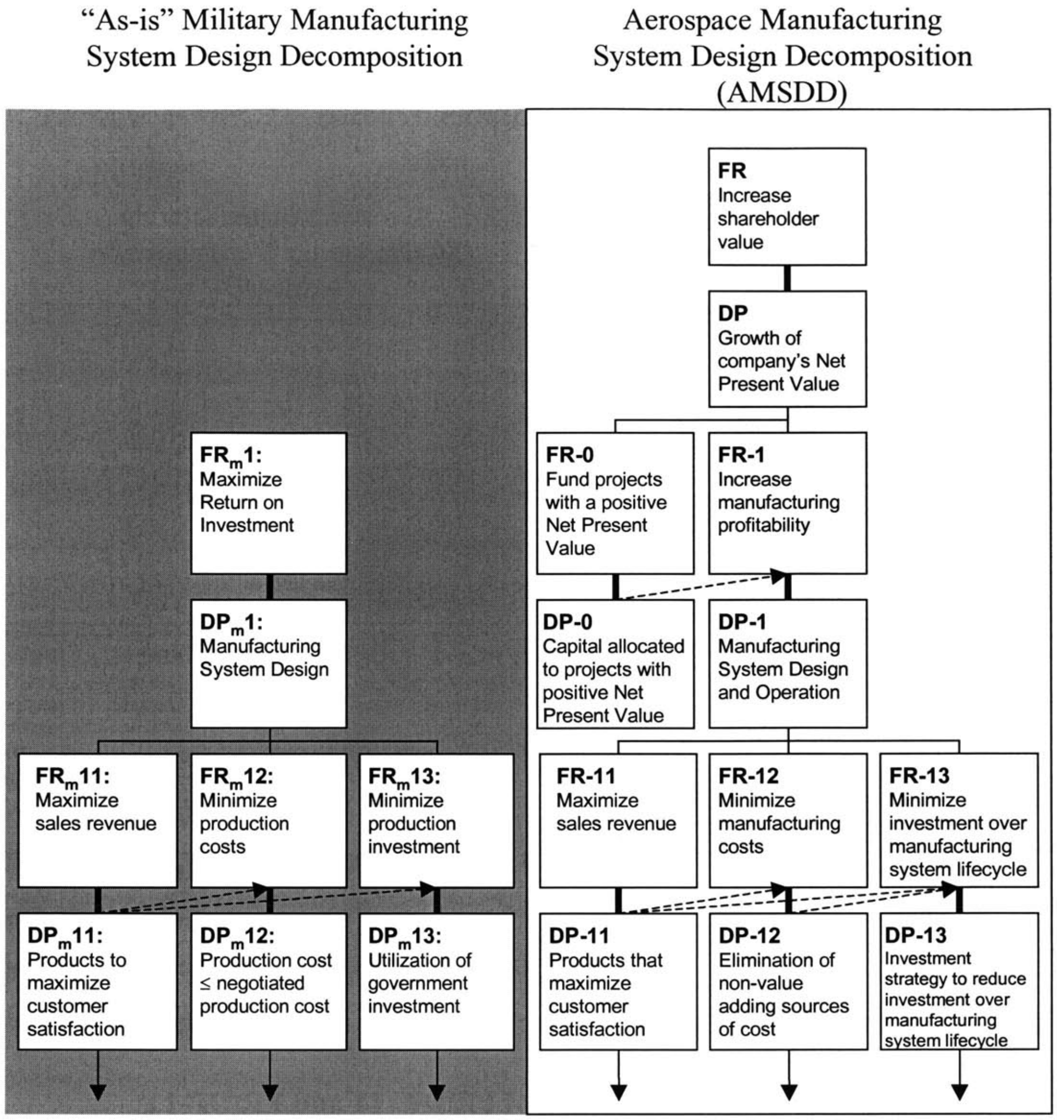

Figure 5.2: Top Levels of the Military Manufacturing System Design Decomposition and the AMSDD

The decomposition of FR/DP$_m$1 and FR/DP-1 into sub-FRs is similar. The DPs that satisfy these FRs are the same for FR$_m$11 and FR-11, but very different for the other FRs. Further decomposition of each FR/DP pair will better illustrate differences between the military and AMSDD approaches.

Maximize Sales Revenue

Both the Military Aircraft Manufacturing System Design Decomposition and the AMSDD specify "products to maximize customer satisfaction" as the DP to satisfy the FR of "maximizing sales revenue." Although each FR/DP pair initially appears identical, the way that each decomposition addresses the *product* focus is different. This difference is illustrated by further decomposition of the FR/DP pairs, shown in Figure 5.3.

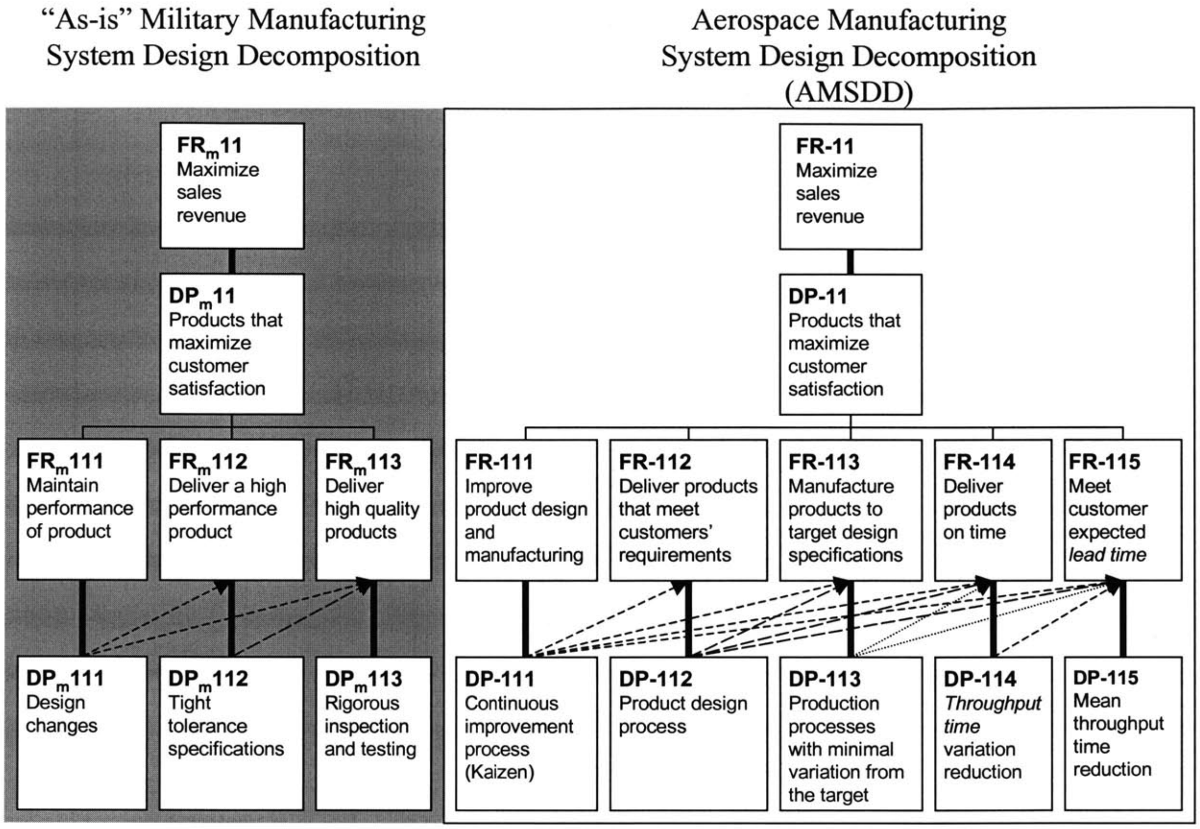

Figure 5.3: Decomposition of FR/DP$_m$11 and FR/DP-11

The military decomposition shows that the need to keep products at top performance creates constant design changes that disrupt production. Even during war times, when aircraft were being produced at high rates, production was constantly being disrupted to implement design changes. Upgrades to give aircraft a tactical advantage in speed, range, armor and other abilities improved performance but increased aircraft cost dramatically. The aggressive design and high performance of aircraft demands that very tight tolerances be specified, which makes the products more difficult to build. Lastly, due in part to the high product complexity and low volume, instead of stabilizing processes, quality is maintained through rigorous inspection to detect errors and painstaking rework to correct them. This adds waste in making the error, looking for the error and then repairing it. [Wang et al, 1999]

In his thesis, Wang noted that "although product design and capability have traditionally dominated how successful a program is, the way a product is produced is becoming more important." [Wang, 1999, p.95] The military decomposition focuses solely on the design and performance of products. The AMSDD recognizes that both the design and production of products is necessary in order to provide "Products that maximize customer satisfaction." By considering both product design *and* production, the AMSDD provides a tool to help address the military concerns of maintaining a high-quality, high-performance product, while also addressing production. The impact of product design decisions upon the entire manufacturing system must be considered in order for the manufacturing system to run smoothly. There may be times when the military is willing to sacrifice production cost or ease of operation. Looking only at product design will not make these tradeoffs visible. The AMSDD can be used to help understand the impacts of product design decisions upon the entire manufacturing system.

Minimize Production Costs

The decomposition of FR/DP_m12 and FR/DP-12 are entirely different because of the differences between DP_m12 and DP-12. To reduce manufacturing costs, the AMSDD specifies DP12, "Elimination of non-value adding sources of cost." In military programs however, since the cost of aircraft per lot is negotiated based on the actual cost performance of closed lots, a more complex dynamic is in place. [Wang et al, 1999] For the manufacturer to minimize its production cost, it wants to ensure that the production cost is equal to or less than the negotiated price as shown in Figure 5.4.

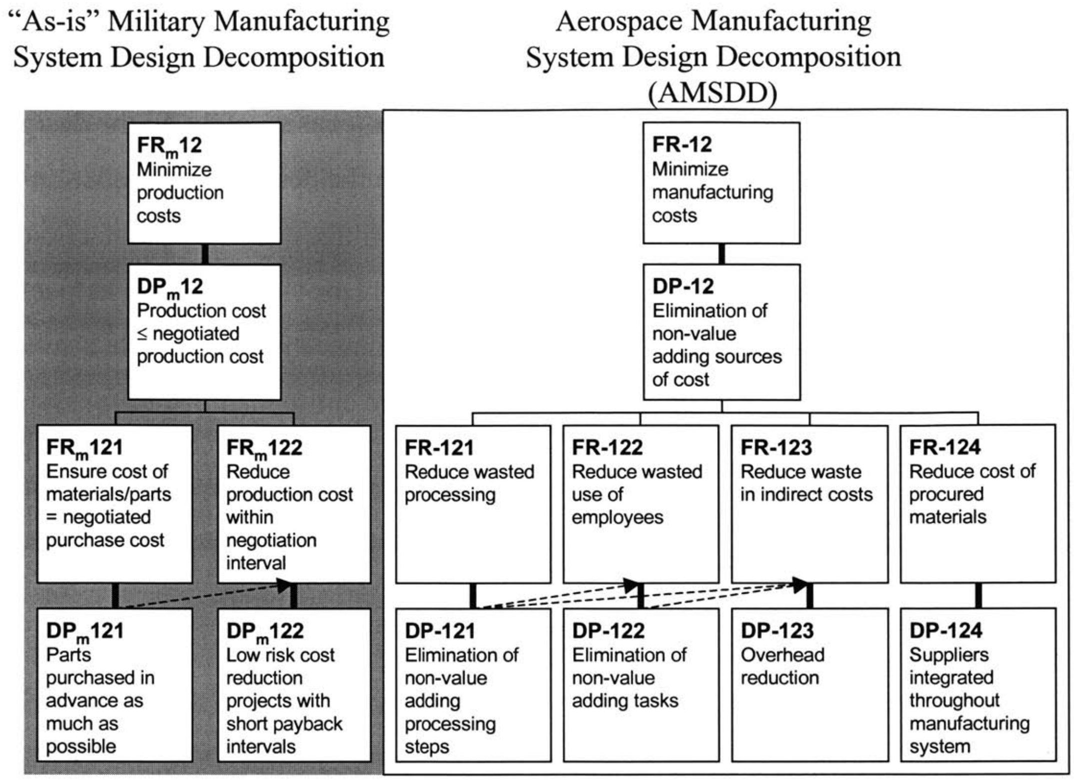

Figure 5.4: Decomposition of FR/DP$_m$12 and FR/DP-12

To minimize the risk of obtaining a negotiated cost that is too low, manufacturers are motivated to ensure that the cost of their materials and their cost projections are attainable. One method to ensure that the cost of expensive parts or high-risk items (where cost varies) is predictable is to purchase these items far in advance so that they will have been paid for before negotiations for the next lot. This practice makes the parts or materials a fixed cost, which is then paid for accordingly. Advanced purchasing eliminates the risk of unexpected increases in the price of a part or expectations from the government to negotiate lower prices with suppliers. [Wang et al, 1999]

To further ensure that production costs are less than or equal to the negotiated cost per lot, the Military Aircraft Manufacturing System Design Decomposition requires FR$_m$122, "Reduce production cost within negotiation interval." To satisfy this FR, cost reductions with a much shorter time frame are implemented. In addition, because companies are responsible for cost overruns, but pass on long term savings to the customer, high risk/high payback projects are avoided. In the military aircraft industry, reducing production cost has a small direct impact on return on investment. Long-term savings in production cost are passed on to the customer. A company that can demonstrate operational efficiency may be more likely to win new contracts and/or have existing contracts extended. However, it is difficult to justify investments to reduce long-term cost when the company will not recover the investments. If the cost savings may be realized within the production lot (since the price is already fixed) the savings do translate into profit so the company may justify those improvements. During negotiations, the government does fund projects to reduce production cost. Because aircraft are procured annually however, the payback for the investment is short-term. Projects with longer-term payback periods are often not considered. By negotiating contracts on an annual basis, DP_m122, "Low risk cost reduction projects with short payback intervals," will be the result, which does not decrease the long-term production cost of the program. [Wang et al, 1999]

Following the AMSDD would require significant changes to military procurement policies. If the military were to change the way that contracts are negotiated, so that it assumes more risk if costs increase and shares the savings when costs decrease, there could be greater opportunities for cost reductions and benefits to both the military and the contractor. Buying products in advance protects companies from being required to absorb price increases, but eliminates the possibility that prices will fall. If the military were willing to assume some of the increased cost when prices rise and share some of the savings when prices fall, contractors would be less likely to purchase parts before the parts are needed.

Companies are frequently not willing to invest in risky projects that could lead to significant long-term cost savings, because if the project is successful the savings will be absorbed by the military during the next negotiation cycle. When the projects are unsuccessful, the contractor receives no savings and is left footing the bill of the failed attempt. If procurement policies were changed so that the military could let contractors keep a percentage of cost savings for themselves over multiple procurement cycles, the contractors would be more willing to invest in long-term cost reduction projects. The government could further encourage cost reduction projects by splitting the costs of unsuccessful projects. Even if the military doesn't fund the improvement projects however, letting contractors keep a share of any savings should result in a net savings for the government compared to the current cost negotiation strategy. These savings will encourage contractors to pursue cost reduction projects independently, because they will be rewarded for cost savings. For such incentives to be effective for the overall program, however, the incentives must agree with the program's goals [Cowap, 1998]. A program that is primarily focused on implementing the most up-to-date technologies may not be considered a success if cost reductions are perceived as inhibiting maximum technology insertion. See Stacey Cowap's Master's Thesis, "Economic Incentives in Aerospace Weapon Systems Procurement," 1999, for a detailed study of economic incentives in government procurement programs.

Minimize Production Investment

The investment approaches of the Military Aircraft Manufacturing System Design Decomposition and the AMSDD vary considerably. The way to minimize production investment described by the military decomposition requires manufacturers to consider two things, the investment that is paid for by the government (tooling, test equipment, assets) and the investment paid for by the company (machine tools, facilities etc.). For a company to minimize its investment and reduce risks to its manufacturing system, it would choose DP_m13, "Utilization of government investment," as shown in Figure 5.5.

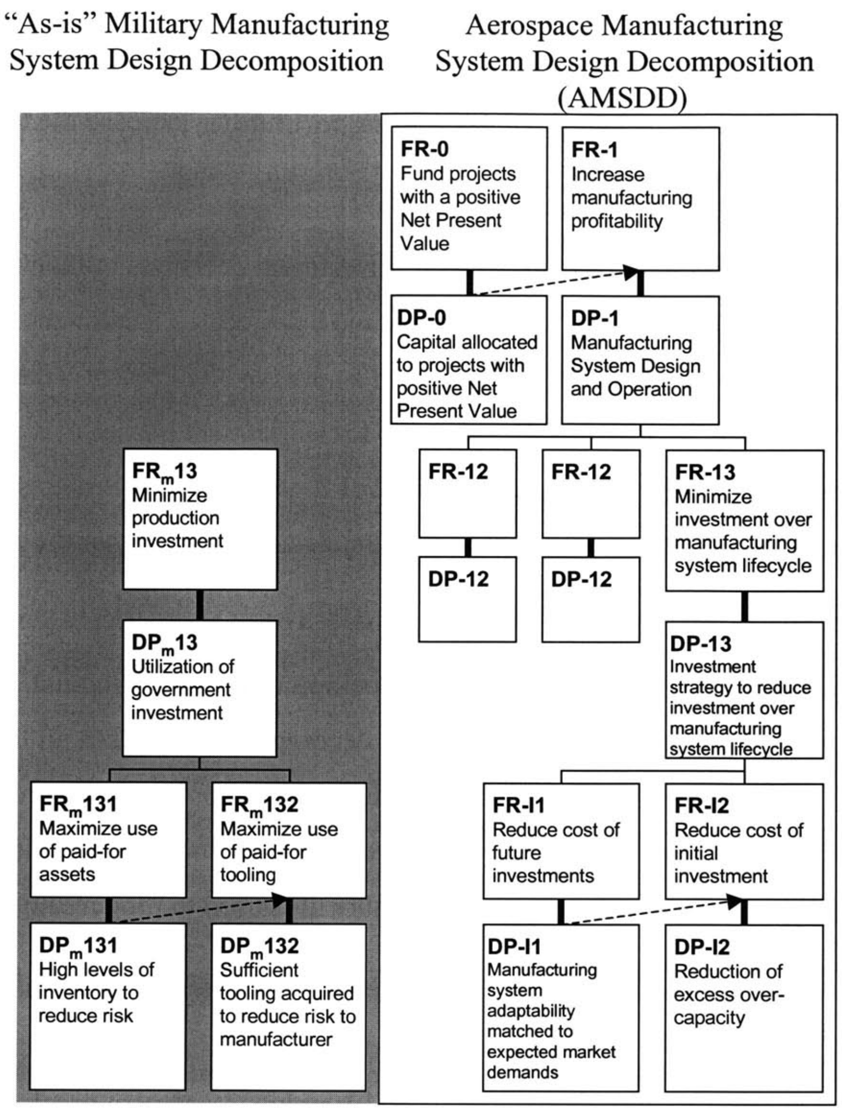

Figure 5.5: Investment in the Military Decomposition and the AMSDD

One part of the investment is the inventory or assets. (Toyota considers inventory a type of waste.) Because the inventory is paid for, the manufacturer has less incentive to minimize this waste and may hold excess levels of inventory as safety stock (DP_m131). This practice adds to the cost because the company must store and manage the inventory. Large amounts of inventory also lead to high potential obsolescence costs since design changes occur frequently. Since the government pays for all of the tooling before full rate production begins, manufacturers may acquire all of the tooling necessary for the highest expected production rate (DP_m132). By acquiring all of the tooling up-front, resources are wasted if the production rate does not reach expected levels (if the demand is changed). [Wang et al, 1999] In addition, existing tooling will be made obsolete if the design changes. New tooling will further increase the total investment required for the manufacturing system.

The AMSDD distinguishes between two types of investment decisions in manufacturing systems. The first decision is whether or not to pursue a project. If a company follows the AMSDD, the company will only fund projects with a positive Net Present Value. The second decision is how to reduce the investment necessary for subsequent phases of a program. Successful investment reduction increases the NPV of future projects. Projects that only have a single investment decision are only subject to the first decision of whether the project should be pursued.

The military manufacturing system design decomposition does not distinguish between initial and continuing investment decisions. The military decomposition focuses on how a company can minimize its own investment in a manufacturing system in order to maximize its return on investment. Although it does not specify when investments are made, the military decomposition indicates that a large, up-front investment is used to procure high levels of inventory and sufficient tooling for an entire project.

The AMSDD indicates that funding a long-term project with a single investment is not the best way to maximize the overall NPV to the company. A single investment precludes companies from making improvements to tooling designs by purchasing tools incrementally, as they are needed. A single investment also prevents companies from deciding not to purchase tooling that is expected to be necessary, but due to design or processing changes becomes obsolete. In addition, the value of money over time must be considered. A sum of small investments over many years may appear to be equal to or even larger than a large single investment, but adjusting for inflation and opportunity costs, this strategy may actually cost less.

Whether using a ROI or a NPV analysis, however, if military funding is provided in a lump sum, it will be in the company's interest to purchase as much inventory and tooling up front as possible. The company bears little risk, because the government will have to pay for tooling changes or additions if the initial purchases were incorrect. The company will also receive a larger cash flow sooner. This investment strategy will almost certainly not minimize the cost of the manufacturing system to the government. Therefore, the government must consider how a company makes investment decisions when deciding how to fund military programs. By providing funding in increments, the government may encourage companies to follow the AMSDD, purchasing tooling and components as they are needed. Furthermore, the government may be able to encourage contractors to pursue improvement projects and lower production costs by allowing the contractors to keep a portion of the savings.

A large initial investment will likely be needed for any project in order to prepare production facilities, purchase equipment, tooling and material, and to train personnel. Trying to predict the full investment up-front however, will likely result in an excessively expensive system design. Procurement policies should encourage contractors to build tooling as it is required, rather than all at once based upon initial estimates.

The following hypothetical NPV analysis illustrates how changing military funding may affect the value of a manufacturing system for both the company and the military. For a new product, it is assumed that the military is planning to spend $5 billion on tooling in preparation for a production rate of 20 products per year at a cost of $50 million each. Production will begin in year four and last through year 10. In the first case, the military pays for 75% of the tooling at the start of the project and pays for the remainder at the end of year 3. The contractor receives a profit of 10% for the tooling it fabricates and for each final product. No major improvements can be made to the manufacturing system, because most tooling was purchased early in the design stage. In the second case, the military pays for tooling in equal payments from year 0 through year 3. The manufacturing system design improves over this time, allowing the product to be produced for only $45 million apiece. The contractor is rewarded for its improvements with an extra $750 thousand profit from each final product (already included in the $45 million price). It is assumed that the contractor has a 12% discount rate and the government has a 6% discount rate. The NPV of the first case is $789 million for the contractor and $-9.49 billion for the military. The NPV of the second case is $766 million for the contractor and $-8.81 billion for the military. The contractor may prefer the first case, which has a slightly higher NPV. The government, however, will prefer the second case, which costs $660 million less than the first case – even allowing the contractor a significantly higher profit from production.

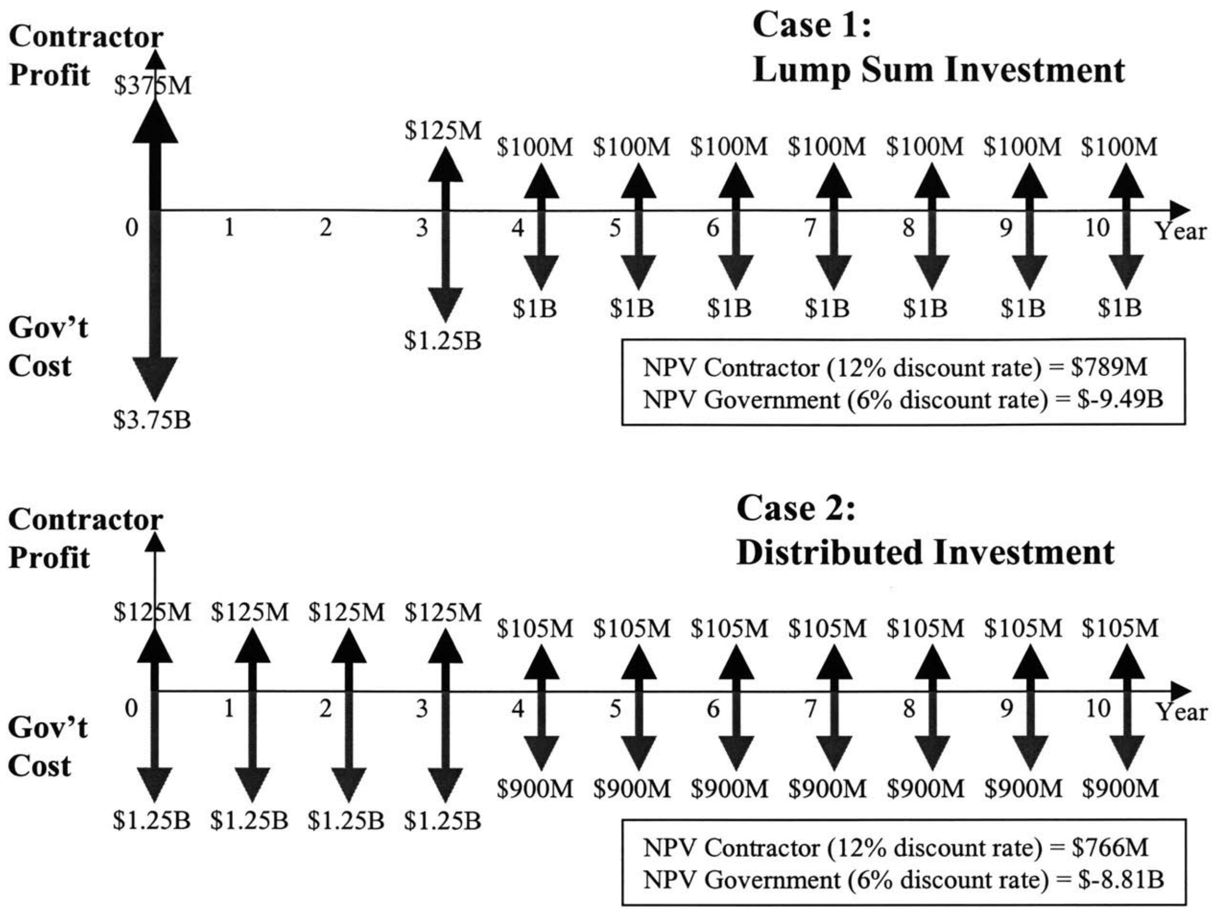

Figure 5.6: Hypothetical NPV Analysis of Government Funding

5.3 Manufacturing System Design Evaluation with the AMSDD

The military has a vested interest in ensuring that the manufacturing systems that produce its products are well designed and achieve the objectives for which they are designed. In the past, a Production Readiness Review (PRR) was performed to ensure that a manufacturing system was ready for full-scale production. The PRR has become an optional procedure, but is recommended by many people within the acquisition community. Although the PRR is meant to evaluate manufacturing systems, industry members say that it is often used as a basis for designing a manufacturing system. This result is a logical outcome, because companies are best rewarded for designing systems to achieve the attributes that are measured. Cochran and Dobbs [2000a] have illustrated how the performance measurement approaches at automotive component manufacturers lead to different manufacturing system designs.

An Aerospace Manufacturing System Design Evaluation Tool (Eval Tool) has been developed from the AMSDD as a tool for use by companies or the military to evaluate the design of aerospace manufacturing systems. If this tool is adopted as a way to measure manufacturing system designs, it may encourage companies to use the AMSDD during the design process. This section describes the development and application of the Eval Tool.

5.3.1 Aerospace Manufacturing System Design Evaluation Tool

An important distinction must be made between evaluating the design of a manufacturing system and measuring its performance. This distinction can be difficult because designs are often evaluated based upon performance. [Wang, 1999, p.101] It is possible for a well-designed system to be run poorly, yielding poor performance results. Conversely, it may be possible for a poorly designed system, which is run with careful attention, to yield some good performance results. The Aerospace Manufacturing System Design Evaluation Tool (Eval Tool) provides a way to evaluate the design of manufacturing systems independent from performance metrics that measure the end result of a system design.

Many lean assessment type tools exist, but most do not reveal the underlying connections between different criteria used in the evaluation. The Eval Tool evaluates how well the FRs of the AMSDD are satisfied. By referring back to the AMSDD, interrelationships between different FRs and DPs can be revealed. The Eval Tool makes explicit the FRs that are being evaluated and how they are derived from the top-level FR/DPs. Figure 5.7 shows how the FRs in the Eval Tool map to the AMSDD. The solid-colored boxes on the AMSDD are the FRs evaluated by the Eval Tool. All of the FRs and DPs from which these selected evaluation FRs were decomposed are shown in the light gray boxes.

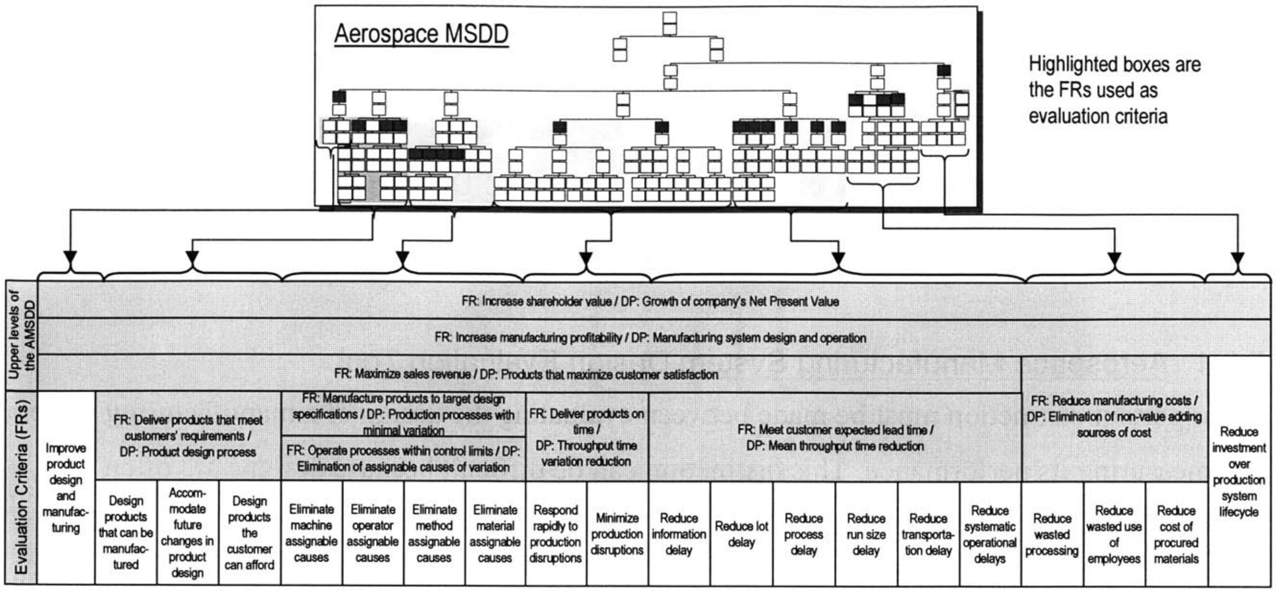

Figure 5.7: Mapping of Evaluation FRs to AMSDD

When selecting which FRs should be used in the Evaluation Tool, the minimum number that would allow a reasonable comparison to the AMSDD was selected. These FRs were selected at a level within the AMSDD that would permit them to be observed and evaluated. At least one FR was selected from each section of the AMSDD.

Continuous Improvement

The first evaluation FR is from the Continuous Improvement section of the AMSDD. This column evaluates how well a company seeks and implements feedback from customers and employees. High achievement requires developing and implementing feedback mechanisms that encourage suggestions and utilize the input for product design and manufacturing system improvements.

Product Design

The next three evaluation FRs are from the Product Design section of the AMSDD. The first of these columns evaluates the ability to design products that are manufacturable by integrating the design of products and their manufacturing processes. The second column evaluates how well a manufacturing system can accommodate future changes in product design. Design and manufacturing should develop a standardized method to apply design changes so that disruptions to the manufacturing system are minimized. The third column evaluates how well the product design process reduces costs. Designers can reduce costs by minimizing the number of unique part types, using "off the shelf parts" when feasible, minimizing the number of processing steps required, and simplifying the required processing steps.

Quality and Stable Processes

Four evaluation FRs are selected from the Quality section of the AMSDD. These columns evaluate a manufacturing system's ability to eliminate assignable causes that result from machines, operators, methods, and materials.

Throughput Time Variation (σ)

The next two evaluation FRs are selected from the sections of the AMSDD that address throughput time variation. The first column evaluates the ability to respond rapidly to production disruptions. The second column evaluates whether predictable resources have been selected in order to minimize the number of production disruptions.

Delay Reduction ($\bar{x}$)

Six evaluation FRs are selected from the Delay Reduction section of the AMSDD. The first column evaluates information delay, which is the delay within a manufacturing system between when a production signal is transmitted and when the signal is received and acted upon. The second column evaluates lot delay, which refers to parts waiting on other parts in the same lot before all parts are transported together. The third column evaluates process delay, which occurs when production is unbalanced and parts arrive at a station at a faster rate than they can be processed. The fourth column evaluates run size delay, which is the delay due to inventory when different part types are produced. The fifth column evaluates transportation delay, which is the amount of time parts spend in transit between operations. The sixth column evaluates systematic operational delays that occur for routine operations, such as material replenishment and preventive maintenance activities.

Cost Reduction

Three evaluation FRs are selected from the Cost Reduction section of the AMSDD. The first column evaluates wasted processing steps, which are any processing steps that do not add value to the final product. The second column evaluates the wasted use of employees. The third column evaluates how well a company can reduce the cost of procured materials by developing close partnerships with suppliers and integrating them into the overall manufacturing system.

Production Investment

The final evaluation FR is selected from the Production Investment section of the AMSDD. This column evaluates whether investment within a manufacturing system is based upon long-term or short-term goals.

The complete Aerospace Manufacturing System Design Evaluation Tool is shown in Figure 5.8, Figure 5.9, and Figure 5.10.

Upper levels of AMSDD (FRs/DPs)	FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
	FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
	FR: Maximize sales revenue / DP: Products that maximize customer satisfaction >>							
Evaluation Criteria (FRs)	**Improve product design and manufacturing**	**FR: Deliver products that meet customers' requirements / DP: Product design process**			**FR: Manufacture products to target design specifications / DP: Production processes with minimal variation**			
					FR: Operate processes within control limits / DP: Elimination of assignable causes of variation			
		Design products that can be manufactured	**Accommodate future changes in product design**	**Design products the customer can afford**	**Eliminate machine assignable causes**	**Eliminate operator assignable causes**	**Eliminate method assignable causes**	**Eliminate material assignable causes**
Level of Achievement (DPs) 1	No formal or informal customer or employee feedback system exists.	Products designed completely independently from manufacturing process development. 0% concurrent engineering. (Designs passed "Over the wall.")	No standard method exists to implement design changes. Changes may occur anywhere in the mfg. process, resulting in unplanned production stoppages.	Products designed with mostly unique, custom-designed parts that may require many complex processing steps.	Poor quality output from machines due to unknown causes of variation (unable to hold mean). No maintenance of machine to ensure quality.	Workers learn tasks by watching others. Tasks may be done differently each time.	Methods are unstable and ill defined. Variation in methods is arbitrary and is not visible.	High variation in incoming parts which cause quality problems. Materials are damaged in storage and transport
2	Occasional improvement meetings held to collect ideas from customers/ employees. Suggestions rarely implemented.	Products designed with little manufacturing input. Infrequent meetings held between design and manufacturing.	No standard method exists to implement design changes. Attempts are made to limit the frequency of changes to reduce production disruptions.	Products designed with many custom-designed parts or parts that require complex processing steps.	Some assignable causes of variation are identified. Maintenance is occasional and is not scheduled.	Limited amounts of formal skills training. Workers learn what tasks to do from instructions.	Methods are known but not documented (shop floor "tribal knowledge")	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.
3	Suggestion system exists for some customers/employees but not frequently utilized. Occasional meetings held to discuss and collect ideas. Small % of ideas implemented.	Most products designed with input from manufacturing. However, few products are designed concurrently with their manufacturing processes.	A standard method exists to implement design changes, but is not followed. Changes often result in unplanned production stoppages.	Products designed with about half custom-designed or unique parts. Many of these parts require complex processing steps.	Most causes of variation are identified but are still not eliminated. Maintenance is only in response to quality problems.	Formal skills training program in place. Workers learn tasks from senior workers. Work standards exist but methods still vary.	Methods have been defined and standards exist but are not always followed/ updated.	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.
4	Suggestion system exists for most customers/employees. Continuous improvement meetings held on a regular, but infrequent basis. ~30% of suggestions implemented	More than half of products designed together with the manufacturing processes. Design and manufacturing meet regularly to discuss issues.	The standard method to implement design changes is usually followed. Changes may result in short periods of unplanned production stoppage.	Products designed with many common parts that do not require complex processing. Most custom parts cannot be eliminated due to design requirements.	Most causes of variation eliminated, some causes are still unable to be removed.	Manual tasks are defined so that they are done the same way each time. Standard work instructions indicate how tasks are performed.	Methods are well defined and repeatable. Standardized and followed.	Supplier responsible for meeting specifications. Little inspection of incoming parts required.
5	Suggestion system extends to most customers and employees. Continuous improvement events held on a regular basis. ~50% of suggestions implemented.	Most products designed together with the manufacturing processes. Design and manufacturing hold regular and frequent status meetings.	Design changes are mostly implemented at predefined stages in the manufacturing process. Changes rarely require unplanned production stoppages.	Products designed with mostly common parts that do not require complex processing.	Causes of variation reduced so that machine output is stabilized and mean shifts rarely occur. Maintenance is scheduled and performed on time.	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and upgraded by workers.	When methods are improved or updated, they are documented and implemented.	Collaboration with suppliers to ensure quality. Material handling and storage designed to maintain quality of products.
6	Suggestion system extends throughout enterprise and all customers. Continuous improvement events held on regular and frequent basis. High % of suggestions implemented.	All products designed together with the manufacturing processes. 100% concurrent engineering.	Design changes only implemented at predefined stages within the manufacturing process. Changes do not require unplanned production stoppages.	Products designed using a small set of common parts that can be fabricated with few, simple processing steps. Use of off-the shelf parts are preferred.	Machines able to maintain mean, within tolerances. All assignable causes of variation eliminated or controlled through a regular maintenance program throughout system.	In addition to level 5, Any mistakes are not translated to defects through mistake proofing (poka-yokes)	Methods are continually being improved and implemented throughout organization. All employees are knowledgeable about the most current methods.	Collaboration with suppliers to improve quality and involvement in developing specifications. Parts transferred and stored to prevent damage.
Comments	Refers to design and/or manufacturing improvements resulting from customer and/or employee feedback. This requires development and implementation of feedback mechanisms that encourage suggestions and utilize the input for continuous improvements. This feedback is often obtained through "kaizen" events.	Integrated design of products and the manufacturing processes used to produce them helps designers to make tradeoff decisions that result in parts that meet functionality requirements and can be manufactured with minimal difficulty.	Design changes are common over the lifecycle of a product. Design and manufacturing should develop a standardized method to apply design changes. Changes may be segmented into blocks based upon units of time or quantity (I.e., implement a set of changes only after *x* months or *y* products have been completed.)	Refers to costs that are directly affected by product design. Costs can be reduced by minimizing the number of unique part types, using "off the shelf parts" when feasible, minimizing the number of processing steps required, and simplifying the required processing steps.	Refers to quality reliability of the machines. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Maintenance in this branch refers to that which maintains quality instead of those that prevent breakdowns.	Refers to attaining predictable quality output from the workers. This is done through training, defining and following standard work and preventing common human errors from translating to defects/quality issues.	Method's are how process are done and include assembly tasks and process plans for machining etc. To prevent variation, these methods must be defined and followed. (standardized)	Material problems may be from suppliers or from handling within the plant.
Metrics	**# of problems identified and corrected**	**% of a product designed in conjunction with its manufacturing system**	**Frequency at which design changes can be incorporated**	**Product price**	**# defects per n parts assignable to equipment**	**# defects per n parts assignable to operators**	**# defects per n parts assignable to the process**	**# defects per n parts assignable to quality of incoming material**
		% customer requirements fulfilled			**# defects per n parts with an assignable cause**			
					Process capability			
	Sales revenue >>							
	Profit from manufacturing >>							
	Rate of NPV growth >>							

Figure 5.8: Aerospace Manufacturing System Design Evaluation Tool (1 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
<< FR: Maximize sales revenue / DP: Products that maximize customer satisfaction							
FR: Deliver products on time / DP: Throughput time variation reduction		FR: Meet customer expected lead time / DP: Mean throughput time reduction					
Respond rapidly to production disruptions	**Minimize production disruptions**	**Reduce information delay**	**Reduce lot delay**	**Reduce process delay**	**Reduce run size delay**	**Reduce transportation delay**	**Reduce systematic operational delays**
Production disruptions occur frequently. Operators work around these disruptions so they are hidden.	Unpredictable resources. Disruptions are frequent and impact delivery.	Production schedules throughout the manufacturing system determined by rigid master schedule.	Large transportation lot sizes between machines or processes to reduce transportation costs.	Machine capacity and rate independent of demand (maximize output). Large and unpredictable levels of WIP between processes to manage system and avoid starvation.	System is designed to operate based on forecast demand, not actual demand. Production in large run size batches to avoid the long setup times.	Mfg. Process focused layout. Machines arranged by function in isolated departments (job shop type). Complex material flow.	Processes must be interrupted frequently for routine tasks such as material handling, machine maintenance, chip removal etc.
End of line inspection is used so quality problems are found late. Slow response to problems.	Disruptions are frequent but do not impact delivery often due to large buffer sizes. Frequency and type of disruptions is unknown.	Production schedules based upon centralized master schedule, but updated based upon actual performance and local considerations.	Single piece flow in only some areas (like assembly). Upstream processes still deliver materials in large lots.	Machines/processes in functional departments are arranged for product flow. High levels of inventory required between departments (varying production rates)	System is designed for production plan based on forecast demand. Run size is based on <1 month's forecast demand.	Process focused layout with departments grouped to reflect product family sequence of operations. Parallel processing occurs. Routing is unclear. (focused factory)	Routine tasks are designed so that they may be done infrequently - loading lots of material, large reservoirs for chips, infrequent maintenance.
Quick response to production disruptions (when they are found) to continue production. Root cause is not eliminated so problems may reoccur.	Machine disruptions (MTTF, MTTR) are recorded and used to determine lead time required for predictable delivery.	Production schedules based upon customer schedule. Schedules translated into daily requirements for each product line.	Single piece flow in only some areas. Upstream processes deliver materials in lots based on standard inventory.	Assembly or transfer line designs running at high speeds feeding multiple customers. Large amount of inventory before and after lines to manage product flow	System is designed for production plan based on forecast demand. Run size is based on <1 week's forecast demand.	Product or customer oriented material flow. Machines/stations in cellular design with some batch processes intermixed (partial cells)	Many routine tasks are scheduled so that they may be done after hours (like maintenance). Production still must stop regularly for other activities.
Production disruptions are addressed quickly and the root cause is eventually addressed. In-process inspection.	Disruptions from machines/ equipment, people, parts and information availability are known. Systems being developed to make resources more predictable.	Production schedule based upon actual demand. Internal production signals generated by withdrawal of parts. Signals relayed electronically or by kanban cards.	Single piece flow within cells/sub-systems. Large lots transferred between sub-systems.	Customers grouped to achieve effective takt times. Machines and people are capable of working to takt time. Some parallel processing/stations exist.	System is not based on actual demand. Run size is based on a schedule that repeats at one or greater than one day. External setup tasks are reduced.	Material flow/cellular design with machines/stations close together. No complicated material flow (well defined cells)	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal and work preparation.
System designed so that production disruptions are visible. In-process checks by operators so quality issues are found quickly. Good root cause analysis.	Systems designed so that disruptions from all resources are reduced. Includes perfect attendance, TPM, std. material supply and reliable information systems.	Production based upon customer demand. Withdrawal of product initiates signal to replenish inventory. Signal relayed by electronic signal and/or kanban card.	All cells/sub-systems using single piece flow. Transfer lots sizes between sub-systems being reduced based on demand interval.	Cells/sub-systems running at takt time with standard inventory of one between stations. Machines and people are capable of working to minimum takt time.	System supports actual demand and expected peaks. Produce exactly what is consumed by the customer on a daily or shift basis. Internal setup tasks are reduced.	Material flow oriented layout design applies throughout value stream. Minimum handling with process close to receiving and shipping docks. (linked cells)	Workers continually make improvements in eliminating interference between people, material handling, maintenance etc.
Co-location of cause and effect (simplified material flow) and systematic method for communicating, and solving problems. Line stop methods in use (Andon)	Production disruptions rarely occur. Throughput time variation is very low and predictable.	Production matches customer demand. Withdrawal of parts authorizes production to replenish. Kanban card or electronic signal relays production signal.	Single piece flow of parts throughout the factory.	Production balanced to takt time throughout value stream. Some flexibility to produce to different takt times. Minimum WIP between processes& sub-systems/cells.	Production of the desired mix and quantity during each demand interval using Heijunka. Almost no setup required between part types.	Reduced transportation throughout supply chain. Production near customer and supplier base. Material flow oriented layout throughout plant.	Processes rarely ever stop for routine activities.
Production disruptions refer to machine breakdowns, quality issues, information, worker availability. This branch deals with how these problems are addressed and eliminated.	Predictable resources are required for minimal production disruptions. Total preventative maintenance (TPM) programs, perfect attendance, reliable part supply and and information are required.	Information delay refers to the delay between when a production signal is transmitted and when the signal is received and acted upon. By conveying products with production signals, such as kanban cards, info. delay is minimized.	Lot delay refers to parts waiting on other parts in the lot before they are transported together. This is avoided with single piece transport. Reducing transportation distance is important to achieve this.	Process delay occurs when arrival rate > service rate (unbalanced rates). Large and unpredictable inventory levels are indicative of process delay. It is reduced by balancing to a constant and predictable takt time. Flexibility to produce to different takt times keeps system balanced when demand changes.	Delay due to inventory when producing different part types. Setup time is the time to change between part types within a station. Knowledge of the part types required is necessary or large inventories of different parts are required. With accurate and timely info, only the parts required are produced.	To reduce transportation delay, the amount of transportation should be minimized. In system design, this is a consideration in factory layout. This is also applicable from a geographical view as well as within the plant	Operational delays are routine disruptions designed into the system (processes stopping for maintenance, material replenishment and other processes). They may be eliminated through machine and station design (Chip removal, control access from rear of station), operator work routine design.
Time between occurrence and resolution of disruptions	**Number of disruptions & amount of time lost to disruptions**	**Time from info. transmitted or requested until info. received**	**Inventory due to lot size delay**	**Inventory due to process delay**	**Inventory due to run size delay**	**Inventory due to transportation delay**	**Production time lost due to interference among resources**
% on-time deliveries		Difference between mean throughput time and customer's expected lead time					
<< Sales revenue							
<< Profit from manufacturing >>							
<< Rate of NPV growth >>							

Figure 5.9: Aerospace Manufacturing System Design Evaluation Tool (2 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value			
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation			
FR: Minimize manufacturing costs / DP: Elimination of non-value adding sources of cost			Minimize investment over production system lifecycle
Reduce wasted processing	**Reduce wasted use of employees**	**Reduce cost of procured materials**	
Processes designed without regard for # of steps. Overly complex or precise processing methods selected.	One person, one machine design - operator watches machine run. Excessive walking to search for tools and materials. Excessive operator motions.	Arms-length relationships between suppliers and customers. Design decisions made from a single-company perspective. Minimal information transfer.	Investment decisions based solely on immediate needs. Long-term product and volume flexibility requirements not considered.
Processes designed with a bias towards too many steps or overly complex methods. Attempts are not made to improve both.	Operator runs single machine, does "fill-in" work between cycles. Excessive walking req'd to obtain tools and mat'ls not located at point of use. Excessive operator motions.	Arms-length relationships between suppliers and customers. High-level design meetings occur only at beginning of project. Info. transfer limited to critical requirements.	Investment decisions focus on meeting short-term business needs. NPV analyses may be used for some long-term projects.
Process design attempts to reduce # or complexity and precision of processing, but the result is unbalanced towards too many steps or overly complex methods.	Operator may run more than one of the same type machine. Workers isolated to stations to avoid walking. Poor ergonomics causes worker to constantly reposition themselves.	Loosely-linked supply chain. Multi-level design meetings occur throughout project. Information protected and transfers limited to critical requirements and non-proprietary info.	Investment decisions seek to maximize NPV, but long-term projects frequently preempted by short-term needs.
Process design generally balances # and complexity of mfg. steps. Several non-value adding or excessively complex steps have been identified, but can't be eliminated.	Operator can run multiple machines of different types. 5S program implemented so that parts, tools, equipment are where required. No operator- process work routine defined.	Integrated supply chain. Suppliers and customers meet frequently to discuss product and mfg. system design. Most information is available to enterprise members.	Investment decisions focus on maximizing NPV. Long-term projects occasionally scaled back because of short-term needs.
Process design balances the # and complexity of manufacturing steps. Few if any non-value adding or excessively complex steps remain.	Multi-skilled operators run several machines/ processes.Machines are small and close to reduce walking distances (in cells.) Operator-process work routine graphs used.	Integrated supply chain. Representatives from suppliers and customers sit on design teams to provide input. Information is available throughout the enterprise.	Investment decisions heavily influenced by NPV analyses. Long-term goals rarely sacrificed to meet short term requirements.
The minimum # and complexity of processing steps have been selected. Reducing steps further would add significant cost to the product.	Number of operators can be varied to achieve range of takt times. Machines run autonomously. Level 5 applied through company. 5S understood & used beyond shop floor.	Highly integrated supply chain. Product and mfg. system design decisions made by teams that cross company borders. Free flow of Information throughout enterprise.	Investment decisions based upon thorough NPV analyses. Decisions allow company to fulfill short and long term requirements.
Wasted processing steps are any steps that do not add value to the final product. Excessive transportation, overly tight tolerances, and unnecessary features are all examples of wasted processing steps.	Wasted use of employees includes operators waiting for machines to finish cycling, walking excessive distances, searching for tools and materials, and poor ergonomics.	Reducing the cost of procured materials requires developing close partnerships with suppliers and integrating them into the overall manufacturing system. Sharing information between suppliers and integrators increases opportunities for improvement and cost reduction.	Companies operating in a fast-changing environment can reduce the NPV of future investments by making a large up-front investing in a highly flexible mfg. system. This flexibility may be wasted, however, for companies that operate in more stable environments and therefore will not require frequent system design changes.
# of wasted processing steps	**% employee time spent on non-value adding activities**	**Cost of procured materials**	**Investment over system lifecycle**
Manufacturing costs			
<< **Profit from manufacturing**			
<< **Rate of NPV growth**			

Figure 5.10: Aerospace Manufacturing System Design Evaluation Tool (3 of 3)

The Evaluation Tool uses a qualitative ranking system to estimate how well a manufacturing system satisfies the FRs of the AMSDD. Performance is graded on a scale from 1 to 6, where 1 is the worst and 6 is the best. A person performing the evaluation fills in sections of a pie chart to indicate the percentage of a manufacturing system that falls into each achievement level for each evaluation category. The fractions of all pies within a column must sum to 100%. An example is shown in Figure 5.11.

	Respond rapidly to production disruptions	
1	Production disruptions occur frequently. Operators work around these disruptions so they are hidden.	= 25%
2	End of line inspection is used so quality problems are found late. Slow response to problems.	= 50%
3	Quick response to production disruptions (when they are found) to continue production. Root cause is not eliminated so problems may reoccur.	= 25%
4	Production disruptions are addressed quickly and the root cause is eventually addressed. In-process inspection.	
5	System designed so that production disruptions are visible. In-process checks by operators so quality issues are found quickly. Good root cause analysis	
6	Co-location of cause and effect (simplified material flow) and systematic method for communicating, and solving problems. Line stop methods in use (Andon)	

Figure 5.11: Qualitative Evaluation Method

In addition to the qualitative evaluation method, the Eval Tool provides companies with a set of Performance Metrics that correspond to each of the evaluation FRs. These metrics are taken from the AMSDD and could be used to collect quantitative evaluation data. These Performance Metrics and their corresponding FRs are shown in Figure 5.12.

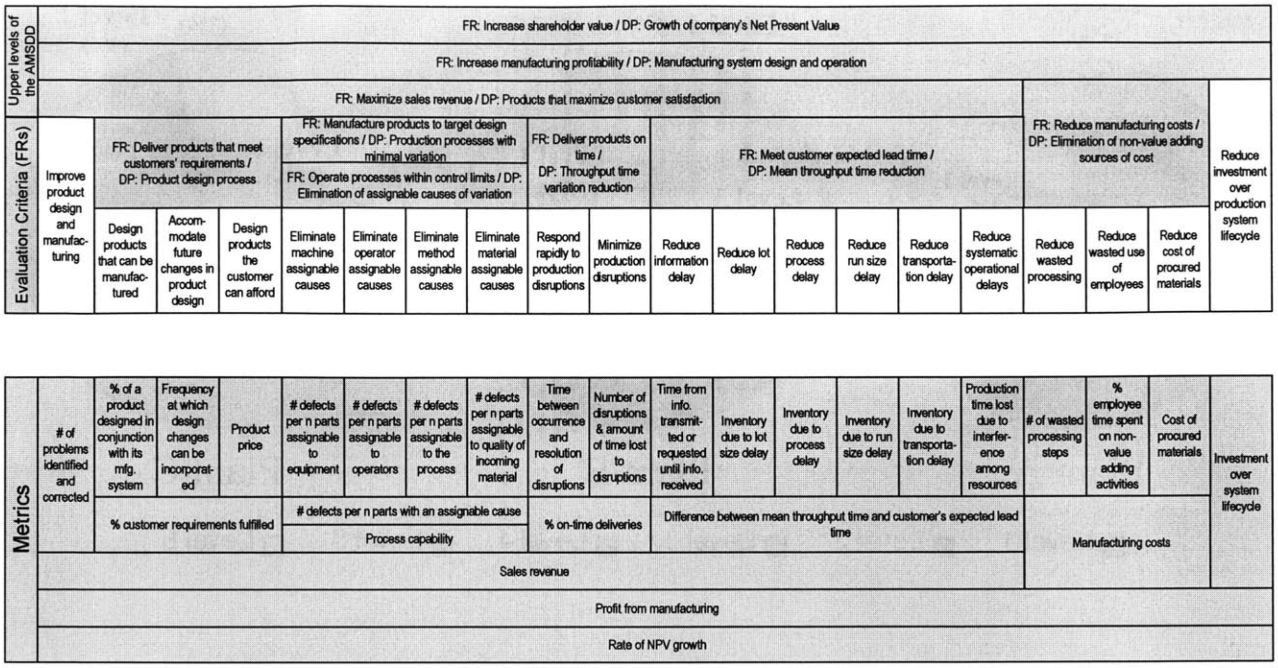

Figure 5.12: Evaluation FRs and Performance Metrics

5.4 Evaluation of Three Aerospace Manufacturing Systems

In order to demonstrate how the Eval Tool can be used by the aerospace industry, this section presents a sample analysis of three manufacturing system designs. The analysis is subjective and based upon the author's impressions at three aerospace manufacturing plants. The author acknowledges that the analysis is based on a limited exposure at each plant, and therefore may not provide entirely accurate representations. The three plants were selected from the sites that contributed to the development of the AMSDD. All three plants specialize in space sector products. Plant A produces propulsion devices, Plant B produces communications systems, and Plant C produces launch vehicles. The evaluations at Plant A and Plant B focus on specific manufacturing lines and sub-systems within the plants. The Plant A evaluation was based upon the assembly & test of a single product. The Plant B evaluation considered electronics sub-assembly, full-product assembly, and testing of an aggregate group of products. The evaluation of Plant C considers an entire plant that contains product fabrication, assembly, and test operations.

5.4.1 Evaluation tool results

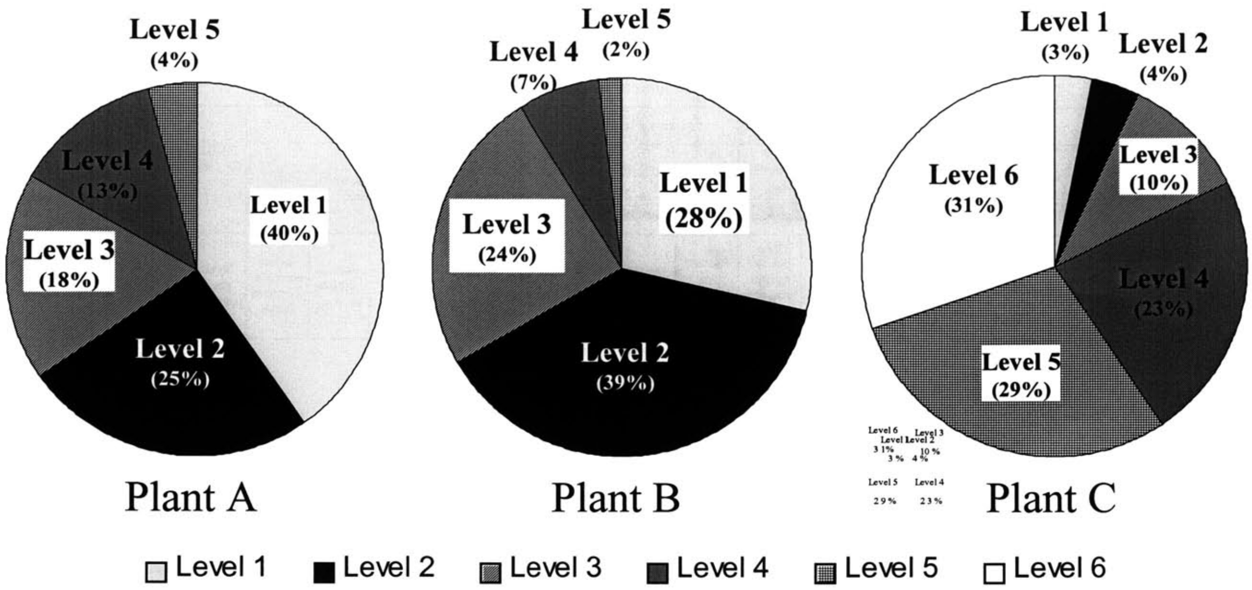

Figure 5.13: Overall Manufacturing System Evaluation

Overall evaluation results for all three plants are shown in Figure 5.13. The results are grouped by levels of achievement to illustrate what levels each plant has achieved and to show the percentage of each plant that falls into each level. The results indicate that only Plant C has designed a manufacturing system that achieves Level 6 on some sections of the Eval Tool. Plants A and B have achieved Level 5 in small portions of their manufacturing systems. The majority of the manufacturing systems at Plants A and B however, achieve only Level 1 or Level 2. Plant C, on the other hand, has achieved Level 4 or higher for the majority of its manufacturing system. Better than half of the manufacturing system at Plant C falls into Level 5 or Level 6. The raw evaluation scores for each plant can be found in Appendix E.

Company	Average Evaluation Tool Score
Company A	2.2
Company B	2.2
Company C	4.6

Table 5-1: Average Evaluation Tool Scores

The average Evaluation Tool scores for each plant are found in Table 5-1. Two of the three companies that were evaluated had very similar scores. Plants A and B both averaged 2.2 on a scale of 1 to 6. Plant C more than doubled these scores with an average score of 4.6. These dramatic differences are very important for several reasons. First, the similar scores of companies A and B indicate that similar factors within the aerospace environment may have influenced the design of these plants' manufacturing systems. Second, the large difference between the Plant C score and the other companies indicates that Plant C may have found a way to overcome many barriers that hinder manufacturing system designs within the aerospace industry. Finally, however, the fact that plant C is still not at the top of the scale at a 6 may indicate that there are additional problems within the aerospace industry that must be addressed. The results of each plant by category are shown in Figure 5.14 and Table 5-2.

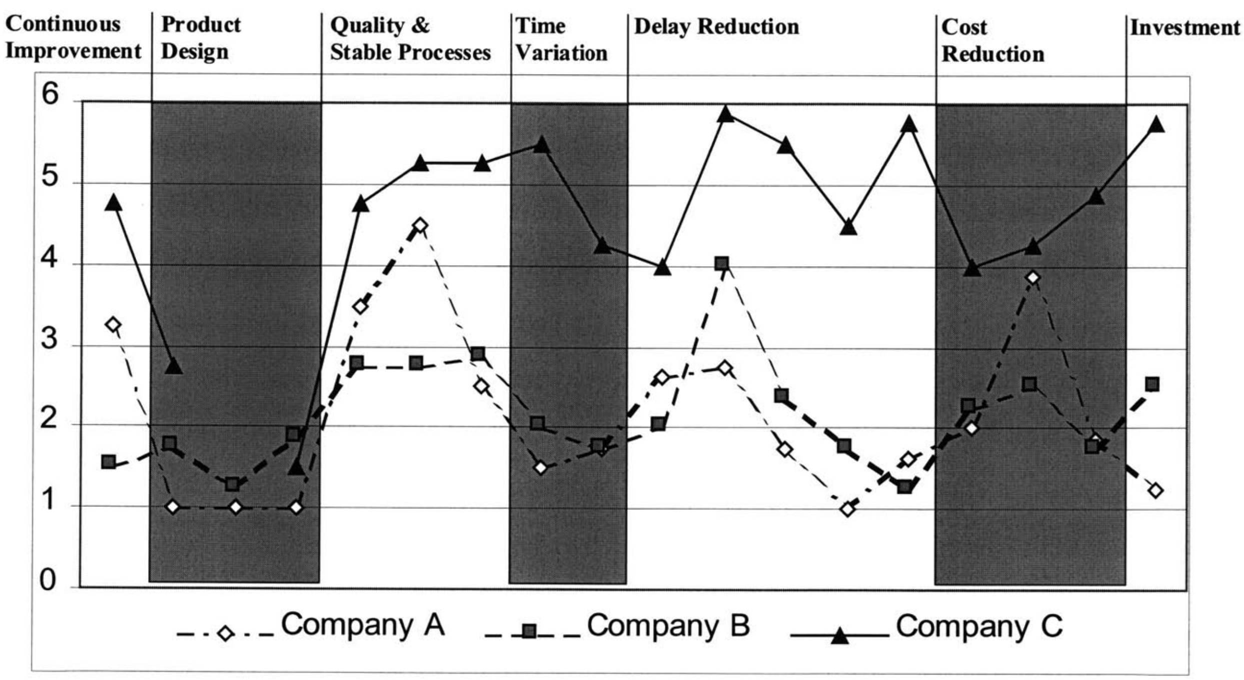

Figure 5.14: Evaluation Tool Scores by Category

	Continuous Improvement	Product Design	Quality & Stable Processes	Time Variation	Delay Reduction	Cost Reduction	Investment
Plant A	3.3	1	3.5	1.6	2.0	2.6	1.3
Plant B	1.5	1.6	2.8	1.9	2.3	2.2	2.5
Plant C	4.8	2.1	5.1	4.9	5.1	4.4	5.8

Table 5-2: Average Evaluation Tool Scores by Category

The evaluation results varied considerably among the three plants for the Continuous Improvement and Investment categories. Plants A and B were relatively high for Quality & Stable Processes, low for Time Variation, and close to their averages for Delay Reduction and Cost Reduction. Interestingly, all three plants scored poorly in the Product Design category.

5.4.2 Explanation of trends and evaluation ratings

Continuous Improvement

Plant A scored relatively well in the Continuous Improvement section because it had organized improvement teams and held periodic small-scale improvement (kaizen) events. Plant B scored poorly because there was little effort to improve knowledge transfer on the shop floor. Operators tended to keep their "tricks" and special skills tightly guarded as a form of job security. There was no visible evidence of improvement efforts, such as kaizen events or suggestion boxes. Plant C scored well for holding frequent, facilitated workshops that involved management, engineering, and the shop floor. The entire plant and some suppliers participated in improvement activities.

Product Design

Plant A scored poorly in Product Design because most of their components required custom fabrication and could not use "off the shelf" or even interchangeable parts. Plant B scored poorly as a result of an "over the wall" mentality between design and manufacturing. There was little interaction between design and manufacturing. Many highly customized components were required for each product and there was little effort to commonize and reuse components. In addition, late and frequent design changes often disrupted the manufacturing schedule. Plant C scored poorly because its product designers were geographically isolated from the manufacturing facility. It was also very difficult to use "off the shelf" parts on Plant C's products.

Quality and Stable Processes

Quality and Stable Processes was the best individual category for both Plant A and Plant B. Plant A had many highly skilled technicians and provided them with detailed process descriptions for each operation. Plant B operators had varying degrees of skill and operations were not always well defined. Plant B also had to cope with a highly unpredictable level of quality in its incoming materials. When necessary, Plant B would work with suppliers to improve quality. Plant C scored very well for its use of mistake-proofing devices and close interaction with suppliers to ensure high quality of incoming materials.

Time Variation

Plants A and B both scored poorly in the Time Variation category. Plant A had a slow response to problems when they occurred. Work was set aside to wait for an engineering disposition, and other work was accelerated to fill the gap. These dispositions created unpredictable throughput times and disrupted an orderly flow of work through the factory. Plant B had varied responses to disruptions throughout its plant. Some areas quickly addressed problems, while other areas took longer. Disruptions resulting from product changes or material issues were frequent, and often required expediting components to keep a product on schedule. Plant C scored well in the Time Variation section because the low levels of WIP in the factory made problems visible immediately. This visibility allowed a quick response to address problems as they became known and prevented them from recurring.

Delay Reduction

Plants A and B scored close to their averages for Delay Reduction. At Plant A, production is determined by a master schedule based on forecast demand, instead of actual customer demand. The factory has some isolated areas that convey parts between processes one-piece at a time, but there is significant batch production throughout most of the manufacturing system. Plant B produces to a master schedule, based upon customer orders, which is adjusted periodically. There is some single-piece flow in the manufacturing system, but in general the facilities are laid out in departments based upon processing requirements and parallel processing is common. At Plant

C, which scored very well in the Delay Reduction category, the production schedule is determined by customer demand. This demand is used to calculate the takt time for the manufacturing system. In production, sub-components and final products follow a single-piece flow path that is paced by takt time throughout the plant.

Cost Reduction

Similar to Delay Reduction, Plants A and B scored close to their averages in the Cost Reduction category. Plant A requires many complex processing steps during part fabrication. The technicians are highly skilled and can perform multiple sets of tasks, but they are often isolated at a single workbench. At Plant B, shop rules limit technicians to performing one set of tasks at a time, preventing them from operating multiple machines. Plant C scored fairly well at Cost Reduction. A single job classification applies to all technicians, which allows any worker to perform any task. Teams meet frequently to identify and eliminate non-value-adding work, standardize operations, and make other improvements. Suppliers are closely integrated into the manufacturing system with some suppliers actually moving on site to improve communication and design efforts for better integration of the supply chain. Having a close supplier base will also allow Plant C and its suppliers to maintain less WIP and balance production with demand.

Investment

Plant A scored very low in the Investment category. Investment decisions were all very low-risk because the product was nearing the end of its contract and future contracts were uncertain. Plant B scored slightly above its average. Investment generally appeared focused on current needs, not future opportunities. Some investments were made to ensure medium-term capacity, but the long-term effects of these investments are unclear. At Plant C, Investment was the highest scoring category. Plant C took a long-term view when it invested in its manufacturing system. Although some of its products are intended for the military, the manufacturing system was designed with significant company capital. The plant is seeking long-term profitability and wanted to meet military requirements, but not be restricted in its commercial business. The company expects the commercial side to supply the majority of its business over the long-term.

5.4.3 Possible procurement policy effects

With only three site evaluations, it is not possible to draw valid conclusions about the entire aerospace industry. If additional sites are evaluated using the Aerospace Manufacturing System Design Evaluation Tool, it may be possible to discern some definite trends that result from military procurement policies. It would be necessary to evaluate and identify manufacturing systems that produce purely military products, purely commercial products, and mixed products. The three plants evaluated in this thesis all supply both military and commercial customers. The following analysis of the evaluation results is not intended to provide concrete conclusions, but may indicate specific areas in which future research can identify procurement policies that hinder improving the overall design of manufacturing systems.

Product design was the weakest category for all three of the plants considered in the evaluation. It should be noted that this category evaluates how product design impacts manufacturing system design and does not address how well product designers meet the design specifications that they are given. These poor results indicate that it was a good idea to add product design to the AMSDD, because the industry appears to need to work on how it integrates product design with manufacturing system design. Minimizing part count and using more common parts may be the most difficult task for product designers, but will certainly have a tremendous impact on product manufacturability.

Assuming that it is possible to improve the interactions between the design of a product and its manufacturing system, it would be valuable to identify whether there are military procurement policies that should be created or eliminated to foster a better overall system design. The evaluation results suggest that the military should perhaps take a more active concern in the actual manufacturing system with which its products will be produced and how that system is designed. The results imply that the current product-focused concerns do not sufficiently consider the impact of product design on the overall manufacturing system design. This weakness supports Andrew Wang's conclusions that the military has focused more upon designing products for performance. [Wang, 1999] Procurement policies should not just ensure that a manufacturing system will produce the specified products. Beginning with product design, the entire system should be designed to produce a high quality product with low throughput times, low inventory, low costs, and with a long-term investment strategy.

The fact that the highest average scores for Plants A and B were in Quality and Stable Processes may indicate that this area is a strong focus within aerospace manufacturing systems. Nonetheless, these scores are fairly low overall, with averages of 3.5 and 2.79 out of 6. Plants A and B may try to focus on quality, but by using a narrow focus and not designing the entire manufacturing system, sub-optimization may prevent these companies from achieving higher levels on the Eval Tool. Plant C, which is a greenfield site, began by designing its operations with an overall system design perspective. Quality is not more or less important at Plant C, but by designing the entire manufacturing system, Plant C is able to achieve a score of 5.08 out of 6. It is possible that within manufacturing systems, military procurement policies have caused companies to address quality issues in ways that lead to a narrow focus and sub-optimization at the expense of overall manufacturing system design. If companies were encouraged to address quality issues within the scope of the complete manufacturing system design, these companies would be able to achieve a higher level of quality according to the AMSDD.

5.5 Summary

This chapter has shown several ways that the Aerospace Manufacturing System Design Decomposition can be used as a tool to support military procurement programs by guiding manufacturing system design. Comparison of the AMSDD and the Military Aircraft Manufacturing System Design Decomposition revealed improvement opportunities in military procurement policies. This comparison showed that: 1) Military procurement programs must not focus solely on product design, but must focus upon design of the entire manufacturing system. 2) Military procurement policies should allow contractors to keep more from cost savings programs to encourage long-term cost savings projects by sharing risks as well as rewards. 3) Military procurement programs should structure investments in a manufacturing system so that the overall investment required, not the initial investment, is minimized.

An Aerospace Manufacturing System Design Evaluation Tool was developed to help companies compare the design of their manufacturing systems to the AMSDD. The Eval Tool uses criteria based upon FRs selected from the AMSDD to identify the strengths and weaknesses in a manufacturing system. Basing the Eval Tool on the AMSDD allows users of the tool to see the interrelationships between different manufacturing system components. This Eval Tool was used to evaluate the manufacturing system designs of three aerospace companies. These evaluations were used to illustrate the strengths and weaknesses of each system. These strengths and weaknesses were then analyzed to understand if they may implicate current procurement policies or suggest new policies that should be implemented.

Chapter 6 Conclusions

6.1 Development and Application of the AMSDD

In this thesis, an Aerospace Manufacturing System Design Decomposition (AMSDD) was developed. The AMSDD is based upon feedback from aerospace industry members regarding the Manufacturing System Design Decomposition (MSDD). The hypothesis of this thesis was that the new AMSDD would be very similar to the MSDD. While this research has resulted in several additions to the AMSDD, the author argues that the original hypothesis has been proven true. The new additions presented in the AMSDD have not changed significantly the content of the original MSDD. Instead, the AMSDD has added sections to address needs of the aerospace industry that had not been explicitly addressed by the MSDD. Development of the AMSDD has built upon the existing MSDD and did not require a complete reconstruction.

The close similarities between the MSDD and the AMSDD show that many of the challenges faced by the aerospace industry are shared by the automotive and consumer products industries for which the MSDD was originally developed. In other words, many of the manufacturing system design issues that must be addressed by the aerospace industry are common to other industries with repetitive, discrete part manufacturing. Many aerospace industry members had doubted the applicability of the MSDD because of the higher volumes associated with the automotive and consumer products industries. The similarity of the AMSDD and MSDD illustrates that the manufacturing system design relationships within these manufacturing systems are independent of volume.

The changes that were made to the AMSDD as a result of aerospace industry feedback are not necessarily unique to the aerospace industry. This commonality further supports the claim that the manufacturing system design relationships that exist in the aerospace industry are common to other industries. The new concepts that were added at the suggestion of aerospace industry members, however, do reveal a focus on different manufacturing issues between the aerospace industry and automotive or consumer product industries. The impact of product design on manufacturing system design was consistently pointed to as missing from the MSDD. The impact of product design on manufacturing system design is very important to the automotive industry. A couple of possible reasons that this omission has gone largely unnoticed by the higher volume industries, but not the aerospace industry, are that:

- In many of the higher volume industries, tens of thousands of the exact same product are produced between design changes. These high-repetition production runs may allow manufacturing engineers to spend more of their time fine-tuning manufacturing processes, rather than readjusting equipment and process plans to accommodate design changes.
- In the aerospace industry, on the other hand, production volumes may be a single unit for highly customized products or several hundred units for relatively high-volume products. Aerospace manufacturing engineers, therefore, may spend a considerably higher percentage of their time determining how to manufacture new products and implementing design changes to existing products.

Most of the aerospace industry members who were interviewed were interested in learning improved manufacturing methods from other industries. Some of these engineers and managers were critical of the aerospace industry for not improving its manufacturing system designs and for making too many excuses why these manufacturing systems couldn't be improved. The feeling among these interviewees was that the aerospace industry could use the MSDD to design manufacturing systems if the industry was willing to discipline itself. One plant manager explained that the manufacturing system at his plant had evolved over time. He said that the system is designed as though it had been extrapolated from a small engineering project into a company. He suggested that the MSDD could be a useful tool for guiding the design of aerospace manufacturing systems. On the other hand, some industry members questioned the value of focusing on manufacturing system design, which they cited as only 10 percent of the total cost of a program. They believed that their efforts would be better spent on other areas in the company, such as overhead reduction and improving product design. Other industry members, however, countered this argument by saying that improving the manufacturing system would drive other improvements within the company.

Some aerospace industry members may initially question how well the AMSDD applies to the entire industry, because a large number of the sites visited were in the space sector. The actual breakdown was half aircraft and half space sector sites. At these sites, some electronics assembly work was observed. No sites from the engine sector were visited for this research. Nonetheless, it is assumed that the AMSDD developed in this thesis is applicable to all sectors of the aerospace industry. This assumption is based upon the fact that the AMSDD and the MSDD, although developed for very different industries, are very similar. Sectors within the aerospace industry vary widely, but it is arguable that the space sector is the least similar to the industries used for the original MSDD. The space sector frequently produces custom designed products and may experience multiple design changes during the production of a single product design. Therefore, if the AMSDD can be applied to the space sector, it is likely that the AMSDD applies to the entire aerospace industry.

The sample analysis of three space sector manufacturing systems, using the Eval Tool developed in this thesis, revealed that the manufacturing system of Plant C corresponded to the AMSDD much closer than the manufacturing systems of the other two sites did. The key difference between Plant C and the other plants was that Plant C was designed primarily for its commercial business. The products at all three plants are sold to both military and commercial customers, so Plant C, along with the other sites, received military funding for tooling and had to conform to military procurement policies. When designing its manufacturing system, however, Plant C invested a large amount of its own capital to lay out the entire factory to minimize transportation. Plant C also designed manufacturing processes to enable the product to be paced according to takt time. By designing the entire manufacturing system, instead of focusing solely on individual processes, Plant C was able to better satisfy the functional requirements of the AMSDD. This result suggests two important implications for military procurement policies:

- First, the military should be more actively concerned about the actual manufacturing system with which its products are produced and how that system is designed.
- Second, for purely military programs, following the AMSDD may require significant changes to military procurement policies. Plant C was able to justify the risk of investing its own capital to design the overall manufacturing system, because of the profit expected from the commercial business. In a purely military program, the government must be more willing to share in potential risks as well as benefits of cost saving programs. A company is not likely to invest its own capital into manufacturing system improvements if the benefits are absorbed by the government during the next procurement cycle.

There are several strengths and weaknesses associated with using an Axiomatic Design approach to manufacturing system design. The Aerospace Manufacturing System Design Decomposition provides a way to see and understand how specific shop floor practices contribute to achieving the top-level goals of a company. The AMSDD also reveals the interrelationships between practices within a manufacturing system. A weakness of the AMSDD is that it is not an implementation methodology. It is not possible to use the AMSDD as an ordered set of steps to follow when designing a manufacturing system. Another weakness is that the AMSDD may initially be non-intuitive and intimidating. Manufacturing system designers must make an effort to understand the Axiomatic Design methodology and to be able to understand the AMSDD.

The Eval Tool developed in this thesis is best suited for use by a company that is attempting to use the AMSDD to guide the development of its manufacturing system. The key to using the Eval Tool is understanding the tool's relationship to the AMSDD. When the Eval Tool is used to identify weaknesses in a company's manufacturing system, the company should refer back to the AMSDD to understand the interrelationships that affect the deficient areas. Efforts should then be applied to improve all of the practices that affect the categories that the Eval Tool identified as needing improvement. A company is unlikely to succeed at improving its performance if improvement attempts focus solely on the individual categories that score poorly.

6.2 Future Work

The new top-level of the AMSDD lends itself to a decomposition of more than just manufacturing. It is possible and may be considered valuable to pursue other decompositions, such as marketing, sales, and other business concerns.

Several parts of the AMSDD may benefit from further decomposition or the exploration of new concepts. The AMSDD does not thoroughly address corporate culture building concepts such as employee involvement and training, nor does it suggest ways to gather and record the first-hand knowledge of workers. These weaknesses indicate that there is still room for improvement in the way that the AMSDD deals with human interactions. It may not be possible to create a decomposition of labor policies and practices, but such a decomposition would be very valuable to companies when trying to build a culture where workers strive to adhere to the practices depicted by the AMSDD.

The three site evaluations illustrated how the Eval Tool could be used to identify trends that reveal the impact of military procurement policies on manufacturing system designs. If additional sites are evaluated, it may be possible to discern more definitive trends across all sectors. A thorough comparison would require identifying and evaluating manufacturing systems from different aerospace sectors that produce purely military products, purely commercial products, and mixed products.

Finally, it would be worthwhile to consider updating the MSDD to reflect some of the changes presented in the AMSDD. Although the AMSDD was developed from aerospace industry feedback, most of the concepts apply to all industries. Continuous improvement and product design issues affect manufacturing designs at every company. Additionally, the top-level goal of increasing shareholder value applies to most industries. The design decomposition approach also provides an opportunity to develop new system designs for product development, marketing, sales, and other business systems in the context of how these systems fit within an enterprise and interface with each other as well as manufacturing system design.

Glossary

Note: Definitions with a (*) are adapted from the "Production Operations Level Transition-To-Lean Roadmap" developed by the Lean Aerospace Initiative [LAI, 2000]

Aerospace industry: In this thesis, the term *aerospace industry* includes companies involved in the design and fabrication of aircraft, spacecraft, avionics, space electronics, and aircraft or spacecraft propulsion systems.

Arrival rate: The rate at which an upstream operation supplies parts to the next station downstream.

Autonomous: Automated so that an operator does not need to monitor equipment or a station during the processing cycle.

Balanced Production Flow*: Balanced production flow means that every day the exact number of products (or parts) needed is produced in every sub-system, right up through the final assembly line. All operations produce at the same cycle time, which is determined by the takt time. A balanced production system means that all components of the production system are designed to operate at the pace of customer demand.

Cycle Time*: Cycle time is the time required to produce one product by a machine, station and/or operator. It is the time required to repeat a given sequence of operations or events.

Decomposition: In this paper, the term decomposition refers to a process in which objectives are broken down into sub-objectives. Satisfying all of a series of sub-objectives will ensure that the original objective is satisfied.

5S*: 5S represents five Japanese terms perceived by many to represent the fundamental elements of a Total Quality Management (TQM) approach:

- Seiri (organization)
- Seiton (neatness)
- Seiso (cleaning)
- Seiketsu (standardization)
- Shitsuke (discipline)

The English Translation:

- Simplify or Sort - Remove unnecessary items from the work area
- Straighten or Simplify - Organize tools, accessories, and paperwork
- Scrub or Shine - Clean, Repair, and keep it clean
- Stabilize or Standardize - Establish and maintain controls and standards
- Sustain or Self-Discipline - Strive for continuous improvement

Just in Time (JIT)*: JIT is an enterprise-wide operational philosophy and an operational strategy of waste elimination, the underlying principle of which is anything that does not add value is eliminated or minimized to the greatest possible extent. The roots of JIT extend deep into Japanese cultural, geographic, and economic history. JIT is commonly used to describe a stockless production manufacturing approach where only the right parts are completed (and/or delivered by suppliers) at the right time. JIT represents four requirements: (1) produce at the right time, (2) at the right pace, (3) in the right quantity and (4) with the right quantity.

Kaizen*: Kaizen is a Japanese word for gradual, unending improvement. A continuous improvement strategy, typically achieved through incremental improvements and involving everyone from top management to supervisors and workers. This process has its roots in the Toyota Production System. The underlying assumption is that small improvements, continuously made to a process, will lead to significant positive change over time.

Kaizen Event*: A Kaizen Event (Blitz) is a short-term, concentrated, assault on workplace wastes and inefficiencies carried out, typically, by a diverse, multi-functional team. The effort might last anywhere from a few hours to a few days, or up to 30 days for very complex efforts. Numerous companies are using this form of rapid improvement to streamline operations. It is used to:

- Reduce non-value-added activities
- Streamline parts, people and information travel within a process
- Reduce cycle time, flow time and lot size
- Reduce set-up times
- Reduce work-in-process inventories
- Reduce floor space requirements.
- Realize improvements in: quality, safety, environmental, and 5S issues.

Kanban*: Kanban is a Japanese term meaning "card," that is, visible records. It is an inventory replenishment system associated with JIT production that was developed by Toyota. It is characterized by an order point scheduling approach that uses fixed lot sizes of materials in standard containers with the cards attached to each. Material reorder is triggered when the container of material is moved to the point of use.

Level Production*: Level production requires that all operations make the quantity and mix of products demanded by the final customer within a given time interval. Level production smoothes the demand for parts through the manufacturing system and reduces the amount of inventory that must be maintained to meet customer demand.

Manufacturing cell: An arrangement of manual and/or semi-automatic stations that can achieve balanced production for a range of takt times. When takt time decreases (i.e., demand increases) workers can be added to a cell to increase throughput. Alternately, when demand decreases, workers can be removed from a cell to decrease throughput. Work loops are predetermined for the expected range of takt times to ensure that all workers have approximately the same work content.

Pitch: The takt time multiplied by the run size. Pitch is used to determine the time interval at with parts should be moved between operations.

Production resources: Any operator, technician, or equipment that directly adds value to a product.

Pull*: Pull refers to a two sub-system linkage in a supply chain. The producing operation does not produce until the standard work in process between the two sub-systems is less than the set point. When the standard work in process is below the set point, this condition signals the need to replenish. Information flows in the reverse direction from product flow to signal production by the upstream cell or manufacturing process.

Push*: Push is a term used in Planning and Control in Operations to indicate the direction of the flow of information in the system which causes materials to be moved and activities to be undertaken. In a "push" system, material and information flow in the same direction through the value stream. For example, each work center has responsibility for sending work to the succeeding part of the operation. The work centers "push" out work without considering whether the succeeding work center can make use of it. Typically, activities are planned centrally but do not reflect actual conditions in terms of idle time, inventory, and queues, for example, that exist on the shop floor. The design is not robust with respect to quality and rate problems. Even the best closed-loop push systems are much less responsive to in-process variation, and therefore much less effective for controlling production and work-in-process than pull systems.

Run size: The number of one type of part produced between machine setups.

Service rate: The rate at which a downstream operation processes incoming parts.

Six Sigma*: Six Sigma is a process quality goal. In statistical terms, "sigma" is a metric used to reflect how well a process is working. It describes the degree of variation in a manufacturing process. Companies operating at a six sigma level of quality would produce only 3.4 defects per million opportunities.

Standard work: standard work is a method of ensuring that all operators perform tasks with the same level of quality and at approximately the same pace. Tools are standardized and tasks are designed so that they are performed in the same order, with the same motions for every operator.

Support resources: Any person or equipment in a manufacturing system that facilitates production resources, so that the production resource can perform its value-adding tasks.

Takt Time*: Takt Time is the available production time divided by the rate of consumer demand (consumption). For example, if a certain piece of equipment operates 540 minutes a day (9 hours) and the rate of consumer demand averages 1.5 machines per day, the Takt Time for that machine would be 540 divided by 1.5, or 360. This Takt Time would be used to pace or synchronize the rate of production to consumer demand/sales, which is central to Lean and/or JIT manufacturing concepts.

TPM*: Total Productive Maintenance (TPM) was originally developed as an approach to plant maintenance that combines productive maintenance procedures with total quality control and employee involvement to maximize the utility of productive resources. TPM aims at improving existing plant conditions and at increasing the knowledge and skills of frontline personnel in order to achieve zero accidents, zero defects, and zero breakdowns.

The five goals of TPM can be defined as:

- Improve equipment effectiveness

- Achieve autonomous maintenance
- Plan maintenance
- Train all staff in relevant maintenance
- Achieve early equipment maintenance

The concepts can be applied on a company-wide basis, not just on the shop floor.

Value*: Value can be defined as worth in usefulness or importance to the possessor's customer. Value is a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer. Only an activity that physically changes the product adds value.

Value Stream (Value Chain)*: A Value Stream is all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product: (1) the production flow from raw material into the arms of a customer, and (2) the design flow from concept to launch. It represents the chain of activities and processes by which value is added to input resulting in the delivery of products and services to customers. By reviewing the chain, you can identify which activities add value and which add cost. Similarly, the concept of the Value Chain holds that activities in a value chain can be divided into two categories. The first is primary activities, which include inbound logistics, such as materials handling; operations; outbound logistics, such as distribution; marketing and sales; and after sales service. The second is support activities, which include human resources management, company infrastructure, procurement, and technology development. It should be noted that each of the primary activities involves its own support activities.

Waste*: Waste or "Muda" in Japanese is the waste of manpower, outputs, money, space, time, information, etc. Toyota, the originator of the JIT concept defines waste as anything other than the minimum amount of equipment, materials, parts, and working time absolutely essential to production. The "seven wastes" are [Ohno, 1988]:

Overproduction	Producing too much, too early
Inventory	Semi-finished parts between operations
Transportation	Moving parts
Processing	Unnecessary processing steps
Making Defects	Parts need rework or are scrap
Motion	Unnecessary worker movements
Waiting	Workers waiting for machines or parts

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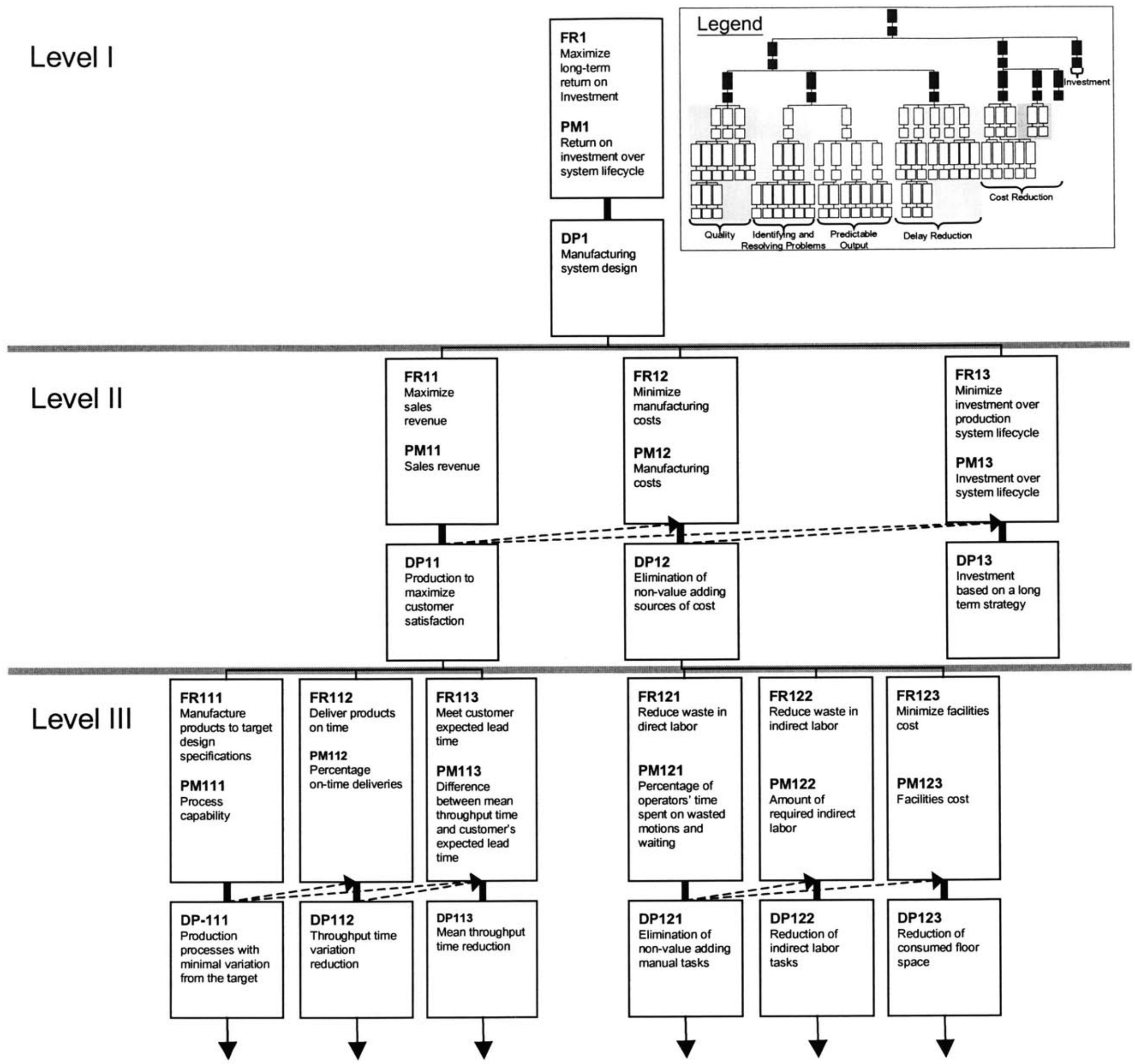
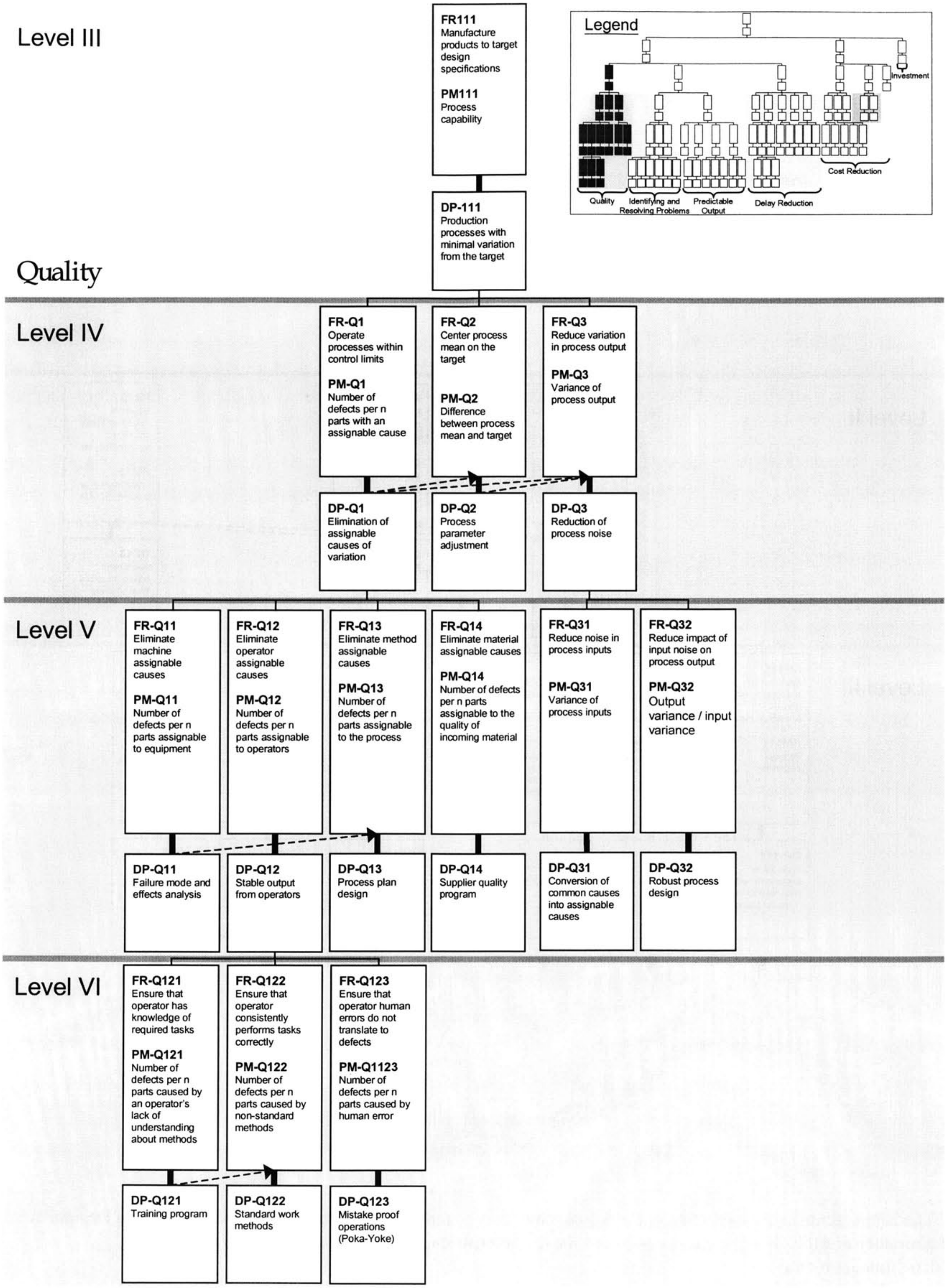
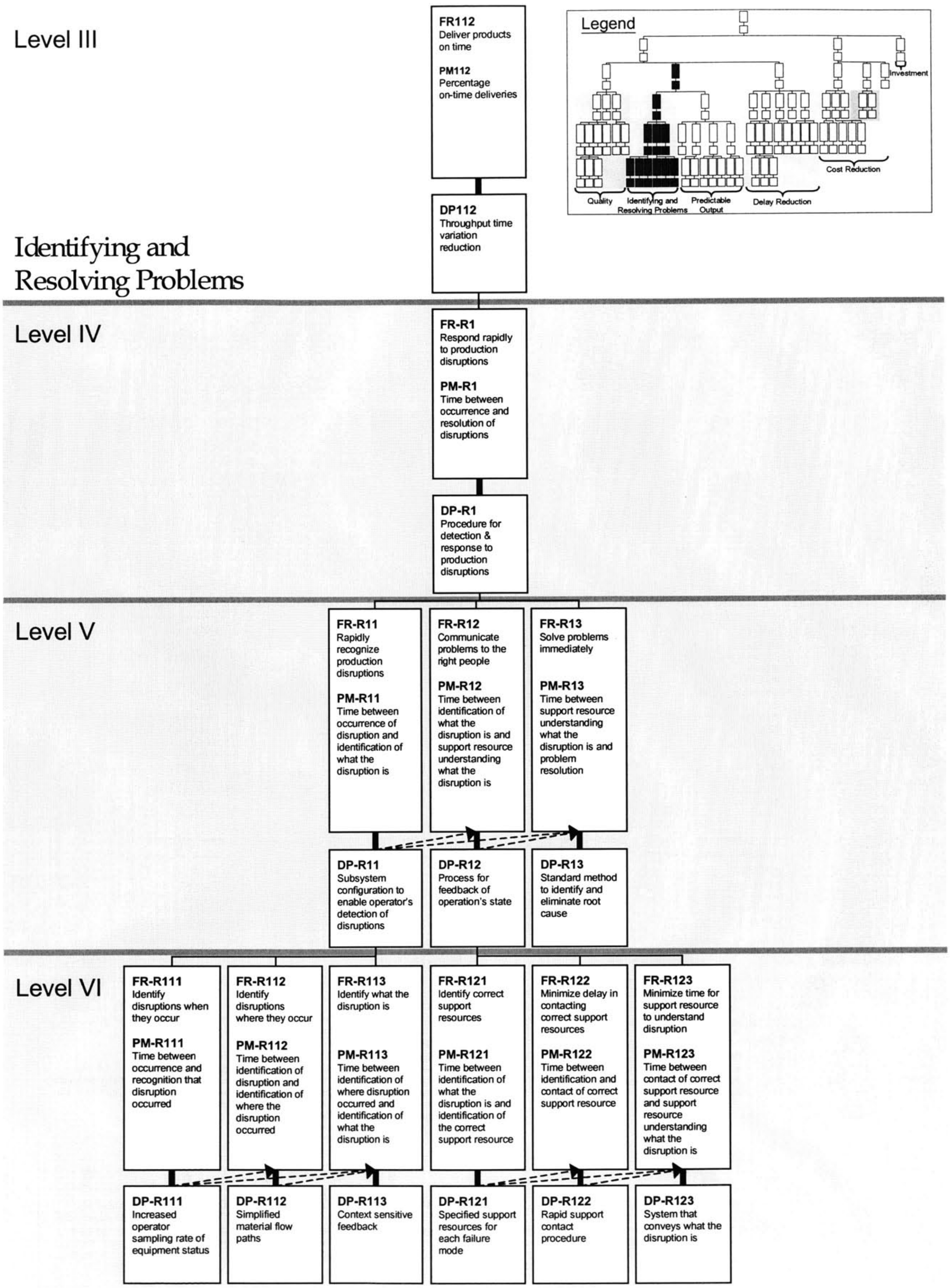
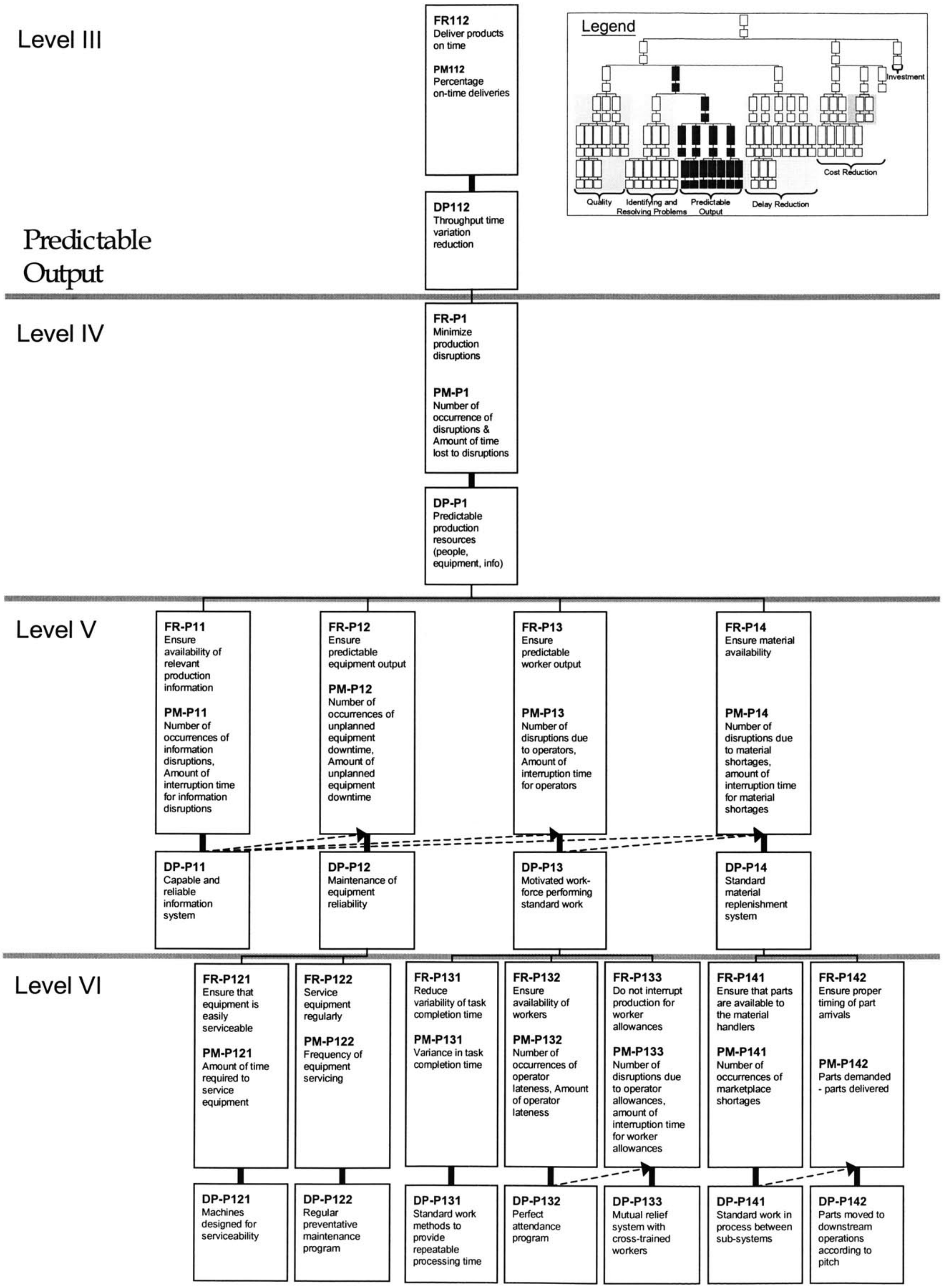
Appendix A: MSDD v.5.1[7]

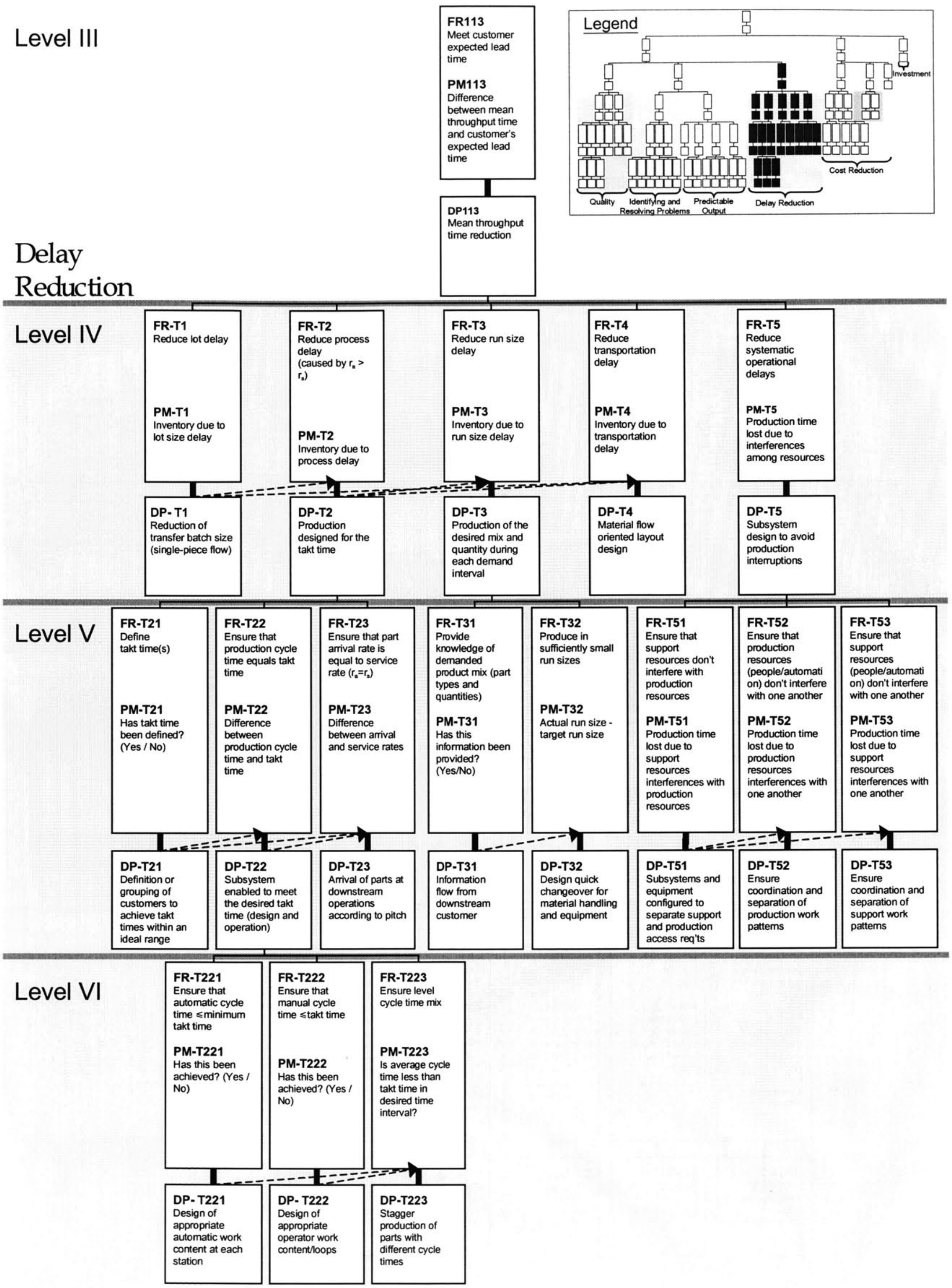


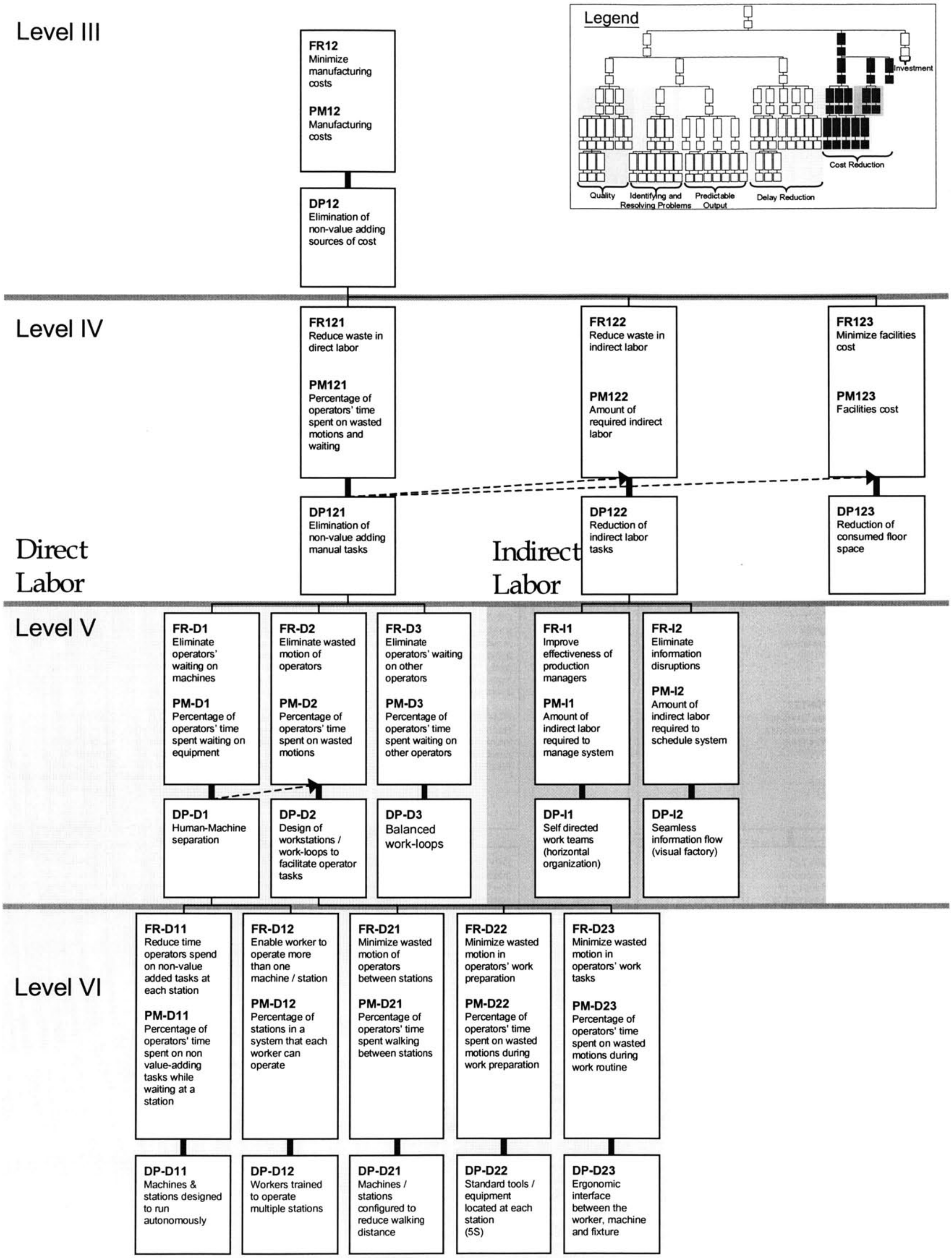
[7] The Manufacturing System Design Decomposition, v. 5.1, was developed by the Production System Design Laboratory at MIT. For the latest version of the decomposition, please contact Prof. David Cochran (dcochran@mit.edu)


Level III
FR111 Manufacture products to target design specifications
PM111 Process capability
DP-111 Production processes with minimal variation from the target
Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
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 that operator human errors do not translate to defects
PM-Q1123 Number of defects per n parts caused by human error
DP-Q121 Training program
DP-Q122 Standard work methods
DP-Q123 Mistake proof operations (Poka-Yoke)

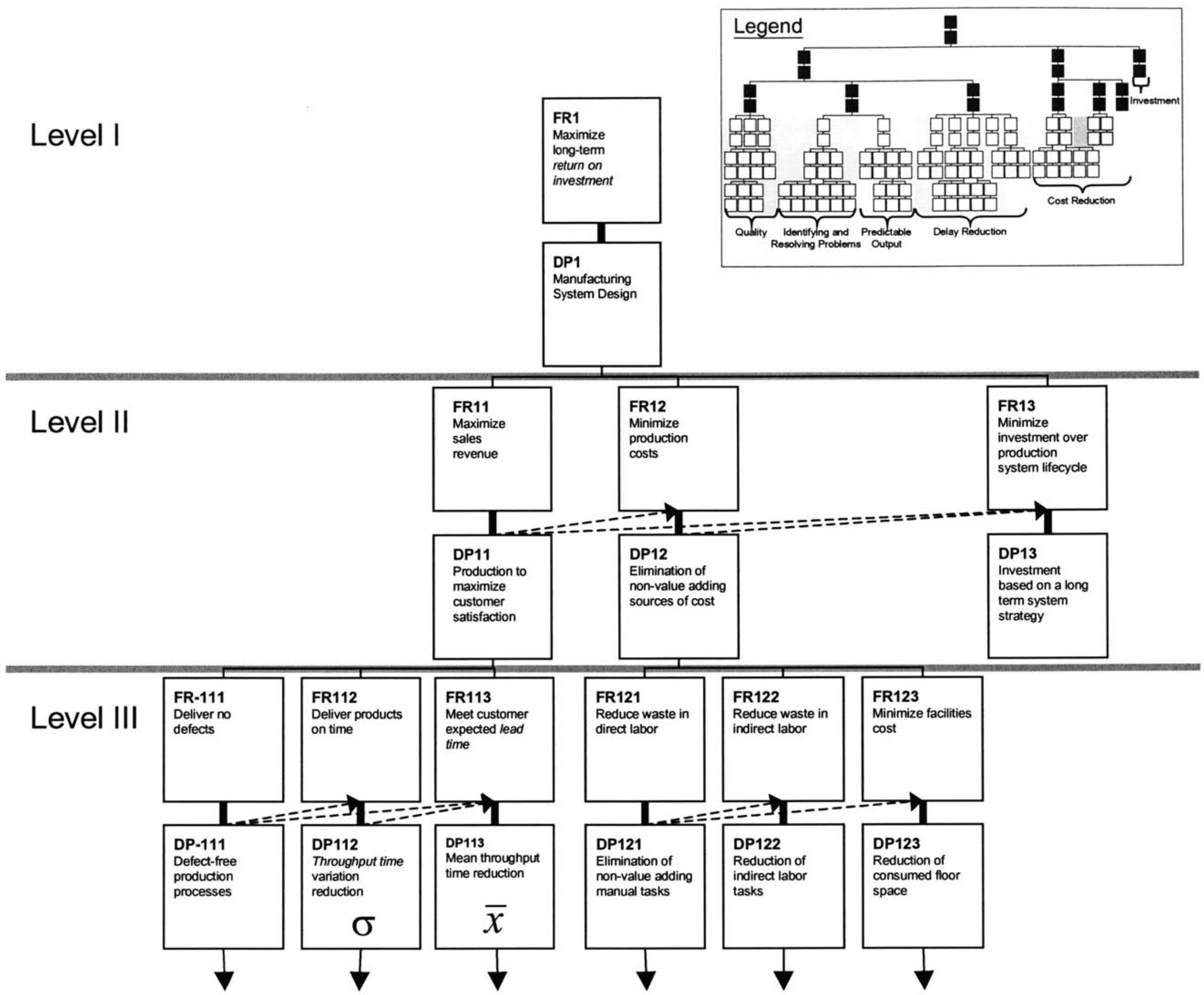

Level III
Identifying and Resolving Problems
FR112
Deliver products on time
PM112
Percentage on-time deliveries
DP112
Throughput time variation reduction
Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Level IV
FR-R1
Respond rapidly to production 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
Standard method to identify and eliminate root cause
Level VI
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 correct support resource and support resource understanding what the disruption is
DP-R111
Increased operator sampling rate of equipment status
DP-R112
Simplified material 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


Level III
Predictable Output
Level IV
Level V
Level VI
FR112 Deliver products on time
PM112 Percentage on-time deliveries
DP112 Throughput time variation reduction
Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
FR-P1 Minimize production disruptions
PM-P1 Number of occurrence of disruptions & Amount of time lost to disruptions
DP-P1 Predictable production resources (people, equipment, info)
FR-P11 Ensure availability of relevant production information
PM-P11 Number of occurrences of information disruptions, Amount of interruption time for information disruptions
DP-P11 Capable and reliable information system
FR-P12 Ensure predictable equipment output
PM-P12 Number of occurrences of unplanned equipment downtime, Amount of unplanned equipment downtime
DP-P12 Maintenance of equipment reliability
FR-P13 Ensure predictable worker output
PM-P13 Number of disruptions due to operators, Amount of interruption time for operators
DP-P13 Motivated work-force performing standard work
FR-P14 Ensure material availability
PM-P14 Number of disruptions due to material shortages, amount of interruption time for material shortages
DP-P14 Standard material replenishment system
FR-P121 Ensure that equipment is easily serviceable
PM-P121 Amount of time required to service equipment
DP-P121 Machines designed for serviceability
FR-P122 Service equipment regularly
PM-P122 Frequency of equipment servicing
DP-P122 Regular preventative maintenance program
FR-P131 Reduce variability of task completion time
PM-P131 Variance in task completion time
DP-P131 Standard work methods to provide repeatable processing time
FR-P132 Ensure availability of workers
PM-P132 Number of occurrences of operator lateness, Amount of operator lateness
DP-P132 Perfect attendance program
FR-P133 Do not interrupt production for worker allowances
PM-P133 Number of disruptions due to operator allowances, amount of interruption time for worker allowances
DP-P133 Mutual relief system with cross-trained workers
FR-P141 Ensure that parts are available to the material handlers
PM-P141 Number of occurrences of marketplace shortages
DP-P141 Standard work in process between sub-systems
FR-P142 Ensure proper timing of part arrivals
PM-P142 Parts demanded - parts delivered
DP-P142 Parts moved to downstream operations according to pitch


Level III
Delay Reduction
Level IV
Level V
Level VI
Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
FR113 Meet customer expected lead time
PM113 Difference between mean throughput time and customer's expected lead time
DP113 Mean throughput time reduction
FR-T1 Reduce lot delay
PM-T1 Inventory due to lot size delay
DP- T1 Reduction of transfer batch size (single-piece flow)
FR-T2 Reduce process delay (caused by $r_a > r_s$)
PM-T2 Inventory due to process delay
DP-T2 Production designed for the takt time
FR-T3 Reduce run size delay
PM-T3 Inventory due to run size delay
DP-T3 Production of the desired mix and quantity during each demand interval
FR-T4 Reduce transportation delay
PM-T4 Inventory due to transportation delay
DP-T4 Material flow oriented layout design
FR-T5 Reduce systematic operational delays
PM-T5 Production time lost due to interferences among resources
DP-T5 Subsystem design to avoid production interruptions
FR-T21 Define takt time(s)
PM-T21 Has takt time been defined? (Yes / No)
DP-T21 Definition or grouping of customers to achieve takt times within an ideal range
FR-T22 Ensure that production cycle time equals takt time
PM-T22 Difference between production cycle time and takt time
DP-T22 Subsystem enabled to meet the desired takt time (design and operation)
FR-T23 Ensure that part arrival rate is equal to service rate ($r_a = r_s$)
PM-T23 Difference between arrival and service rates
DP-T23 Arrival of parts at downstream operations according to pitch
FR-T31 Provide knowledge of demanded product mix (part types and quantities)
PM-T31 Has this information been provided? (Yes/No)
DP-T31 Information flow from downstream customer
FR-T32 Produce in sufficiently small run sizes
PM-T32 Actual run size - target run size
DP-T32 Design quick changeover for material handling and equipment
FR-T51 Ensure that support resources don't interfere with production resources
PM-T51 Production time lost due to support resources interferences with production resources
DP-T51 Subsystems and equipment configured to separate support and production access req'ts
FR-T52 Ensure that production resources (people/automation) don't interfere with one another
PM-T52 Production time lost due to production resources interferences with one another
DP-T52 Ensure coordination and separation of production work patterns
FR-T53 Ensure that support resources (people/automation) don't interfere with one another
PM-T53 Production time lost due to support resources interferences with one another
DP-T53 Ensure coordination and separation of support work patterns
FR-T221 Ensure that automatic cycle time ≤minimum takt time
PM-T221 Has this been achieved? (Yes / No)
DP- T221 Design of appropriate automatic work content at each station
FR-T222 Ensure that manual cycle time ≤takt time
PM-T222 Has this been achieved? (Yes / No)
DP- T222 Design of appropriate operator work content/loops
FR-T223 Ensure level cycle time mix
PM-T223 Is average cycle time less than takt time in desired time interval?
DP-T223 Stagger production of parts with different cycle times


Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Level III
FR12 Minimize manufacturing costs
PM12 Manufacturing costs
DP12 Elimination of non-value adding sources of cost
Level IV
FR121 Reduce waste in direct labor
PM121 Percentage of operators' time spent on wasted motions and waiting
DP121 Elimination of non-value adding manual tasks
FR122 Reduce waste in indirect labor
PM122 Amount of required indirect labor
DP122 Reduction of indirect labor tasks
FR123 Minimize facilities cost
PM123 Facilities cost
DP123 Reduction of consumed floor space
Direct Labor
Indirect Labor
Level V
FR-D1 Eliminate operators' waiting on machines
PM-D1 Percentage of operators' time spent waiting on equipment
DP-D1 Human-Machine separation
FR-D2 Eliminate wasted motion of operators
PM-D2 Percentage of operators' time spent on wasted motions
DP-D2 Design of workstations / work-loops to facilitate operator tasks
FR-D3 Eliminate operators' waiting on other operators
PM-D3 Percentage of operators' time spent waiting on other operators
DP-D3 Balanced work-loops
FR-I1 Improve effectiveness of production managers
PM-I1 Amount of indirect labor required to manage system
DP-I1 Self directed work teams (horizontal organization)
FR-I2 Eliminate information disruptions
PM-I2 Amount of indirect labor required to schedule system
DP-I2 Seamless information flow (visual factory)
Level VI
FR-D11 Reduce time operators spend on non-value added tasks at each station
PM-D11 Percentage of operators' time spent on non value-adding tasks while waiting at a station
DP-D11 Machines & stations designed to run autonomously
FR-D12 Enable worker to operate more than one machine / station
PM-D12 Percentage of stations in a system that each worker can operate
DP-D12 Workers trained to operate multiple stations
FR-D21 Minimize wasted motion of operators between stations
PM-D21 Percentage of operators' time spent walking between stations
DP-D21 Machines / stations configured to reduce walking distance
FR-D22 Minimize wasted motion in operators' work preparation
PM-D22 Percentage of operators' time spent on wasted motions during work preparation
DP-D22 Standard tools / equipment located at each station (5S)
FR-D23 Minimize wasted motion in operators' work tasks
PM-D23 Percentage of operators' time spent on wasted motions during work routine
DP-D23 Ergonomic interface between the worker, machine and fixture

Appendix B: MSDD v.5.0[8]



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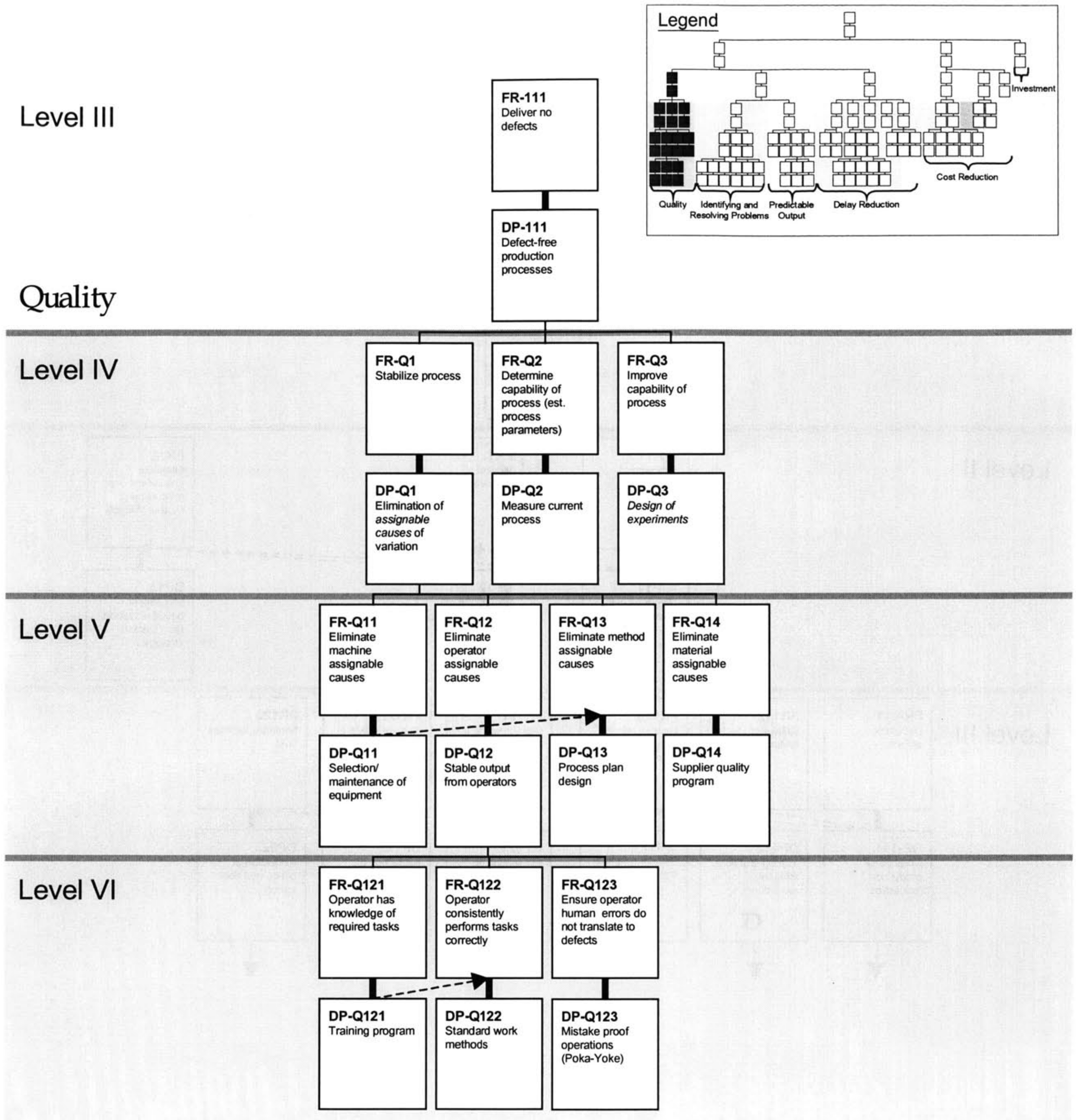
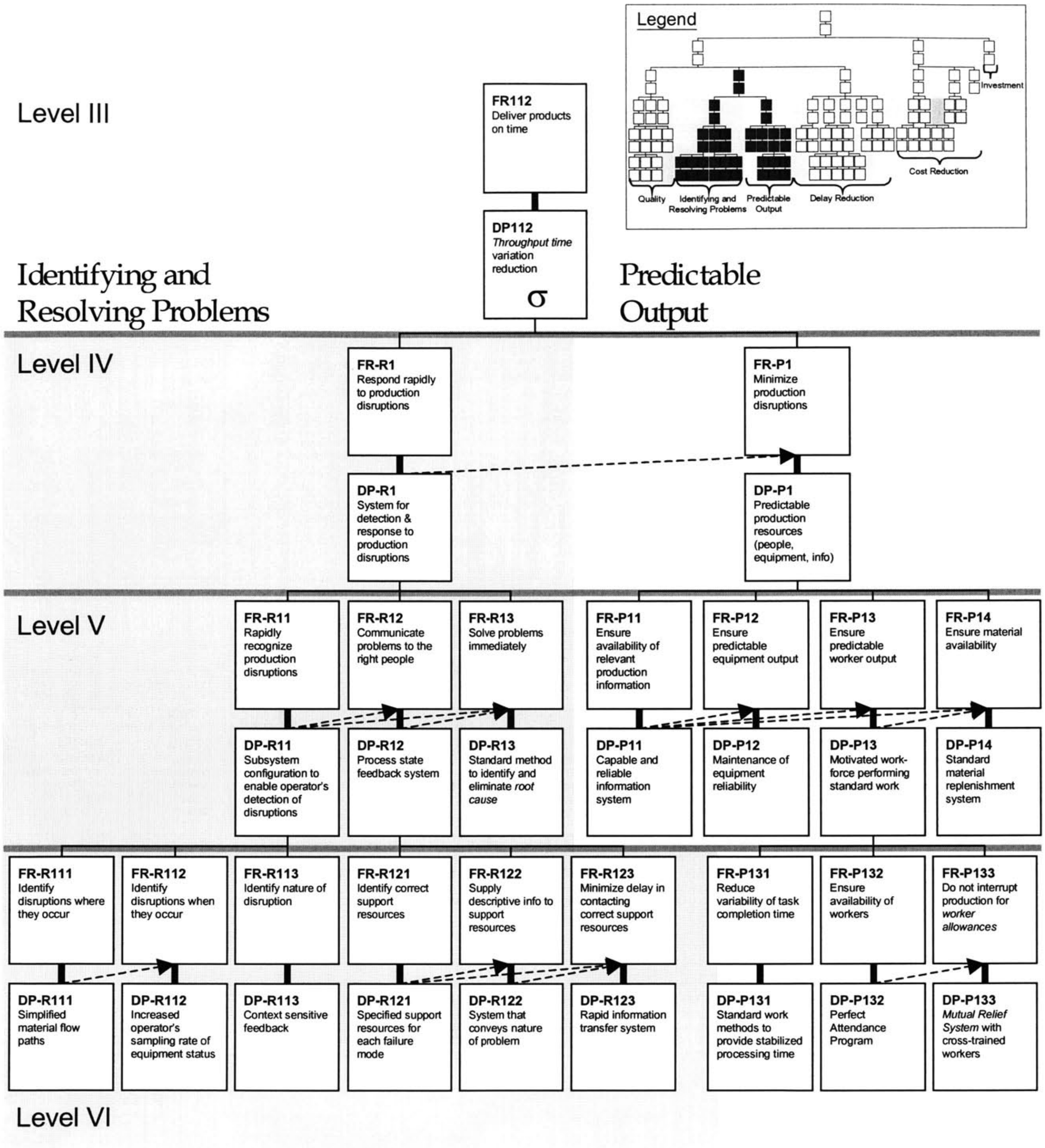
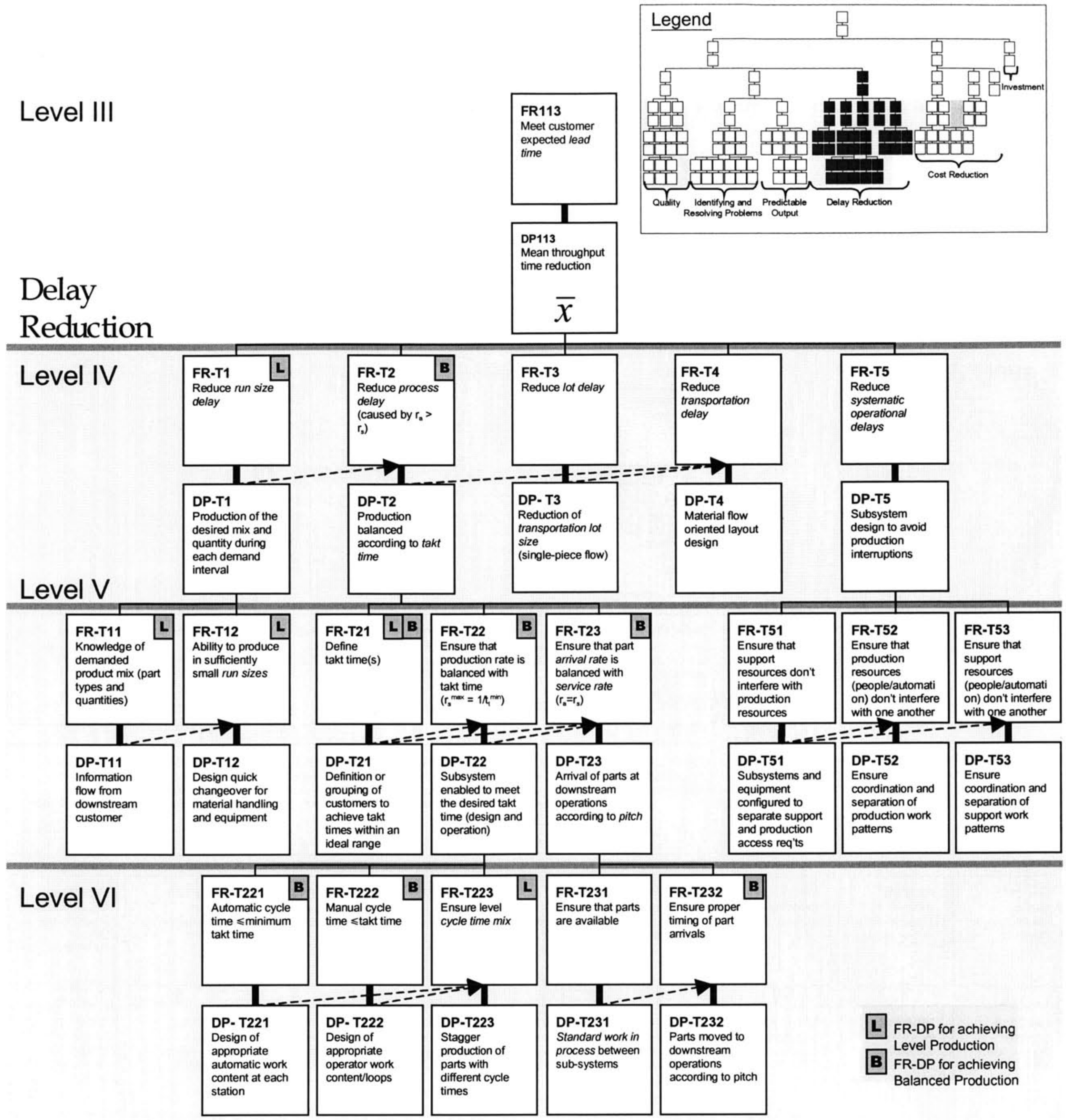
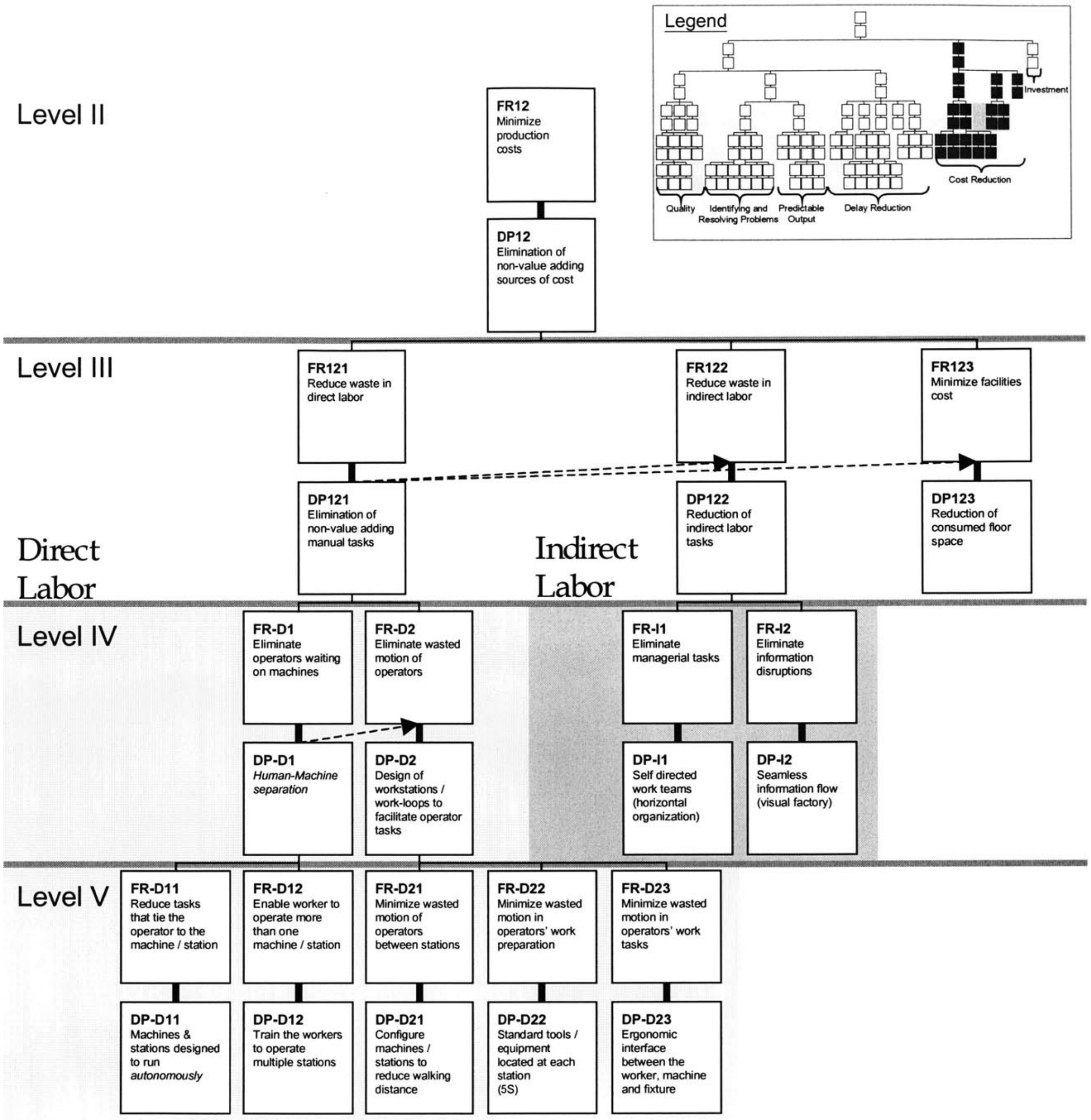
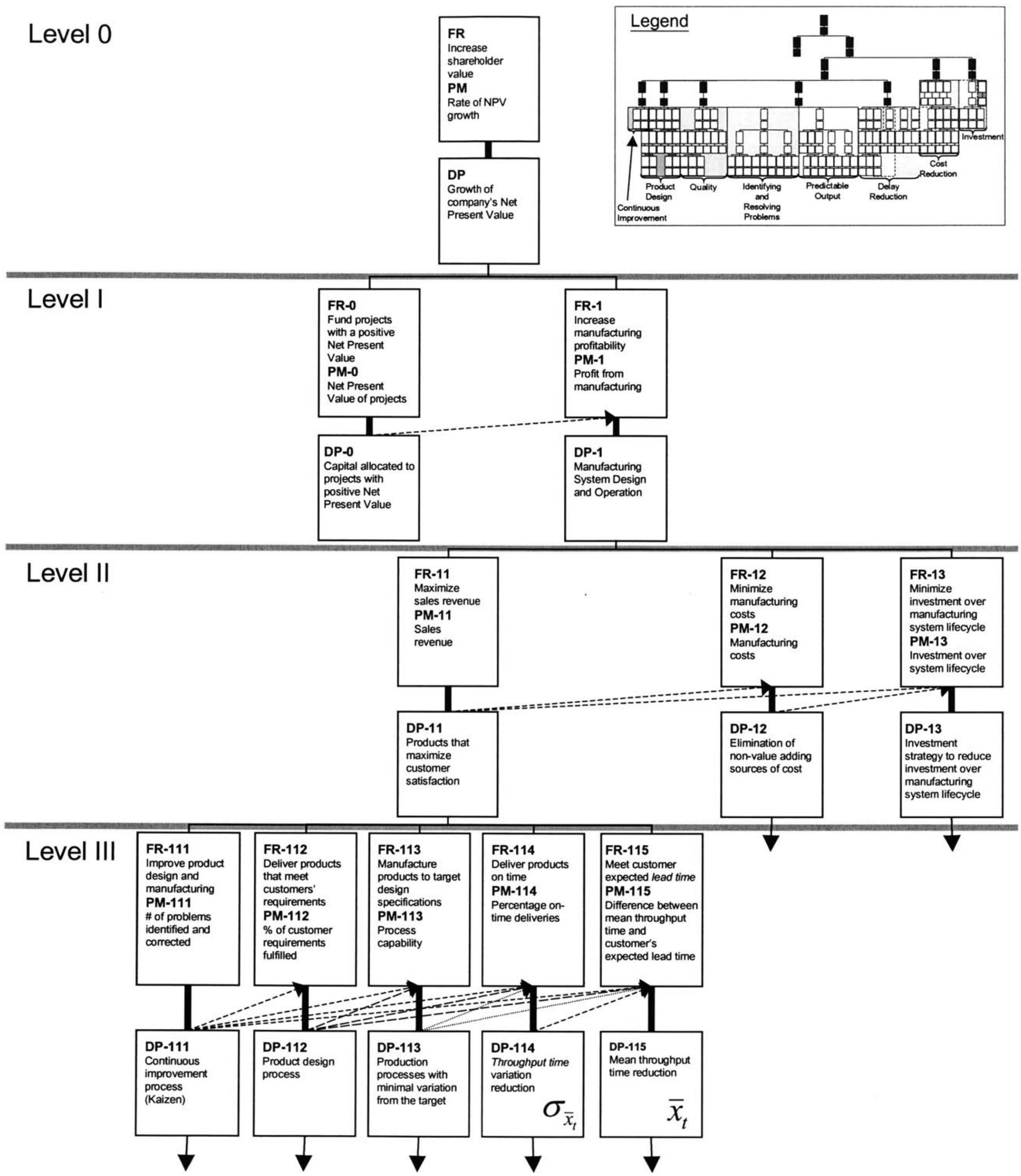

Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Level III
Quality
Level IV
Level V
Level VI
FR-111 Deliver no defects
DP-111 Defect-free production processes
FR-Q1 Stabilize process
FR-Q2 Determine capability of process (est. process parameters)
FR-Q3 Improve capability of process
DP-Q1 Elimination of assignable causes of variation
DP-Q2 Measure current process
DP-Q3 Design of experiments
FR-Q11 Eliminate machine assignable causes
FR-Q12 Eliminate operator assignable causes
FR-Q13 Eliminate method assignable causes
FR-Q14 Eliminate material assignable causes
DP-Q11 Selection/ maintenance of equipment
DP-Q12 Stable output from operators
DP-Q13 Process plan design
DP-Q14 Supplier quality program
FR-Q121 Operator has knowledge of required tasks
FR-Q122 Operator consistently performs tasks correctly
FR-Q123 Ensure operator human errors do not translate to defects
DP-Q121 Training program
DP-Q122 Standard work methods
DP-Q123 Mistake proof operations (Poka-Yoke)


Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Level III
FR112 Deliver products on time
DP112 Throughput time variation reduction σ
Identifying and Resolving Problems
Predictable Output
Level IV
FR-R1 Respond rapidly to production disruptions
DP-R1 System for detection & response to production disruptions
FR-P1 Minimize production disruptions
DP-P1 Predictable production resources (people, equipment, info)
Level V
FR-R11 Rapidly recognize production disruptions
FR-R12 Communicate problems to the right people
FR-R13 Solve problems immediately
FR-P11 Ensure availability of relevant production information
FR-P12 Ensure predictable equipment output
FR-P13 Ensure predictable worker output
FR-P14 Ensure material availability
DP-R11 Subsystem configuration to enable operator's detection of disruptions
DP-R12 Process state feedback system
DP-R13 Standard method to identify and eliminate root cause
DP-P11 Capable and reliable information system
DP-P12 Maintenance of equipment reliability
DP-P13 Motivated work-force performing standard work
DP-P14 Standard material replenishment system
FR-R111 Identify disruptions where they occur
FR-R112 Identify disruptions when they occur
FR-R113 Identify nature of disruption
FR-R121 Identify correct support resources
FR-R122 Supply descriptive info to support resources
FR-R123 Minimize delay in contacting correct support resources
FR-P131 Reduce variability of task completion time
FR-P132 Ensure availability of workers
FR-P133 Do not interrupt production for worker allowances
DP-R111 Simplified material flow paths
DP-R112 Increased operator's sampling rate of equipment status
DP-R113 Context sensitive feedback
DP-R121 Specified support resources for each failure mode
DP-R122 System that conveys nature of problem
DP-R123 Rapid information transfer system
DP-P131 Standard work methods to provide stabilized processing time
DP-P132 Perfect Attendance Program
DP-P133 Mutual Relief System with cross-trained workers
Level VI

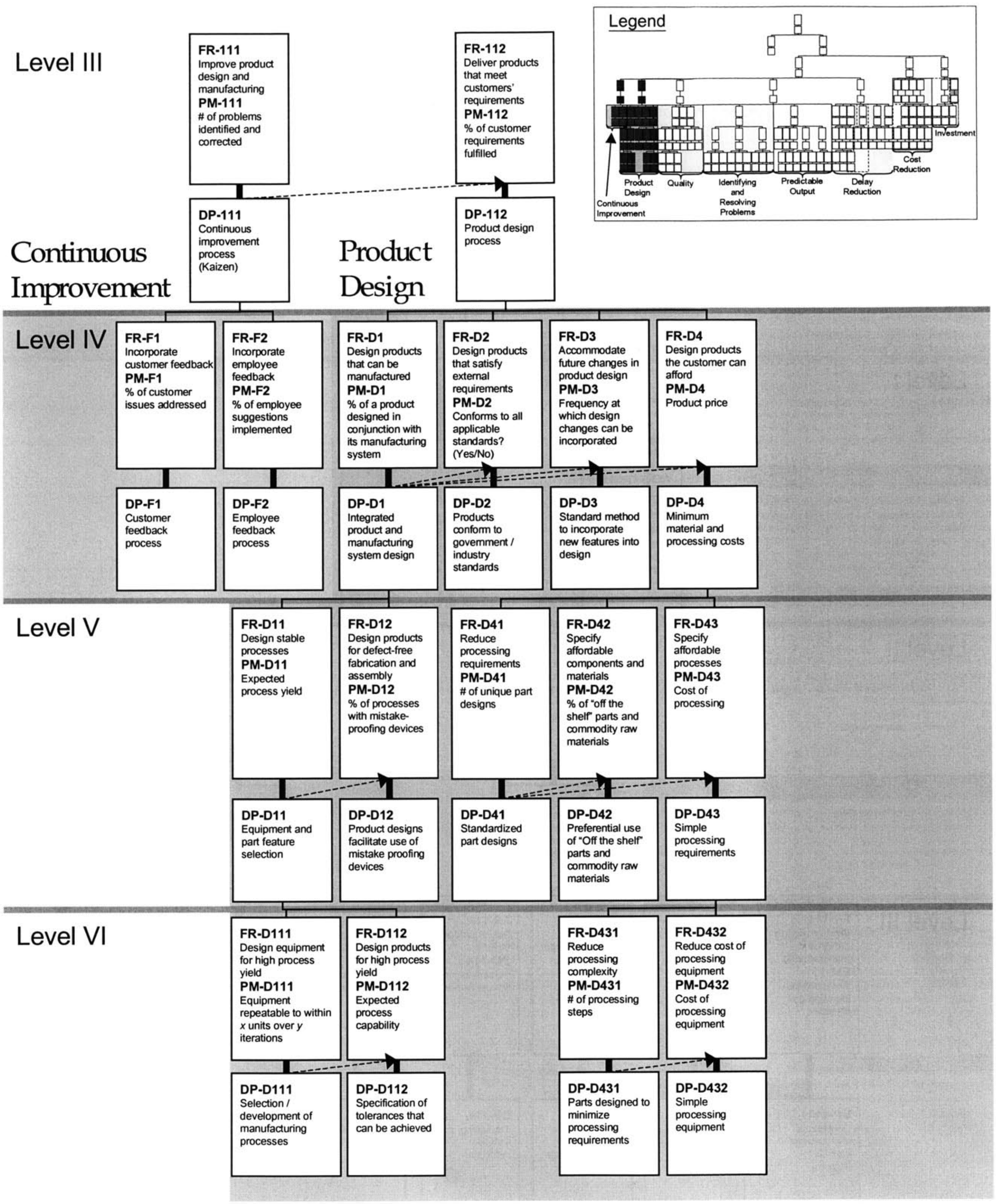

Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Level III
FR113 Meet customer expected lead time
DP113 Mean throughput time reduction
Delay Reduction
Level IV
FR-T1 L Reduce run size delay
FR-T2 B Reduce process delay (caused by $r_a > r_s$)
FR-T3 Reduce lot delay
FR-T4 Reduce transportation delay
FR-T5 Reduce systematic operational delays
DP-T1 Production of the desired mix and quantity during each demand interval
DP-T2 Production balanced according to takt time
DP- T3 Reduction of transportation lot size (single-piece flow)
DP-T4 Material flow oriented layout design
DP-T5 Subsystem design to avoid production interruptions
Level V
FR-T11 L Knowledge of demanded product mix (part types and quantities)
FR-T12 L Ability to produce in sufficiently small run sizes
FR-T21 L B Define takt time(s)
FR-T22 B Ensure that production rate is balanced with takt time ($r_s^{max} = 1/t_t^{min}$)
FR-T23 B Ensure that part arrival rate is balanced with service rate ($r_a=r_s$)
FR-T51 Ensure that support resources don't interfere with production resources
FR-T52 Ensure that production resources (people/automation) don't interfere with one another
FR-T53 Ensure that support resources (people/automation) don't interfere with one another
DP-T11 Information flow from downstream customer
DP-T12 Design quick changeover for material handling and equipment
DP-T21 Definition or grouping of customers to achieve takt times within an ideal range
DP-T22 Subsystem enabled to meet the desired takt time (design and operation)
DP-T23 Arrival of parts at downstream operations according to pitch
DP-T51 Subsystems and equipment configured to separate support and production access req'ts
DP-T52 Ensure coordination and separation of production work patterns
DP-T53 Ensure coordination and separation of support work patterns
Level VI
FR-T221 B Automatic cycle time ≤minimum takt time
FR-T222 B Manual cycle time ≤takt time
FR-T223 L Ensure level cycle time mix
FR-T231 Ensure that parts are available
FR-T232 B Ensure proper timing of part arrivals
DP- T221 Design of appropriate automatic work content at each station
DP- T222 Design of appropriate operator work content/loops
DP-T223 Stagger production of parts with different cycle times
DP-T231 Standard work in process between sub-systems
DP-T232 Parts moved to downstream operations according to pitch
L FR-DP for achieving Level Production
B FR-DP for achieving Balanced Production

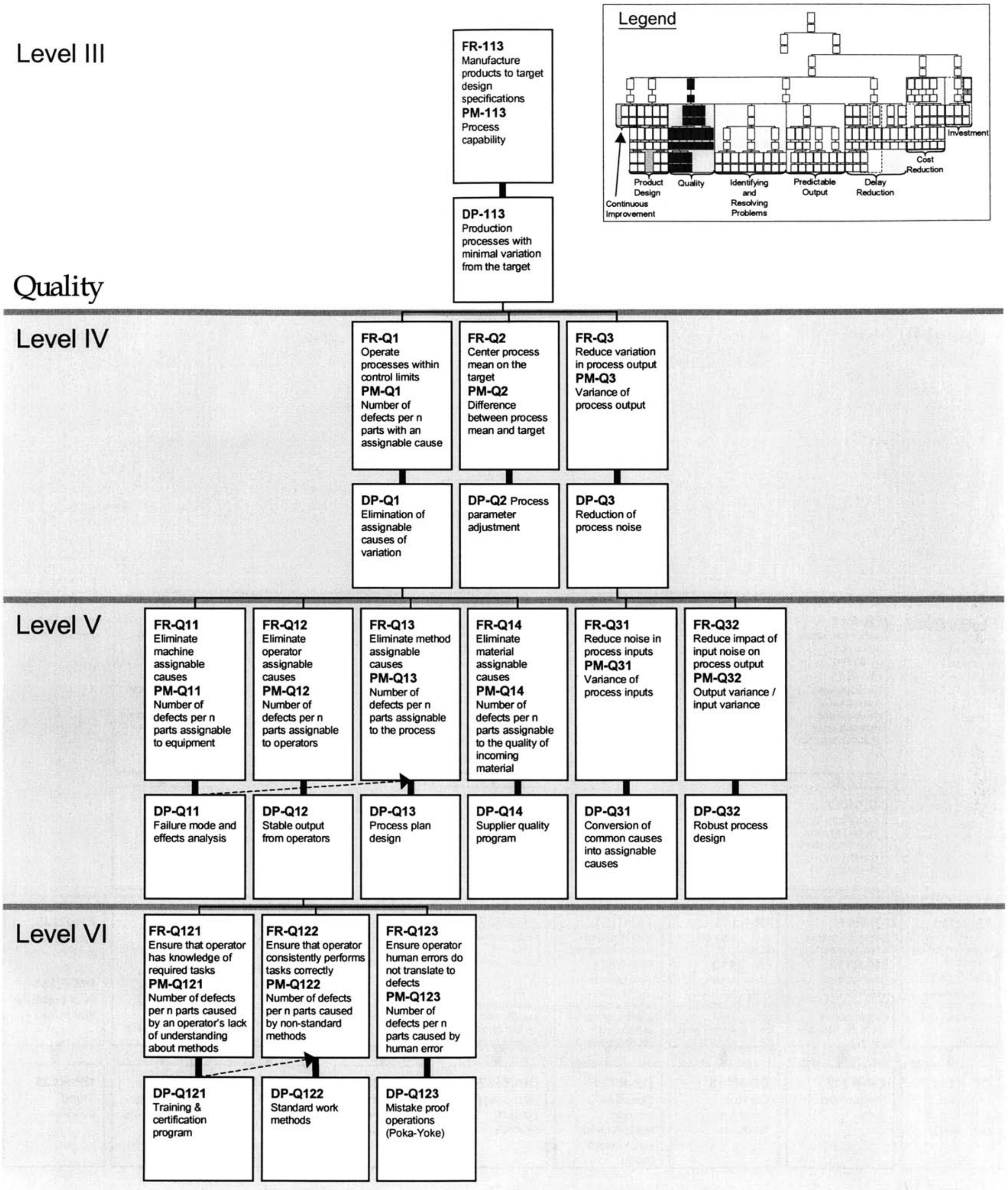

Legend
Investment
Cost Reduction
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Level II
FR12 Minimize production costs
DP12 Elimination of non-value adding sources of cost
Level III
FR121 Reduce waste in direct labor
FR122 Reduce waste in indirect labor
FR123 Minimize facilities cost
DP121 Elimination of non-value adding manual tasks
DP122 Reduction of indirect labor tasks
DP123 Reduction of consumed floor space
Direct Labor
Indirect Labor
Level IV
FR-D1 Eliminate operators waiting on machines
FR-D2 Eliminate wasted motion of operators
FR-I1 Eliminate managerial tasks
FR-I2 Eliminate information disruptions
DP-D1 Human-Machine separation
DP-D2 Design of workstations / work-loops to facilitate operator tasks
DP-I1 Self directed work teams (horizontal organization)
DP-I2 Seamless information flow (visual factory)
Level V
FR-D11 Reduce tasks that tie the operator to the machine / station
FR-D12 Enable worker to operate more than one machine / station
FR-D21 Minimize wasted motion of operators between stations
FR-D22 Minimize wasted motion in operators' work preparation
FR-D23 Minimize wasted motion in operators' work tasks
DP-D11 Machines & stations designed to run autonomously
DP-D12 Train the workers to operate multiple stations
DP-D21 Configure machines / stations to reduce walking distance
DP-D22 Standard tools / equipment located at each station (5S)
DP-D23 Ergonomic interface between the worker, machine and fixture

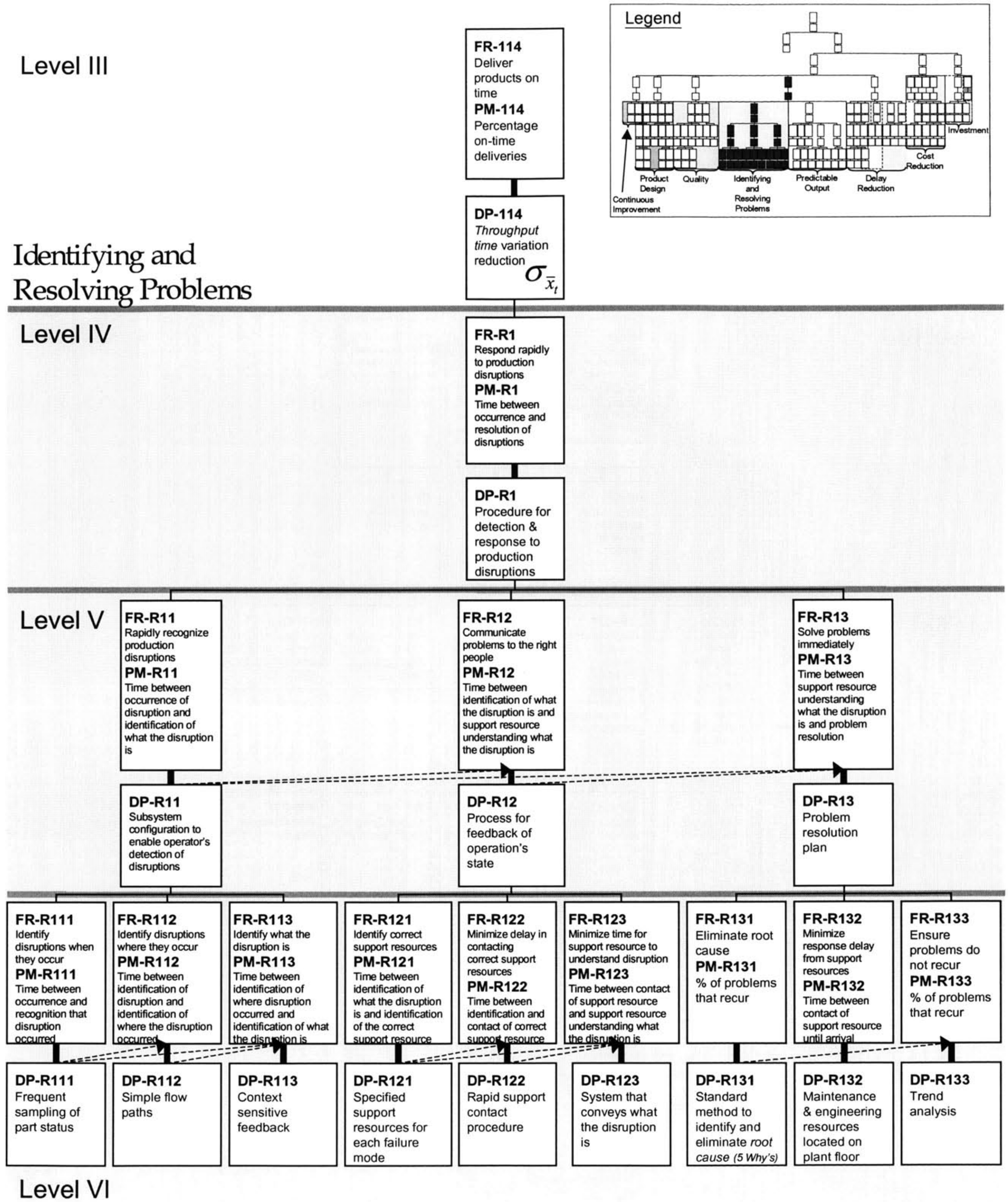
Appendix C: AMSDD v.1.1[9]

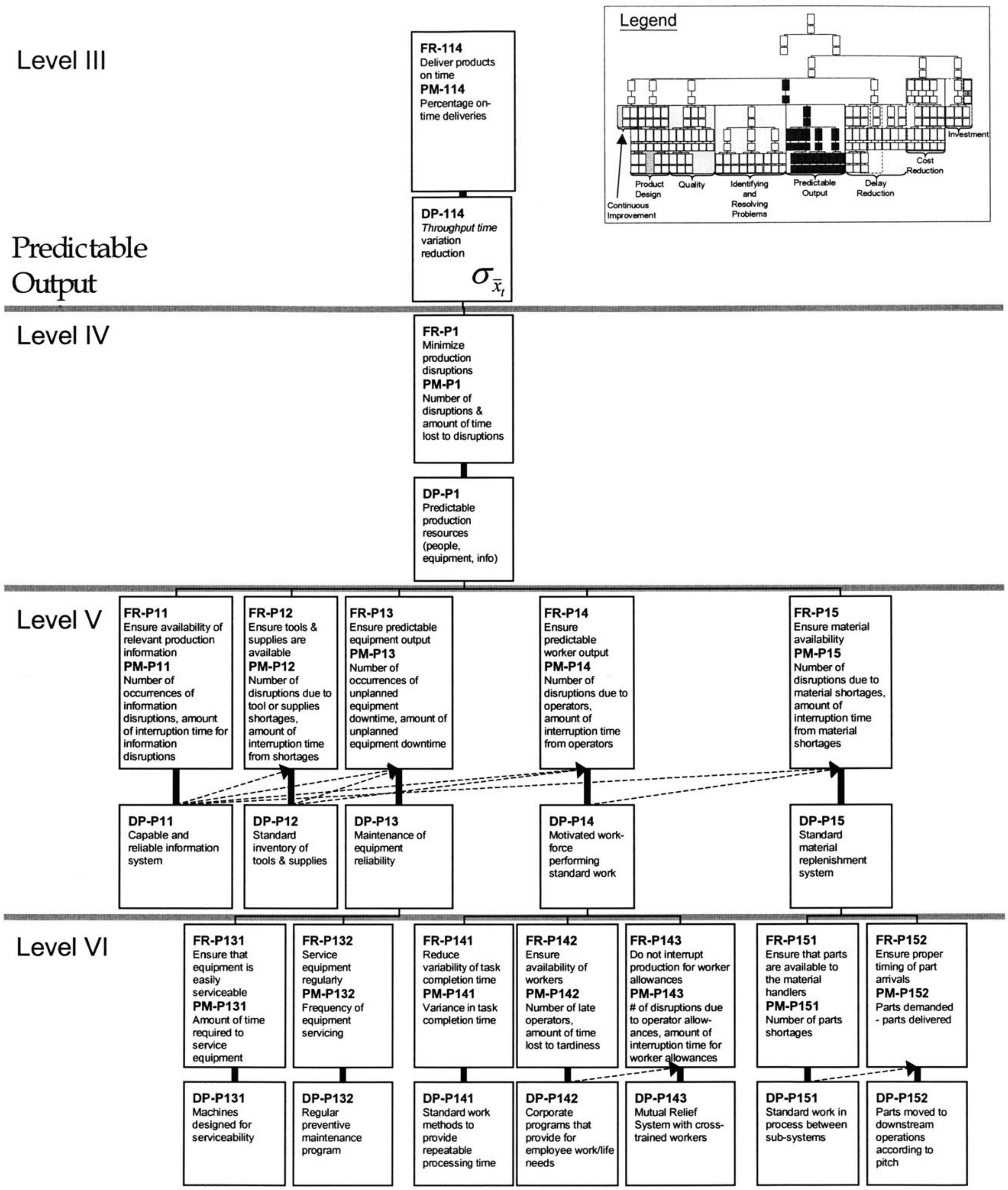


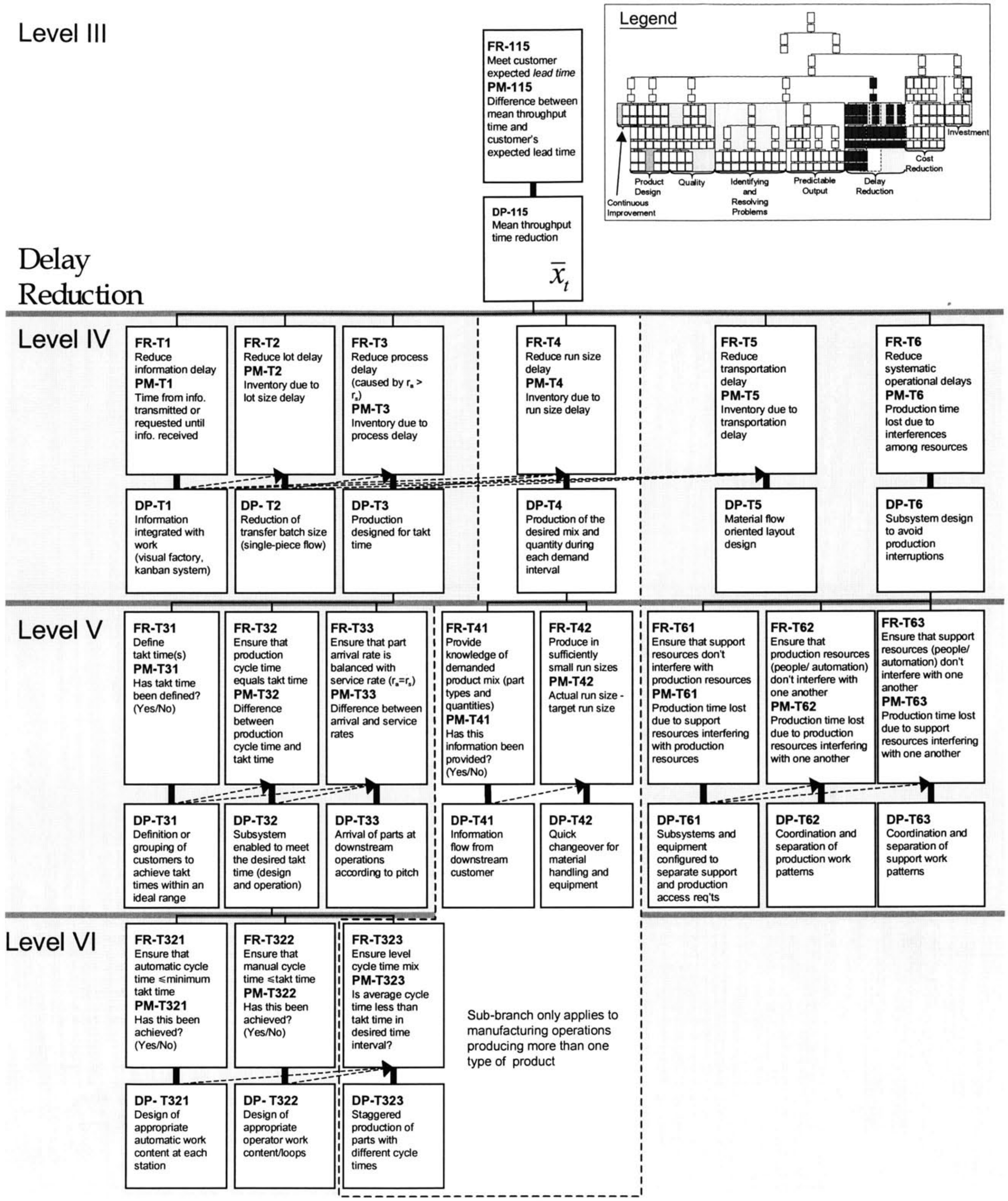
[9] The Aerospace Manufacturing System Design Decomposition, v.1.0, was developed by the Production System Design Laboratory at MIT. For the latest version of the decomposition, please contact Prof. David Cochran (dcochran@mit.edu)

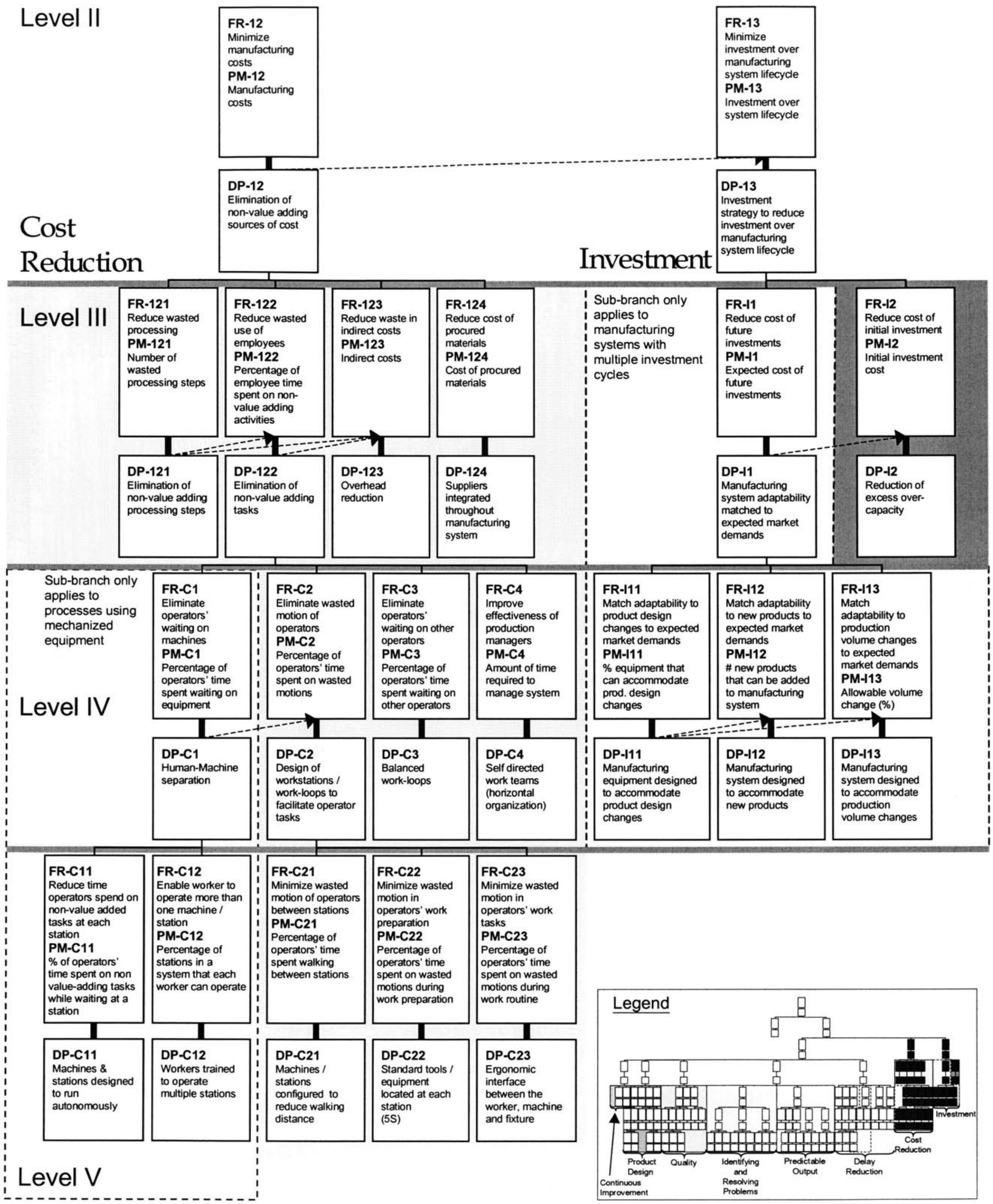

Level III
FR-111 Improve product design and manufacturing PM-111 # of problems identified and corrected
FR-112 Deliver products that meet customers' requirements PM-112 % of customer requirements fulfilled
DP-111 Continuous improvement process (Kaizen)
DP-112 Product design process
Continuous Improvement
Product Design
Legend
Investment
Cost Reduction
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Continuous Improvement
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


Legend
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Cost Reduction
Investment
Continuous Improvement
Level III
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)


Legend
Investment
Cost Reduction
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Continuous Improvement
Level III
FR-114
Deliver products on time
PM-114
Percentage on-time deliveries
DP-114
Throughput time variation reduction $\sigma_{\bar{x}_t}$
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


Legend
Investment
Cost Reduction
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Continuous Improvement
Level III
Predictable Output
FR-114
Deliver products on time
PM-114
Percentage on-time deliveries
DP-114
Throughput time variation reduction
$\sigma_{\bar{x}_t}$
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 allow-ances, 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
Delay Reduction
Legend
Product Design
Quality
Identifying and Resolving Problems
Predictable Output
Delay Reduction
Cost Reduction
Investment
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
$\overline{x}_t$
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?
Sub-branch only applies to manufacturing operations producing more than one type of product
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


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 D

Opportunity Cost

Opportunity cost is the cost associated with foregone business decisions. [Pindyck and Rubinfeld, 1998] For example, if a manufacturing company owns a piece of fully depreciated processing equipment that could be sold for $50,000, the opportunity cost of keeping the equipment is $50,000. If the company believes that keeping the equipment will earn it more than $50,000, it is probably in the company's best interest to keep the equipment. Otherwise, it is probably better to sell the equipment. The following section on NPV discusses ways to evaluate potential investments / divestments.

Net Present Value (NPV)

Net present value is equal to the difference between the present value of revenues and the present value of expenditures. [de Neufville, p.215, 1990] The present value of revenues and costs are calculated from the company's expected revenues, costs, and its discount rate. The discount rate determines how much a given amount of money paid or received in the future is worth in current dollars. The discount rate represents the average rate of return that a company expects to receive on its investments. Consider once again the company that owns processing equipment that it could sell for $50,000. Call this company "Company A" and assume that Company A will need its equipment for another 10 years. Company B offers to purchase the equipment from Company A and lease it back for $7,500 per year. Whether this agreement is a good option for Company A depends upon Company A's discount rate, *r*. If Company A sold its equipment, it could invest the $50,000, but would have to pay Company B $7,500 per year.

The present value of future payments (or revenues) is given by the present value formula:

$$P = F(1+r)^{-N}$$

where *P* is the present value of future payment, *F* in period *N*. In order for selling the equipment to be worthwhile for Company A, the present value of its payments to Company B would have to be less than or equal to the $50,000 received for selling the equipment. If Company A has a discount rate of 8%, the net present value of selling the equipment would equal -$4,352. If

Company A has a discount rate of 12% the NPV of selling the equipment would equal $2,538. Therefore, it would be worthwhile for Company A to sell its equipment to Company B if it has a discount rate of 12%, but not if its discount rate is 8%. Table 6-1 shows the full NPV analysis with the present value of payments for years 1 through 10.

	Present value of payment	
year	r = 8%	r = 12%
1	$ 7,500	$ 7,500
2	$ 6,944	$ 6,696
3	$ 6,430	$ 5,979
4	$ 5,954	$ 5,338
5	$ 5,513	$ 4,766
6	$ 5,104	$ 4,256
7	$ 4,726	$ 3,800
8	$ 4,376	$ 3,393
9	$ 4,052	$ 3,029
10	$ 3,752	$ 2,705
Total:	$ 54,352	$ 47,462
Revenue:	$ 50,000	$ 50,000
NPV:	$ (4,352)	$ 2,538

Table 6-1: Net Present Value of Decision to Sell Equipment

Consider a more complex scenario. Company X is trying to decide whether to pursue a new product line. The product is expected to generate revenue of $30 million per year and be viable in the market for 7 years from the time the decision is made. Purchasing a new facility would cost $40 million and require an 2 year wait before production could begin. Renting an existing facility would cost $12 million per year, but could start 1 year after the decision is made. (Assume that purchase or rental charges begin as soon as the decision is made.) Manufacturing equipment can be purchased for $15 million or leased for $4 million per year. (Assume that these prices include maintenance costs and that charges do not begin until manufacturing has begun.) Material costs are negligible.

Net Present Value (in millions of $)				
Option	Own facility, own equipment	Own facility, lease equipment	Rent facility, own equipment	Rent facility, lease equipment
r = 5%	$ 62.81	$ 61.32	$ 57.11	$ 51.81
r = 10%	$ 38.99	$ 40.20	$ 39.52	$ 37.10
r = 15%	$ 21.04	$ 24.38	$ 26.31	$ 26.17
r = 20%	$ 7.30	$ 12.34	$ 16.23	$ 17.93
r = 25%	$ (3.37)	$ 3.03	$ 8.42	$ 11.61

Table 6-2: Net Present Value of Manufacturing Strategies (in $M)

In this case, the manufacturing strategy is entirely dependent upon the company's discount rate. If the company has a low discount rate, the best choice will be to purchase the required facility and own the processing equipment. As the discount rate increases the strategy shifts until it becomes most profitable to rent the facility and lease the equipment.

Appendix E

Aerospace Manufacturing System Design Evaluation Tool, Plant A (1 of 3)

Upper levels of AMSDD (FRs/DPs)	FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
	FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
	FR: Maximize sales revenue / DP: Products that maximize customer satisfaction >>							
Evaluation Criteria (FRs)	Improve product design and manufacturing	FR: Deliver products that meet customers' requirements / DP: Product design process			FR: Manufacture products to target design specifications / DP: Production processes with minimal variation			
					FR: Operate processes within control limits / DP: Elimination of assignable causes of variation			
		Design products that can be manufactured	Accommodate future changes in product design	Design products the customer can afford	Eliminate machine assignable causes	Eliminate operator assignable causes	Eliminate method assignable causes	Eliminate material assignable causes
Level of Achievement (DPs) 1	No formal or informal customer or employee feedback system exists.	Products designed completely independently from manufacturing process development. 0% concurrent engineering. (Designs passed "Over the wall.")	No standard method exists to implement design changes. Changes may occur anywhere in the mfg. process, resulting in unplanned production stoppages.	Products designed with mostly unique, custom-designed parts that may require many complex processing steps.	Poor quality output from machines due to unknown causes of variation (unable to hold mean). No maintenance of machine to ensure quality.	Workers learn tasks by watching others. Tasks may be done differently each time.	Methods are unstable and ill defined. Variation in methods is arbitrary and is not visible.	High variation in incoming parts which cause quality problems. Materials are damaged in storage and transport
2	Occasional improvement meetings held to collect ideas from customers/ employees. Suggestions rarely implemented.	Products designed with little manufacturing input. Infrequent meetings held between design and manufacturing.	No standard method exists to implement design changes. Attempts are made to limit the frequency of changes to reduce production disruptions.	Products designed with many custom-designed parts or parts that require complex processing steps.	Some assignable causes of variation are identified. Maintenance is occasional and is not scheduled.	Limited amounts of formal skills training. Workers learn what tasks to do from instructions.	Methods are known but not documented (shop floor "tribal knowledge")	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.
3	Suggestion system exists for some customers/employees but not frequently utilized. Occasional meetings held to discuss and collect ideas. Small % of ideas implemented.	Most products designed with input from manufacturing. However, few products are designed concurrently with their manufacturing processes.	A standard method exists to implement design changes, but is not followed. Changes often result in unplanned production stoppages.	Products designed with about half custom-designed or unique parts. Many of these parts require complex processing steps.	Most causes of variation are identified but are still not eliminated. Maintenance is only in response to quality problems.	Formal skills training program in place. Workers learn tasks from senior workers. Work standards exist but methods still vary.	Methods have been defined and standards exist but are not always followed/ updated.	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.
4	Suggestion system exists for most customers/employees. Continuous improvement meetings held on a regular, but infrequent basis. ~ 30% of suggestions implemented	More than half of products designed together with the manufacturing processes. Design and manufacturing meet regularly to discuss issues.	The standard method to implement design changes is usually followed. Changes may result in short periods of unplanned production stoppage.	Products designed with many common parts that do not require complex processing. Most custom parts cannot be eliminated due to design requirements.	Most causes of variation eliminated, some causes are still unable to be removed.	Manual tasks are defined so that they are done the same way each time. Standard work instructions indicate how tasks are performed.	Methods are well defined and repeatable. Standardized and followed.	Supplier responsible for meeting specifications. Little inspection of incoming parts required.
5	Suggestion system extends to most customers and employees. Continuous improvement events held on a regular basis. ~ 50% of suggestions implemented.	Most products designed together with the manufacturing processes. Design and manufacturing hold regular and frequent status meetings.	Design changes are mostly implemented at predefined stages in the manufacturing process. Changes rarely require unplanned production stoppages.	Products designed with mostly common parts that do not require complex processing.	Causes of variation reduced so that machine output is stabilized and mean shifts rarely occur. Maintenance is scheduled and performed on time.	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and upgraded by workers.	When methods are improved or updated, they are documented and implemented.	Collaboration with suppliers to ensure quality. Material handling and storage designed to maintain quality of products.
6	Suggestion system extends throughout enterprise and all customers. Continuous improvement events held on regular and frequent basis. High % of suggestions implemented.	All products designed together with the manufacturing processes. 100% concurrent engineering.	Design changes only implemented at predefined stages within the manufacturing process. Changes do not require unplanned production stoppages.	Products designed using a small set of common parts that can be fabricated with few, simple processing steps. Use of off-the shelf parts are preferred.	Machines able to maintain mean, within tolerances. All assignable causes of variation eliminated or controlled through a regular maintenance program throughout system.	In addition to level 5, Any mistakes are not translated to defects through mistake proofing (poka-yokes)	Methods are continually being improved and implemented throughout organization. All employees are knowledgeable about the most current methods.	Collaboration with suppliers to improve quality and involvement in developing specifications. Parts transferred and stored to prevent damage.
Comments	Refers to design and/or manufacturing improvements resulting from customer and/or employee feedback. This requires development and implementation of feedback mechanisms that encourage suggestions and utilize the input for continuous improvements. This feedback is often obtained through "kaizen" events.	Integrated design of products and the manufacturing processes used to produce them helps designers to make tradeoff decisions that result in parts that meet functionality requirements and can be manufactured with minimal difficulty.	Design changes are common over the lifecycle of a product. Design and manufacturing should develop a standardized method to apply design changes. Changes may be segmented into blocks based upon units of time or quantity (I.e., implement a set of changes only after *x* months or *y* products have been completed.)	Refers to costs that are directly affected by product design. Costs can be reduced by minimizing the number of unique part types, using "off the shelf parts" when feasible, minimizing the number of processing steps required, and simplifying the required processing steps.	Refers to quality reliability of the machines. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Maintenance in this branch refers to that which maintains quality instead of those that prevent breakdowns.	Refers to attaining predictable quality output from the workers. This is done through training, defining and following standard work and preventing common human errors from translating to defects/quality issues.	Method's are how process are done and include assembly tasks and process plans for machining etc. To prevent variation, these methods must be defined and followed. (standardized)	Material problems may be from suppliers or from handling within the plant.
Metrics	# of problems identified and corrected	% of a product designed in conjunction with its manufacturing system	Frequency at which design changes can be incorporated	Product price	# defects per n parts assignable to equipment	# defects per n parts assignable to operators	# defects per n parts assignable to the process	# defects per n parts assignable to quality of incoming material
		% customer requirements fulfilled			# defects per n parts with an assignable cause			
					Process capability			
	Sales revenue >>							
	Profit from manufacturing >>							
	Rate of NPV growth >>							

Aerospace Manufacturing System Design Evaluation Tool, Plant A (2 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
<< FR: Maximize sales revenue / DP: Products that maximize customer satisfaction							
FR: Deliver products on time / DP: Throughput time variation reduction		FR: Meet customer expected lead time / DP: Mean throughput time reduction					
Respond rapidly to production disruptions	**Minimize production disruptions**	**Reduce information delay**	**Reduce lot delay**	**Reduce process delay**	**Reduce run size delay**	**Reduce transportation delay**	**Reduce systematic operational delays**
Production disruptions occur frequently. Operators work around these disruptions so they are hidden.	Unpredictable resources. Disruptions are frequent and impact delivery.	Production schedules throughout the manufacturing system determined by rigid master schedule.	Large transportation lot sizes between machines or processes to reduce transportation costs.	Machine capacity and rate independent of demand (maximize output). Large and unpredictable levels of WIP between processes to manage system and avoid starvation.	System is designed to operate based on forecast demand, not actual demand. Production in large run size batches to avoid the long setup times.	Mfg. Process focused layout. Machines arranged by function in isolated departments (job shop type). Complex material flow.	Processes must be interrupted frequently for routine tasks such as material handling, machine maintenance, chip removal etc.
End of line inspection is used so quality problems are found late. Slow response to problems.	Disruptions are frequent but do not impact delivery often due to large buffer sizes. Frequency and type of disruptions is unknown.	Production schedules based upon centralized master schedule, but updated based upon actual performance and local considerations.	Single piece flow in only some areas (like assembly). Upstream processes still deliver materials in large lots.	Machines/processes in functional departments are arranged for product flow. High levels of inventory required between departments (varying production rates)	System is designed for production plan based on forecast demand. Run size is based on <1 month's forecast demand.	Process focused layout with departments grouped to reflect product family sequence of operations. Parallel processing occurs. Routing is unclear. (focused factory)	Routine tasks are designed so that they may be done infrequently - loading lots of material, large reservoirs for chips, infrequent maintenance.
Quick response to production disruptions (when they are found) to continue production. Root cause is not eliminated so problems may reoccur.	Machine disruptions (MTTF, MTTR) are recorded and used to determine lead time required for predictable delivery.	Production schedules based upon customer schedule. Schedules translated into daily requirements for each product line.	Single piece flow in only some areas. Upstream processes deliver materials in lots based on standard inventory.	Assembly or transfer line designs running at high speeds feeding multiple customers. Large amount of inventory before and after lines to manage product flow	System is designed for production plan based on forecast demand. Run size is based on <1 week's forecast demand.	Product or customer oriented material flow. Machines/stations in cellular design with some batch processes intermixed (partial cells)	Many routine tasks are scheduled so that they may be done after hours (like maintenance). Production still must stop regularly for other activities.
Production disruptions are addressed quickly and the root cause is eventually addressed. In-process inspection.	Disruptions from machines/ equipment, people, parts and information availability are known. Systems being developed to make resources more predictable.	Production schedule based upon actual demand. Internal production signals generated by withdrawal of parts. Signals relayed electronically or by kanban cards.	Single piece flow within cells/sub-systems. Large lots transferred between sub-systems.	Customers grouped to achieve effective takt times. Machines and people are capable of working to takt time. Some parallel processing/stations exist.	System is not based on actual demand. Run size is based on a schedule that repeats at one or greater than one day. External setup tasks are reduced.	Material flow/cellular design with machines/stations close together. No complicated material flow (well defined cells)	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal and work preparation.
System designed so that production disruptions are visible. In-process checks by operators so quality issues are found quickly. Good root cause analysis.	Systems designed so that disruptions from all resources are reduced. Includes perfect attendance, TPM, std. material supply and reliable information systems.	Production based upon customer demand. Withdrawal of product initiates signal to replenish inventory. Signal relayed by electronic signal and/or kanban card.	All cells/sub-systems using single piece flow. Transfer lots sizes between sub-systems being reduced based on demand interval.	Cells/sub-systems running at takt time with standard inventory of one between stations. Machines and people are capable of working to minimum takt time.	System supports actual demand and expected peaks. Produce exactly what is consumed by the customer on a daily or shift basis. Internal setup tasks are reduced.	Material flow oriented layout design applies throughout value stream. Minimum handling with process close to receiving and shipping docks. (linked cells)	Workers continually make improvements in eliminating interference between people, material handling, maintenance etc.
Co-location of cause and effect (simplified material flow) and systematic method for communicating, and solving problems. Line stop methods in use (Andon)	Production disruptions rarely occur. Throughput time variation is very low and predictable.	Production matches customer demand. Withdrawal of parts authorizes production to replenish. Kanban card or electronic signal relays production signal.	Single piece flow of parts throughout the factory.	Production balanced to takt time throughout value stream. Some flexibility to produce to different takt times. Minimum WIP between processes& sub-systems/cells.	Production of the desired mix and quantity during each demand interval using Heijunka. Almost no setup required between part types.	Reduced transportation throughout supply chain. Production near customer and supplier base. Material flow oriented layout throughout plant.	Processes rarely ever stop for routine activities.
Production disruptions refer to machine breakdowns, quality issues, information, worker availability. This branch deals with how these problems are addressed and eliminated.	Predictable resources are required for minimal production disruptions. Total preventative maintenance (TPM) programs, perfect attendance, reliable part supply and and information are required.	Information delay refers to the delay between when a production signal is transmitted and when the signal is received and acted upon. By conveying products with production signals, such as kanban cards, info. delay is minimized.	Lot delay refers to parts waiting on other parts in the lot before they are transported together. This is avoided with single piece transport. Reducing transportation distance is important to achieve this.	Process delay occurs when arrival rate > service rate (unbalanced rates). Large and unpredictable inventory levels are indicative of process delay. It is reduced by balancing to a constant and predictable takt time. Flexibility to produce to different takt times keeps system balanced when demand changes.	Delay due to inventory when producing different part types. Setup time is the time to change between part types within a station. Knowledge of the part types required is necessary or large inventories of different parts are required. With accurate and timely info, only the parts required are produced.	To reduce transportation delay, the amount of transportation should be minimized. In system design, this is a consideration in factory layout. This is also applicable from a geographical view as well as within the plant	Operational delays are routine disruptions designed into the system (processes stopping for maintenance, material replenishment and other processes). They may be eliminated through machine and station design (Chip removal, control access from rear of station), operator work routine design.
Time between occurrence and resolution of disruptions	**Number of disruptions & amount of time lost to disruptions**	**Time from info. transmitted or requested until info. received**	**Inventory due to lot size delay**	**Inventory due to process delay**	**Inventory due to run size delay**	**Inventory due to transportation delay**	**Production time lost due to interference among resources**
% on-time deliveries		Difference between mean throughput time and customer's expected lead time					
<< Sales revenue							
<< Profit from manufacturing >>							
<< Rate of NPV growth >>							

Aerospace Manufacturing System Design Evaluation Tool, Plant A (3 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value			
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation			
FR: Minimize manufacturing costs / DP: Elimination of non-value adding sources of cost			**Minimize investment over production system lifecycle**
Reduce wasted processing	**Reduce wasted use of employees**	**Reduce cost of procured materials**	
Processes designed without regard for # of steps. Overly complex or precise processing methods selected.	One person, one machine design - operator watches machine run. Excessive walking to search for tools and materials. Excessive operator motions.	Arms-length relationships between suppliers and customers. Design decisions made from a single-company perspective. Minimal information transfer.	Investment decisions based solely on immediate needs. Long-term product and volume flexibility requirements not considered.
Processes designed with a bias towards too many steps or overly complex methods. Attempts are not made to improve both.	Operator runs single machine, does "fill-in" work between cycles. Excessive walking req'd to obtain tools and mat'ls not located at point of use. Excessive operator motions.	Arms-length relationships between suppliers and customers. High-level design meetings occur only at beginning of project. Info. transfer limited to critical requirements.	Investment decisions focus on meeting short-term business needs. NPV analyses may be used for some long-term projects.
Process design attempts to reduce # or complexity and precision of processing, but the result is unbalanced towards too many steps or overly complex methods.	Operator may run more than one of the same type machine. Workers isolated to stations to avoid walking. Poor ergonomics causes worker to constantly reposition themselves.	Loosely-linked supply chain. Multi-level design meetings occur throughout project. Information protected and transfers limited to critical requirements and non-proprietary info.	Investment decisions seek to maximize NPV, but long-term projects frequently preempted by short-term needs.
Process design generally balances # and complexity of mfg. steps. Several non-value adding or excessively complex steps have been identified, but can't be eliminated.	Operator can run multiple machines of different types. 5S program implemented so that parts, tools, equipment are where required. No operator- process work routine defined.	Integrated supply chain. Suppliers and customers meet frequently to discuss product and mfg. system design. Most information is available to enterprise members.	Investment decisions focus on maximizing NPV. Long-term projects occasionally scaled back because of short-term needs.
Process design balances the # and complexity of manufacturing steps. Few if any non-value adding or excessively complex steps remain.	Multi-skilled operators run several machines/ processes.Machines are small and close to reduce walking distances (in cells.) Operator-process work routine graphs used.	Integrated supply chain. Representatives from suppliers and customers sit on design teams to provide input. Information is available throughout the enterprise.	Investment decisions heavily influenced by NPV analyses. Long-term goals rarely sacrificed to meet short term requirements.
The minimum # and complexity of processing steps have been selected. Reducing steps further would add significant cost to the product.	Number of operators can be varied to achieve range of takt times. Machines run autonomously. Level 5 applied through company. 5S understood & used beyond shop floor.	Highly integrated supply chain. Product and mfg. system design decisions made by teams that cross company borders. Free flow of Information throughout enterprise.	Investment decisions based upon thorough NPV analyses. Decisions allow company to fulfill short and long term requirements.
Wasted processing steps are any steps that do not add value to the final product. Excessive transportation, overly tight tolerances, and unnecessary features are all examples of wasted processing steps.	Wasted use of employees includes operators waiting for machines to finish cycling, walking excessive distances, searching for tools and materials, and poor ergonomics.	Reducing the cost of procured materials requires developing close partnerships with suppliers and integrating them into the overall manufacturing system. Sharing information between suppliers and integrators increases opportunities for improvement and cost reduction.	Companies operating in a fast-changing environment can reduce the NPV of future investments by making a large up-front investing in a highly flexible mfg. system. This flexibility may be wasted, however, for companies that operate in more stable environments and therefore will not require frequent system design changes.
# of wasted processing steps	**% employee time spent on non-value adding activities**	**Cost of procured materials**	**Investment over system lifecycle**
Manufacturing costs			
<< **Profit from manufacturing**			
<< **Rate of NPV growth**			

Aerospace Manufacturing System Design Evaluation Tool, Plant B (1 of 3)

Upper levels of AMSDD (FRs/DPs)		FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
		FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
		FR: Maximize sales revenue / DP: Products that maximize customer satisfaction >>							
Evaluation Criteria (FRs)		Improve product design and manufacturing	FR: Deliver products that meet customers' requirements / DP: Product design process			FR: Manufacture products to target design specifications / DP: Production processes with minimal variation			
						FR: Operate processes within control limits / DP: Elimination of assignable causes of variation			
			Design products that can be manufactured	Accommodate future changes in product design	Design products the customer can afford	Eliminate machine assignable causes	Eliminate operator assignable causes	Eliminate method assignable causes	Eliminate material assignable causes
Level of Achievement (DPs)	1	No formal or informal customer or employee feedback system exists.	Products designed completely independently from manufacturing process development. 0% concurrent engineering. (Designs passed "Over the wall.")	No standard method exists to implement design changes. Changes may occur anywhere in the mfg. process, resulting in unplanned production stoppages.	Products designed with mostly unique, custom-designed parts that may require many complex processing steps.	Poor quality output from machines due to unknown causes of variation (unable to hold mean). No maintenance of machine to ensure quality.	Workers learn tasks by watching others. Tasks may be done differently each time.	Methods are unstable and ill defined. Variation in methods is arbitrary and is not visible.	High variation in incoming parts which cause quality problems. Materials are damaged in storage and transport
	2	Occasional improvement meetings held to collect ideas from customers/ employees. Suggestions rarely implemented.	Products designed with little manufacturing input. Infrequent meetings held between design and manufacturing.	No standard method exists to implement design changes. Attempts are made to limit the frequency of changes to reduce production disruptions.	Products designed with many custom-designed parts or parts that require complex processing steps.	Some assignable causes of variation are identified. Maintenance is occasional and is not scheduled.	Limited amounts of formal skills training. Workers learn what tasks to do from instructions.	Methods are known but not documented (shop floor "tribal knowledge")	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.
	3	Suggestion system exists for some customers/employees but not frequently utilized. Occasional meetings held to discuss and collect ideas. Small % of ideas implemented.	Most products designed with input from manufacturing. However, few products are designed concurrently with their manufacturing processes.	A standard method exists to implement design changes, but is not followed. Changes often result in unplanned production stoppages.	Products designed with about half custom-designed or unique parts. Many of these parts require complex processing steps.	Most causes of variation are identified but are still not eliminated. Maintenance is only in response to quality problems.	Formal skills training program in place. Workers learn tasks from senior workers. Work standards exist but methods still vary.	Methods have been defined and standards exist but are not always followed/ updated.	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.
	4	Suggestion system exists for most customers/employees. Continuous improvement meetings held on a regular, but infrequent basis. ~ 30% of suggestions implemented	More than half of products designed together with the manufacturing processes. Design and manufacturing meet regularly to discuss issues.	The standard method to implement design changes is usually followed. Changes may result in short periods of unplanned production stoppage.	Products designed with many common parts that do not require complex processing. Most custom parts cannot be eliminated due to design requirements.	Most causes of variation eliminated, some causes are still unable to be removed.	Manual tasks are defined so that they are done the same way each time. Standard work instructions indicate how tasks are performed.	Methods are well defined and repeatable. Standardized and followed.	Supplier responsible for meeting specifications. Little inspection of incoming parts required.
	5	Suggestion system extends to most customers and employees. Continuous improvement events held on a regular basis. ~ 50% of suggestions implemented.	Most products designed together with the manufacturing processes. Design and manufacturing hold regular and frequent status meetings.	Design changes are mostly implemented at predefined stages in the manufacturing process. Changes rarely require unplanned production stoppages.	Products designed with mostly common parts that do not require complex processing.	Causes of variation reduced so that machine output is stabilized and mean shifts rarely occur. Maintenance is scheduled and performed on time.	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and upgraded by workers.	When methods are improved or updated, they are documented and implemented.	Collaboration with suppliers to ensure quality. Material handling and storage designed to maintain quality of products.
	6	Suggestion system extends throughout enterprise and all customers. Continuous improvement events held on regular and frequent basis. High % of suggestions implemented.	All products designed together with the manufacturing processes. 100% concurrent engineering.	Design changes only implemented at predefined stages within the manufacturing process. Changes do not require unplanned production stoppages.	Products designed using a small set of common parts that can be fabricated with few, simple processing steps. Use of off-the shelf parts are preferred.	Machines able to maintain mean, within tolerances. All assignable causes of variation eliminated or controlled through a regular maintenance program throughout system.	In addition to level 5, Any mistakes are not translated to defects through mistake proofing (poka-yokes)	Methods are continually being improved and implemented throughout organization. All employees are knowledgeable about the most current methods.	Collaboration with suppliers to improve quality and involvement in developing specifications. Parts transferred and stored to prevent damage.
Comments		Refers to design and/or manufacturing improvements resulting from customer and/or employee feedback. This requires development and implementation of feedback mechanisms that encourage suggestions and utilize the input for continuous improvements. This feedback is often obtained through "kaizen" events.	Integrated design of products and the manufacturing processes used to produce them helps designers to make tradeoff decisions that result in parts that meet functionality requirements and can be manufactured with minimal difficulty.	Design changes are common over the lifecycle of a product. Design and manufacturing should develop a standardized method to apply design changes. Changes may be segmented into blocks based upon units of time or quantity (I.e., implement a set of changes only after *x* months or *y* products have been completed.)	Refers to costs that are directly affected by product design. Costs can be reduced by minimizing the number of unique part types, using "off the shelf parts" when feasible, minimizing the number of processing steps required, and simplifying the required processing steps.	Refers to quality reliability of the machines. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Maintenance in this branch refers to that which maintains quality instead of those that prevent breakdowns.	Refers to attaining predictable quality output from the workers. This is done through training, defining and following standard work and preventing common human errors from translating to defects/quality issues.	Method's are how process are done and include assembly tasks and process plans for machining etc. To prevent variation, these methods must be defined and followed. (standardized)	Material problems may be from suppliers or from handling within the plant.
Metrics		# of problems identified and corrected	% of a product designed in conjunction with its manufacturing system	Frequency at which design changes can be incorporated	Product price	# defects per n parts assignable to equipment	# defects per n parts assignable to operators	# defects per n parts assignable to the process	# defects per n parts assignable to quality of incoming material
			% customer requirements fulfilled			# defects per n parts with an assignable cause			
						Process capability			
		Sales revenue >>							
		Profit from manufacturing >>							
		Rate of NPV growth >>							

Aerospace Manufacturing System Design Evaluation Tool, Plant B (2 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
<< FR: Maximize sales revenue / DP: Products that maximize customer satisfaction							
FR: Deliver products on time / DP: Throughput time variation reduction		FR: Meet customer expected lead time / DP: Mean throughput time reduction					
Respond rapidly to production disruptions	**Minimize production disruptions**	**Reduce information delay**	**Reduce lot delay**	**Reduce process delay**	**Reduce run size delay**	**Reduce transportation delay**	**Reduce systematic operational delays**
Production disruptions occur frequently. Operators work around these disruptions so they are hidden.	Unpredictable resources. Disruptions are frequent and impact delivery.	Production schedules throughout the manufacturing system determined by rigid master schedule.	Large transportation lot sizes between machines or processes to reduce transportation costs.	Machine capacity and rate independent of demand (maximize output). Large and unpredictable levels of WIP between processes to manage system and avoid starvation.	System is designed to operate based on forecast demand, not actual demand. Production in large run size batches to avoid the long setup times.	Mfg. Process focused layout. Machines arranged by function in isolated departments (job shop type). Complex material flow.	Processes must be interrupted frequently for routine tasks such as material handling, machine maintenance, chip removal etc.
End of line inspection is used so quality problems are found late. Slow response to problems.	Disruptions are frequent but do not impact delivery often due to large buffer sizes. Frequency and type of disruptions is unknown.	Production schedules based upon centralized master schedule, but updated based upon actual performance and local considerations.	Single piece flow in only some areas (like assembly). Upstream processes still deliver materials in large lots.	Machines/processes in functional departments are arranged for product flow. High levels of inventory required between departments (varying production rates)	System is designed for production plan based on forecast demand. Run size is based on <1 month's forecast demand.	Process focused layout with departments grouped to reflect product family sequence of operations. Parallel processing occurs. Routing is unclear. (focused factory)	Routine tasks are designed so that they may be done infrequently - loading lots of material, large reservoirs for chips, infrequent maintenance.
Quick response to production disruptions (when they are found) to continue production. Root cause is not eliminated so problems may reoccur.	Machine disruptions (MTTF, MTTR) are recorded and used to determine lead time required for predictable delivery.	Production schedules based upon customer schedule. Schedules translated into daily requirements for each product line.	Single piece flow in only some areas. Upstream processes deliver materials in lots based on standard inventory.	Assembly or transfer line designs running at high speeds feeding multiple customers. Large amount of inventory before and after lines to manage product flow	System is designed for production plan based on forecast demand. Run size is based on <1 week's forecast demand.	Product or customer oriented material flow. Machines/stations in cellular design with some batch processes intermixed (partial cells)	Many routine tasks are scheduled so that they may be done after hours (like maintenance). Production still must stop regularly for other activities.
Production disruptions are addressed quickly and the root cause is eventually addressed. In-process inspection.	Disruptions from machines/ equipment, people, parts and information availability are known. Systems being developed to make resources more predictable.	Production schedule based upon actual demand. Internal production signals generated by withdrawal of parts. Signals relayed electronically or by kanban cards.	Single piece flow within cells/sub-systems. Large lots transferred between sub-systems.	Customers grouped to achieve effective takt times. Machines and people are capable of working to takt time. Some parallel processing/stations exist.	System is not based on actual demand. Run size is based on a schedule that repeats at one or greater than one day. External setup tasks are reduced.	Material flow/cellular design with machines/stations close together. No complicated material flow (well defined cells)	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal and work preparation.
System designed so that production disruptions are visible. In-process checks by operators so quality issues are found quickly. Good root cause analysis.	Systems designed so that disruptions from all resources are reduced. Includes perfect attendance, TPM, std. material supply and reliable information systems.	Production based upon customer demand. Withdrawal of product initiates signal to replenish inventory. Signal relayed by electronic signal and/or kanban card.	All cells/sub-systems using single piece flow. Transfer lots sizes between sub-systems being reduced based on demand interval.	Cells/sub-systems running at takt time with standard inventory of one between stations. Machines and people are capable of working to minimum takt time.	System supports actual demand and expected peaks. Produce exactly what is consumed by the customer on a daily or shift basis. Internal setup tasks are reduced.	Material flow oriented layout design applies throughout value stream. Minimum handling with process close to receiving and shipping docks. (linked cells)	Workers continually make improvements in eliminating interference between people, material handling, maintenance etc.
Co-location of cause and effect (simplified material flow) and systematic method for communicating, and solving problems. Line stop methods in use (Andon)	Production disruptions rarely occur. Throughput time variation is very low and predictable.	Production matches customer demand. Withdrawal of parts authorizes production to replenish. Kanban card or electronic signal relays production signal.	Single piece flow of parts throughout the factory.	Production balanced to takt time throughout value stream. Some flexibility to produce to different takt times. Minimum WIP between processes& sub-systems/cells.	Production of the desired mix and quantity during each demand interval using Heijunka. Almost no setup required between part types.	Reduced transportation throughout supply chain. Production near customer and supplier base. Material flow oriented layout throughout plant.	Processes rarely ever stop for routine activities.
Production disruptions refer to machine breakdowns, quality issues, information, worker availability. This branch deals with how these problems are addressed and eliminated.	Predictable resources are required for minimal production disruptions. Total preventative maintenance (TPM) programs, perfect attendance, reliable part supply and and information are required.	Information delay refers to the delay between when a production signal is transmitted and when the signal is received and acted upon. By conveying products with production signals, such as kanban cards, info. delay is minimized.	Lot delay refers to parts waiting on other parts in the lot before they are transported together. This is avoided with single piece transport. Reducing transportation distance is important to achieve this.	Process delay occurs when arrival rate > service rate (unbalanced rates). Large and unpredictable inventory levels are indicative of process delay. It is reduced by balancing to a constant and predictable takt time. Flexibility to produce to different takt times keeps system balanced when demand changes.	Delay due to inventory when producing different part types. Setup time is the time to change between part types within a station. Knowledge of the part types required is necessary or large inventories of different parts are required. With accurate and timely info, only the parts required are produced.	To reduce transportation delay, the amount of transportation should be minimized. In system design, this is a consideration in factory layout. This is also applicable from a geographical view as well as within the plant	Operational delays are routine disruptions designed into the system (processes stopping for maintenance, material replenishment and other processes). They may be eliminated through machine and station design (Chip removal, control access from rear of station), operator work routine design.
Time between occurrence and resolution of disruptions	**Number of disruptions & amount of time lost to disruptions**	**Time from info. transmitted or requested until info. received**	**Inventory due to lot size delay**	**Inventory due to process delay**	**Inventory due to run size delay**	**Inventory due to transportation delay**	**Production time lost due to interference among resources**
% on-time deliveries		Difference between mean throughput time and customer's expected lead time					
<< Sales revenue							
<< Profit from manufacturing >>							
<< Rate of NPV growth >>							

Aerospace Manufacturing System Design Evaluation Tool, Plant B (3 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value			
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation			
FR: Minimize manufacturing costs / DP: Elimination of non-value adding sources of cost			Minimize investment over production system lifecycle
Reduce wasted processing	**Reduce wasted use of employees**	**Reduce cost of procured materials**	
Processes designed without regard for # of steps. Overly complex or precise processing methods selected.	One person, one machine design - operator watches machine run. Excessive walking to search for tools and materials. Excessive operator motions.	Arms-length relationships between suppliers and customers. Design decisions made from a single-company perspective. Minimal information transfer.	Investment decisions based solely on immediate needs. Long-term product and volume flexibility requirements not considered.
Processes designed with a bias towards too many steps or overly complex methods. Attempts are not made to improve both.	Operator runs single machine, does "fill-in" work between cycles. Excessive walking req'd to obtain tools and mat'ls not located at point of use. Excessive operator motions.	Arms-length relationships between suppliers and customers. High-level design meetings occur only at beginning of project. Info. transfer limited to critical requirements.	Investment decisions focus on meeting short-term business needs. NPV analyses may be used for some long-term projects.
Process design attempts to reduce # or complexity and precision of processing, but the result is unbalanced towards too many steps or overly complex methods.	Operator may run more than one of the same type machine. Workers isolated to stations to avoid walking. Poor ergonomics causes worker to constantly reposition themselves.	Loosely-linked supply chain. Multi-level design meetings occur throughout project. Information protected and transfers limited to critical requirements and non-proprietary info.	Investment decisions seek to maximize NPV, but long-term projects frequently preempted by short-term needs.
Process design generally balances # and complexity of mfg. steps. Several non-value adding or excessively complex steps have been identified, but can't be eliminated.	Operator can run multiple machines of different types. 5S program implemented so that parts, tools, equipment are where required. No operator- process work routine defined.	Integrated supply chain. Suppliers and customers meet frequently to discuss product and mfg. system design. Most information is available to enterprise members.	Investment decisions focus on maximizing NPV. Long-term projects occasionally scaled back because of short-term needs.
Process design balances the # and complexity of manufacturing steps. Few if any non-value adding or excessively complex steps remain.	Multi-skilled operators run several machines/ processes.Machines are small and close to reduce walking distances (in cells.) Operator-process work routine graphs used.	Integrated supply chain. Representatives from suppliers and customers sit on design teams to provide input. Information is available throughout the enterprise.	Investment decisions heavily influenced by NPV analyses. Long-term goals rarely sacrificed to meet short term requirements.
The minimum # and complexity of processing steps have been selected. Reducing steps further would add significant cost to the product.	Number of operators can be varied to achieve range of takt times. Machines run autonomously. Level 5 applied through company. 5S understood & used beyond shop floor.	Highly integrated supply chain. Product and mfg. system design decisions made by teams that cross company borders. Free flow of Information throughout enterprise.	Investment decisions based upon thorough NPV analyses. Decisions allow company to fulfill short and long term requirements.
Wasted processing steps are any steps that do not add value to the final product. Excessive transportation, overly tight tolerances, and unnecessary features are all examples of wasted processing steps.	Wasted use of employees includes operators waiting for machines to finish cycling, walking excessive distances, searching for tools and materials, and poor ergonomics.	Reducing the cost of procured materials requires developing close partnerships with suppliers and integrating them into the overall manufacturing system. Sharing information between suppliers and integrators increases opportunities for improvement and cost reduction.	Companies operating in a fast-changing environment can reduce the NPV of future investments by making a large up-front investing in a highly flexible mfg. system. This flexibility may be wasted, however, for companies that operate in more stable environments and therefore will not require frequent system design changes.
# of wasted processing steps	**% employee time spent on non-value adding activities**	**Cost of procured materials**	**Investment over system lifecycle**
Manufacturing costs			
<< Profit from manufacturing			
<< Rate of NPV growth			

Aerospace Manufacturing System Design Evaluation Tool, Plant C (1 of 3)

Upper levels of AMSDD (FRs/DPs)		FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
		FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
		FR: Maximize sales revenue / DP: Products that maximize customer satisfaction >>							
Evaluation Criteria (FRs)		Improve product design and manufacturing	FR: Deliver products that meet customers' requirements / DP: Product design process			FR: Manufacture products to target design specifications / DP: Production processes with minimal variation			
						FR: Operate processes within control limits / DP: Elimination of assignable causes of variation			
			Design products that can be manufactured	Accommodate future changes in product design	Design products the customer can afford	Eliminate machine assignable causes	Eliminate operator assignable causes	Eliminate method assignable causes	Eliminate material assignable causes
Level of Achievement (DPs)	1	No formal or informal customer or employee feedback system exists.	Products designed completely independently from manufacturing process development. 0% concurrent engineering. (Designs passed "Over the wall.")	No standard method exists to implement design changes. Changes may occur anywhere in the mfg. process, resulting in unplanned production stoppages.	Products designed with mostly unique, custom-designed parts that may require many complex processing steps.	Poor quality output from machines due to unknown causes of variation (unable to hold mean). No maintenance of machine to ensure quality.	Workers learn tasks by watching others. Tasks may be done differently each time.	Methods are unstable and ill defined. Variation in methods is arbitrary and is not visible.	High variation in incoming parts which cause quality problems. Materials are damaged in storage and transport
	2	Occasional improvement meetings held to collect ideas from customers/ employees. Suggestions rarely implemented.	Products designed with little manufacturing input. Infrequent meetings held between design and manufacturing.	No standard method exists to implement design changes. Attempts are made to limit the frequency of changes to reduce production disruptions.	Products designed with many custom-designed parts or parts that require complex processing steps.	Some assignable causes of variation are identified. Maintenance is occasional and is not scheduled.	Limited amounts of formal skills training. Workers learn what tasks to do from instructions.	Methods are known but not documented (shop floor "tribal knowledge")	Parts arrive with questionable quality and must be inspected before use. Entire lots are sent back if there are bad parts.
	3	Suggestion system exists for some customers/employees but not frequently utilized. Occasional meetings held to discuss and collect ideas. Small % of ideas implemented.	Most products designed with input from manufacturing. However, few products are designed concurrently with their manufacturing processes.	A standard method exists to implement design changes, but is not followed. Changes often result in unplanned production stoppages.	Products designed with about half custom-designed or unique parts. Many of these parts require complex processing steps.	Most causes of variation are identified but are still not eliminated. Maintenance is only in response to quality problems.	Formal skills training program in place. Workers learn tasks from senior workers. Work standards exist but methods still vary.	Methods have been defined and standards exist but are not always followed/ updated.	Supplier responsible for meeting specifications. Little inspection of incoming parts required. Some parts are still damaged within the plant.
	4	Suggestion system exists for most customers/employees. Continuous improvement meetings held on a regular, but infrequent basis. ~ 30% of suggestions implemented	More than half of products designed together with the manufacturing processes. Design and manufacturing meet regularly to discuss issues.	The standard method to implement design changes is usually followed. Changes may result in short periods of unplanned production stoppage.	Products designed with many common parts that do not require complex processing. Most custom parts cannot be eliminated due to design requirements.	Most causes of variation eliminated, some causes are still unable to be removed.	Manual tasks are defined so that they are done the same way each time. Standard work instructions indicate how tasks are performed.	Methods are well defined and repeatable. Standardized and followed.	Supplier responsible for meeting specifications. Little inspection of incoming parts required.
	5	Suggestion system extends to most customers and employees. Continuous improvement events held on a regular basis. ~ 50% of suggestions implemented.	Most products designed together with the manufacturing processes. Design and manufacturing hold regular and frequent status meetings.	Design changes are mostly implemented at predefined stages in the manufacturing process. Changes rarely require unplanned production stoppages.	Products designed with mostly common parts that do not require complex processing.	Causes of variation reduced so that machine output is stabilized and mean shifts rarely occur. Maintenance is scheduled and performed on time.	Formal training is extended beyond skills to OJT by certified instructors. Standards are followed and upgraded by workers.	When methods are improved or updated, they are documented and implemented.	Collaboration with suppliers to ensure quality. Material handling and storage designed to maintain quality of products.
	6	Suggestion system extends throughout enterprise and all customers. Continuous improvement events held on regular and frequent basis. High % of suggestions implemented.	All products designed together with the manufacturing processes. 100% concurrent engineering.	Design changes only implemented at predefined stages within the manufacturing process. Changes do not require unplanned production stoppages.	Products designed using a small set of common parts that can be fabricated with few, simple processing steps. Use of off-the shelf parts are preferred.	Machines able to maintain mean, within tolerances. All assignable causes of variation eliminated or controlled through a regular maintenance program throughout system.	In addition to level 5, Any mistakes are not translated to defects through mistake proofing (poka-yokes)	Methods are continually being improved and implemented throughout organization. All employees are knowledgeable about the most current methods.	Collaboration with suppliers to improve quality and involvement in developing specifications. Parts transferred and stored to prevent damage.
Comments		Refers to design and/or manufacturing improvements resulting from customer and/or employee feedback. This requires development and implementation of feedback mechanisms that encourage suggestions and utilize the input for continuous improvements. This feedback is often obtained through "kaizen" events.	Integrated design of products and the manufacturing processes used to produce them helps designers to make tradeoff decisions that result in parts that meet functionality requirements and can be manufactured with minimal difficulty.	Design changes are common over the lifecycle of a product. Design and manufacturing should develop a standardized method to apply design changes. Changes may be segmented into blocks based upon units of time or quantity (I.e., implement a set of changes only after *x* months or *y* products have been completed.)	Refers to costs that are directly affected by product design. Costs can be reduced by minimizing the number of unique part types, using "off the shelf parts" when feasible, minimizing the number of processing steps required, and simplifying the required processing steps.	Refers to quality reliability of the machines. Assignable causes are those that cause the process to go out of control and may be: tool wear/breakage, bearing failures, etc. Maintenance in this branch refers to that which maintains quality instead of those that prevent breakdowns.	Refers to attaining predictable quality output from the workers. This is done through training, defining and following standard work and preventing common human errors from translating to defects/quality issues.	Method's are how process are done and include assembly tasks and process plans for machining etc. To prevent variation, these methods must be defined and followed. (standardized)	Material problems may be from suppliers or from handling within the plant.
Metrics		# of problems identified and corrected	% of a product designed in conjunction with its manufacturing system	Frequency at which design changes can be incorporated	Product price	# defects per n parts assignable to equipment	# defects per n parts assignable to operators	# defects per n parts assignable to the process	# defects per n parts assignable to quality of incoming material
			% customer requirements fulfilled			# defects per n parts with an assignable cause			
						Process capability			
		Sales revenue >>							
		Profit from manufacturing >>							
		Rate of NPV growth >>							

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<< FR: Increase shareholder value / DP: Growth of company's Net Present Value >>							
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation >>							
<< FR: Maximize sales revenue / DP: Products that maximize customer satisfaction							
FR: Deliver products on time / DP: Throughput time variation reduction		**FR: Meet customer expected lead time / DP: Mean throughput time reduction**					
Respond rapidly to production disruptions	**Minimize production disruptions**	**Reduce information delay**	**Reduce lot delay**	**Reduce process delay**	**Reduce run size delay**	**Reduce transportation delay**	**Reduce systematic operational delays**
Production disruptions occur frequently. Operators work around these disruptions so they are hidden.	Unpredictable resources. Disruptions are frequent and impact delivery.	Production schedules throughout the manufacturing system determined by rigid master schedule.	Large transportation lot sizes between machines or processes to reduce transportation costs.	Machine capacity and rate independent of demand (maximize output). Large and unpredictable levels of WIP between processes to manage system and avoid starvation.	System is designed to operate based on forecast demand, not actual demand. Production in large run size batches to avoid the long setup times.	Mfg. Process focused layout. Machines arranged by function in isolated departments (job shop type). Complex material flow.	Processes must be interrupted frequently for routine tasks such as material handling, machine maintenance, chip removal etc.
End of line inspection is used so quality problems are found late. Slow response to problems.	Disruptions are frequent but do not impact delivery often due to large buffer sizes. Frequency and type of disruptions is unknown.	Production schedules based upon centralized master schedule, but updated based upon actual performance and local considerations.	Single piece flow in only some areas (like assembly). Upstream processes still deliver materials in large lots.	Machines/processes in functional departments are arranged for product flow. High levels of inventory required between departments (varying production rates)	System is designed for production plan based on forecast demand. Run size is based on <1 month's forecast demand.	Process focused layout with departments grouped to reflect product family sequence of operations. Parallel processing occurs. Routing is unclear. (focused factory)	Routine tasks are designed so that they may be done infrequently - loading lots of material, large reservoirs for chips, infrequent maintenance.
Quick response to production disruptions (when they are found) to continue production. Root cause is not eliminated so problems may reoccur.	Machine disruptions (MTTF, MTTR) are recorded and used to determine lead time required for predictable delivery.	Production schedules based upon customer schedule. Schedules translated into daily requirements for each product line.	Single piece flow in only some areas. Upstream processes deliver materials in lots based on standard inventory.	Assembly or transfer line designs running at high speeds feeding multiple customers. Large amount of inventory before and after lines to manage product flow	System is designed for production plan based on forecast demand. Run size is based on <1 week's forecast demand.	Product or customer oriented material flow. Machines/stations in cellular design with some batch processes intermixed (partial cells)	Many routine tasks are scheduled so that they may be done after hours (like maintenance). Production still must stop regularly for other activities.
Production disruptions are addressed quickly and the root cause is eventually addressed. In-process inspection.	Disruptions from machines/ equipment, people, parts and information availability are known. Systems being developed to make resources more predictable.	Production schedule based upon actual demand. Internal production signals generated by withdrawal of parts. Signals relayed electronically or by kanban cards.	Single piece flow within cells/sub-systems. Large lots transferred between sub-systems.	Customers grouped to achieve effective takt times. Machines and people are capable of working to takt time. Some parallel processing/stations exist.	System is not based on actual demand. Run size is based on a schedule that repeats at one or greater than one day. External setup tasks are reduced.	Material flow/cellular design with machines/stations close together. No complicated material flow (well defined cells)	Machines/processes designed so they do not have to be interrupted for routine material replenishment, chip removal and work preparation.
System designed so that production disruptions are visible. In-process checks by operators so quality issues are found quickly. Good root cause analysis.	Systems designed so that disruptions from all resources are reduced. Includes perfect attendance, TPM, std. material supply and reliable information systems.	Production based upon customer demand. Withdrawal of product initiates signal to replenish inventory. Signal relayed by electronic signal and/or kanban card.	All cells/sub-systems using single piece flow. Transfer lots sizes between sub-systems being reduced based on demand interval.	Cells/sub-systems running at takt time with standard inventory of one between stations. Machines and people are capable of working to minimum takt time.	System supports actual demand and expected peaks. Produce exactly what is consumed by the customer on a daily or shift basis. Internal setup tasks are reduced.	Material flow oriented layout design applies throughout value stream. Minimum handling with process close to receiving and shipping docks. (linked cells)	Workers continually make improvements in eliminating interference between people, material handling, maintenance etc.
Co-location of cause and effect (simplified material flow) and systematic method for communicating, and solving problems. Line stop methods in use (Andon)	Production disruptions rarely occur. Throughput time variation is very low and predictable.	Production matches customer demand. Withdrawal of parts authorizes production to replenish. Kanban card or electronic signal relays production signal.	Single piece flow of parts throughout the factory.	Production balanced to takt time throughout value stream. Some flexibility to produce to different takt times. Minimum WIP between processes& sub-systems/cells.	Production of the desired mix and quantity during each demand interval using Heijunka. Almost no setup required between part types.	Reduced transportation throughout supply chain. Production near customer and supplier base. Material flow oriented layout throughout plant.	Processes rarely ever stop for routine activities.
Production disruptions refer to machine breakdowns, quality issues, information, worker availability. This branch deals with how these problems are addressed and eliminated.	Predictable resources are required for minimal production disruptions. Total preventative maintenance (TPM) programs, perfect attendance, reliable part supply and and information are required.	Information delay refers to the delay between when a production signal is transmitted and when the signal is received and acted upon. By conveying products with production signals, such as kanban cards, info. delay is minimized.	Lot delay refers to parts waiting on other parts in the lot before they are transported together. This is avoided with single piece transport. Reducing transportation distance is important to achieve this.	Process delay occurs when arrival rate > service rate (unbalanced rates). Large and unpredictable inventory levels are indicative of process delay. It is reduced by balancing to a constant and predictable takt time. Flexibility to produce to different takt times keeps system balanced when demand changes.	Delay due to inventory when producing different part types. Setup time is the time to change between part types within a station. Knowledge of the part types required is necessary or large inventories of different parts are required. With accurate and timely info, only the parts required are produced.	To reduce transportation delay, the amount of transportation should be minimized. In system design, this is a consideration in factory layout. This is also applicable from a geographical view as well as within the plant	Operational delays are routine disruptions designed into the system (processes stopping for maintenance, material replenishment and other processes). They may be eliminated through machine and station design (Chip removal, control access from rear of station), operator work routine design.
Time between occurrence and resolution of disruptions	**Number of disruptions & amount of time lost to disruptions**	**Time from info. transmitted or requested until info. received**	**Inventory due to lot size delay**	**Inventory due to process delay**	**Inventory due to run size delay**	**Inventory due to transportation delay**	**Production time lost due to interference among resources**
% on-time deliveries		**Difference between mean throughput time and customer's expected lead time**					
<< Sales revenue							
<< Profit from manufacturing >>							
<< Rate of NPV growth >>							

Aerospace Manufacturing System Design Evaluation Tool, Plant C (3 of 3)

<< FR: Increase shareholder value / DP: Growth of company's Net Present Value			
<< FR: Increase manufacturing profitability / DP: Manufacturing system design and operation			
FR: Minimize manufacturing costs / DP: Elimination of non-value adding sources of cost			Minimize investment over production system lifecycle
Reduce wasted processing	Reduce wasted use of employees	Reduce cost of procured materials	
Processes designed without regard for # of steps. Overly complex or precise processing methods selected.	One person, one machine design - operator watches machine run. Excessive walking to search for tools and materials. Excessive operator motions.	Arms-length relationships between suppliers and customers. Design decisions made from a single-company perspective. Minimal information transfer.	Investment decisions based solely on immediate needs. Long-term product and volume flexibility requirements not considered.
Processes designed with a bias towards too many steps or overly complex methods. Attempts are not made to improve both.	Operator runs single machine, does "fill-in" work between cycles. Excessive walking req'd to obtain tools and mat'ls not located at point of use. Excessive operator motions.	Arms-length relationships between suppliers and customers. High-level design meetings occur only at beginning of project. Info. transfer limited to critical requirements.	Investment decisions focus on meeting short-term business needs. NPV analyses may be used for some long-term projects.
Process design attempts to reduce # or complexity and precision of processing, but the result is unbalanced towards too many steps or overly complex methods.	Operator may run more than one of the same type machine. Workers isolated to stations to avoid walking. Poor ergonomics causes worker to constantly reposition themselves.	Loosely-linked supply chain. Multi-level design meetings occur throughout project. Information protected and transfers limited to critical requirements and non-proprietary info.	Investment decisions seek to maximize NPV, but long-term projects frequently preempted by short-term needs.
Process design generally balances # and complexity of mfg. steps. Several non-value adding or excessively complex steps have been identified, but can't be eliminated.	Operator can run multiple machines of different types. 5S program implemented so that parts, tools, equipment are where required. No operator- process work routine defined.	Integrated supply chain. Suppliers and customers meet frequently to discuss product and mfg. system design. Most information is available to enterprise members.	Investment decisions focus on maximizing NPV. Long-term projects occasionally scaled back because of short-term needs.
Process design balances the # and complexity of manufacturing steps. Few if any non-value adding or excessively complex steps remain.	Multi-skilled operators run several machines/ processes.Machines are small and close to reduce walking distances (in cells.) Operator-process work routine graphs used.	Integrated supply chain. Representatives from suppliers and customers sit on design teams to provide input. Information is available throughout the enterprise.	Investment decisions heavily influenced by NPV analyses. Long-term goals rarely sacrificed to meet short term requirements.
The minimum # and complexity of processing steps have been selected. Reducing steps further would add significant cost to the product.	Number of operators can be varied to achieve range of takt times. Machines run autonomously. Level 5 applied through company. 5S understood & used beyond shop floor.	Highly integrated supply chain. Product and mfg. system design decisions made by teams that cross company borders. Free flow of Information throughout enterprise.	Investment decisions based upon thorough NPV analyses. Decisions allow company to fulfill short and long term requirements.
Wasted processing steps are any steps that do not add value to the final product. Excessive transportation, overly tight tolerances, and unnecessary features are all examples of wasted processing steps.	Wasted use of employees includes operators waiting for machines to finish cycling, walking excessive distances, searching for tools and materials, and poor ergonomics.	Reducing the cost of procured materials requires developing close partnerships with suppliers and integrating them into the overall manufacturing system. Sharing information between suppliers and integrators increases opportunities for improvement and cost reduction.	Companies operating in a fast-changing environment can reduce the NPV of future investments by making a large up-front investing in a highly flexible mfg. system. This flexibility may be wasted, however, for companies that operate in more stable environments and therefore will not require frequent system design changes.
# of wasted processing steps	% employee time spent on non-value adding activities	Cost of procured materials	Investment over system lifecycle
Manufacturing costs			
<< Profit from manufacturing			
<< Rate of NPV growth			

Appendix F: AMSDD FRs and DPs

FR		DP		Intention
FR	Increase shareholder value	**DP**	Growth of company's Net Present Value	Identify and satisfy a company's top-level goal
FR-0	Fund projects with a positive Net Present Value	**DP-0**	Capital allocated to projects with positive Net Present Value	Only select and fund projects that will increase the company's value.
FR-1	Increase manufacturing profitability	**DP-1**	Manufacturing System Design and Operation	In order to increase the profitability of a company's manufacturing system, the system must be designed, not allowed to evolve haphazardly. After being designed, the manufacturing system must be operated in the manner in which it was designed.
FR-11	Maximize sales revenue	**DP-11**	Products that maximize customer satisfaction	To maximize sales revenue, as a result of actions taken within the manufacturing system, a company must deliver products that maximize customer satisfaction.
FR-111	Improve product design and manufacturing	**DP-111**	Continuous improvement process (Kaizen)	In order to incorporate lessons learned in the manufacturing system and feedback from customers and employees, a continuous improvement process must be implemented.
FR-F1	Incorporate customer feedback	**DP-F1**	Customer feedback process	In order to obtain and implement customer feedback, a process must be developed to solicit feedback and apply it to the manufacturing system design.
FR-F2	Incorporate employee feedback	**DP-F2**	Employee feedback process	In order to obtain and implement employee feedback, a process must be developed to solicit feedback and apply it to the manufacturing system design.
FR-112	Deliver products that meet customers' requirements	**DP-112**	Product design process	To ensure that the manufacturing system produces products that meet the customers' requirements, a process for designing products is required.
FR-D1	Design products that can be manufactured	**DP-D1**	Integrated product and manufacturing system design	To ensure manufacturability of products, the manufacturing system must be designed in conjunction with the product design

FR		DP		Intention
FR-D11	Design stable processes	**DP-D11**	Equipment and part feature selection	To ensure that manufacturing processes are stable requires selecting the proper equipment and designing features on parts for stable processing
FR-D111	Design equipment for high process yield	**DP-D111**	Selection / development of manufacturing processes	To ensure a high process yield requires selecting the correct manufacturing process or developing a new process if necessary.
FR-D112	Design products for high process yield	**DP-D112**	Specification of tolerances that can be achieved	To ensure that manufacturing processes have high yields, part specifications should be achievable by the selected processing methods.
FR-D12	Design products for defect-free fabrication and assembly	**DP-D12**	Product designs facilitate use of mistake-proofing devices	Products should be designed with common features, shapes, etc., to facilitate the use of mistake-proofing devices during part fabrication and assembly.
FR-D2	Design products that satisfy external requirements	**DP-D2**	Products confrom to government / industry standards	Products must meet government and industry standards to satisfy requirements external to customer specifications
FR-D3	Accommodate future changes in product design	**DP-D3**	Standard method to incorporate new features into design	In order to upgrade and improve product designs, a standard method for incorporating design changes must be developed. (I.e., incorporate a block of changes after *x* products have been manufactured.)
FR-D4	Design products the customer can afford	**DP-D4**	Minimum material and processing costs	To reduce the cost of products, the minimum possible material and processing costs should be pursued
FR-D41	Reduce processing requirements	**DP-D41**	Standardized part designs	By using common part designs across product families, setups and the unique number of processing steps can be reduced
FR-D42	Specify affordable components and materials	**DP-D42**	Preferential use of "Off the shelf" parts and commodity raw materials	Attempting to use components and materials that are readily available helps reduce product cost.
FR-D43	Specify affordable processes	**DP-D43**	Simple processing requirements	By reducing the complexity of processing steps and processing equipment, overall processing becomes less expensive.

FR		DP		Intention
FR-D431	Reduce processing complexity	**DP-D431**	Parts designed to minimize processing requirements	To reduce the complexity of processing steps, parts should be designed to minimize processing requirements. This may involve reducint the number of steps, duration of processing, etc.
FR-D432	Reduce cost of processing equipment	**DP-D432**	Simple processing equipment	To reduce the cost of the processing equipment, simple machines that achieve only the required functions should be selected.
FR-113	Manufacture products to target design specifications	**DP-113**	Production processes with minimal variation from the target	To manufacture products to their design specifications, production processes should have little variation from the processing target.
FR-Q1	Operate processes within control limits	**DP-Q1**	Elimination of assignable causes of variation	To ensure that manufacturing processes stay within the control limits, assignable causes of variation must be eliminated
FR-Q11	Eliminate machine assignable causes	**DP-Q11**	Failure mode and effects analysis	To eliminate machine assignable causes, a failure mode and effects analysis should be performed. The results should be used to prevent errors from impacting product quality.
FR-Q12	Eliminate operator assignable causes	**DP-Q12**	Stable output from operators	To eliminate operator assignable causes, operators must produce stable output.
FR-Q121	Ensure that operator has knowledge of required tasks	**DP-Q121**	Training & certification program	To ensure that each operator is knowledgable in the tasks that they must perform, they must complete a training and certification program.
FR-Q122	Ensure that operator consistently performs tasks correctly	**DP-Q122**	Standard work methods	To ensure that every operator always performs tasks correctly, standard work methods should be specified for each process.
FR-Q123	Ensure operator human errors do not translate to defects	**DP-Q123**	Mistake proof operations (Poka-Yoke)	To ensure that human errors do not produce defective products, processes should be designed to prevent operators from making an error in the first place.
FR-Q13	Eliminate method assignable causes	**DP-Q13**	Process plan design	To ensure that processing methods minimize processing variation, care must be taken when designing the processing plans.

FR		DP		Intention
FR-Q14	Eliminate material assignable causes	**DP-Q14**	Supplier quality program	To ensure that incoming parts do not have defects, companies should work with suppliers to improve the suppliers' quality.
FR-Q2	Center process mean on the target	**DP-Q2**	Process parameter adjustment	Manufacturing processes should be adjusted so that the process mean is the same as the process target.
FR-Q3	Reduce variation in process output	**DP-Q3**	Reduction of process noise	To reduce variation in the output of a process, the process noise must be reduced.
FR-Q31	Reduce noise in process inputs	**DP-Q31**	Conversion of common causes into assignable causes	To reduce the incoming noise to a process, the noise components must be identified and converted to assignable causes, so that they can be eliminated.
FR-Q32	Reduce impact of input noise on process output	**DP-Q32**	Robust process design	To reduce the impact of input noise on a process, a robust process that is insensitive to incoming noise should be selected.
FR-114	Deliver products on time	**DP-114**	Throughput time variation reduction	To deliver products in the required time, the variation in manufacturing system throughput times must be reduced.
FR-R1	Respond rapidly to production disruptions	**DP-R1**	Procedure for detection & response to production disruptions	When there is a disruption in the manufacturing system, it must be detected and responded to quickly
FR-R11	Rapidly recognize production disruptions	**DP-R11**	Subsystem configuration to enable operator's detection of disruptions	The manufacturing system should be designed to quickly alert operators to production disruptions.
FR-R111	Identify disruptions when they occur	**DP-R111**	Frequent sampling of part status	Parts should be checked frequently so that a disruption will be found soon after it has occurred.
FR-R112	Identify disruptions where they occur	**DP-R112**	Simple flow paths	Simple flow paths allow the location of disruptions to be quickly identified, because there is no confusion about where the disruption has occurred.
FR-R113	Identify what the disruption is	**DP-R113**	Context sensitive feedback	When a disruption is detected, the equipment or operator should provide specific information rather than simply indicating that a problem exists.

FR		DP		Intention
FR-R12	Communicate problems to the right people	**DP-R12**	Process for feedback of operation's state	The manufacturing system must be able to communicate the status of operations to the correct resources that can solve problems.
FR-R121	Identify correct support resources	**DP-R121**	Specified support resources for each failure mode	To prevent confusion and speed notification of the correct resource, resources should be assigned for each type of problem.
FR-R122	Minimize delay in contacting correct support resources	**DP-R122**	Rapid support contact procedure	A system should be developed to contact the correct support resource quickly when a problem occurs. This could include lights above equipment and electronic pagers.
FR-R123	Minimize time for support resource to understand disruption	**DP-R123**	System that conveys what the disruption is	When support resources are notified about disruptions, the notification system should provide them with specific information about the problem.
FR-R13	Solve problems immediately	**DP-R13**	Problem resolution plan	A predetermined method should exist for quickly solving problems.
FR-R131	Eliminate root cause	**DP-R131**	Standard method to identify and eliminate root cause (5 Why's)	A standard method of identifying and eliminating the root cause of problems should be used to ensure that the correct cause(s) is/are identified.
FR-R132	Minimize response delay from support resources	**DP-R132**	Maintenance & engineering resources located on plant floor	Maintenance and engineering resources should be located on the plant floor to minimize the time required to respond to disruptions.
FR-R133	Ensure problems do not recur	**DP-R133**	Trend analysis	Analyzing trends helps to ensure that the true root cause has been identified and that there is not an additional cause remaining to be addressed.
FR-P1	Minimize production disruptions	**DP-P1**	Predictable production resources (people, equipment, info)	To minimize the number of production disruptions requires predictable resources in the manufacturing system.
FR-P11	Ensure availability of relevant production information	**DP-P11**	Capable and reliable information system	To ensure that production information is up to date and correct, a capable and reliable information system is required.
FR-P12	Ensure tools & supplies are available	**DP-P12**	Standard inventory of tools & supplies	To ensure that tools and supplies are readily available to production workers, a standard inventory of these items should be maintained

FR		DP		Intention
FR-P13	Ensure predictable equipment output	DP-P13	Maintenance of equipment reliability	To ensure that equipment output remains predictable, the equipment must be well maintained.
FR-P131	Ensure that equipment is easily serviceable	DP-P131	Machines designed for serviceability	To facilitate servicing equipment, the equipment should be designed with consideration for required access, replacement, and repair of components.
FR-P132	Service equipment regularly	DP-P132	Regular preventive maintenance program	Equipment should be serviced regularly by scheduling regular preventive maintenance activities so that problems are fixed before they occur.
FR-P14	Ensure predictable worker output	DP-P14	Motivated work-force performing standard work	To ensure that workers perform predictably and well, the workforce should be motivated and perform standard work.
FR-P141	Reduce variability of task completion time	DP-P141	Standard work methods to provide repeatable processing time	To reduce the variation in manual processing times, workers should perform tasks in a standardized, repeatable manner.
FR-P142	Ensure availability of workers	DP-P142	Corporate programs that provide for employee work/life needs	To ensure worker attendance and reduce tardiness, companies must provide for employees' work and life needs, rather than focus solely on job performance.
FR-P143	Do not interrupt production for worker allowances	DP-P143	Mutual Relief System with cross-trained workers	Production should not stop when a worker is temporarily unavailable. Cross-trained employees should be able to fill in for a missing co-worker.
FR-P15	Ensure material availability	DP-P15	Standard material replenishment system	To ensure that material is available when it is needed, a standard replenishment system must be developed.
FR-P151	Ensure that parts are available to the material handlers	DP-P151	Standard work in process between sub-systems	To ensure that parts are always available for conveyance between sub-systems, a standard amount of work in process (WIP) should be maintained.
FR-P152	Ensure proper timing of part arrivals	DP-P152	Parts moved to downstream operations according to pitch	To ensure the proper arrival of parts, all parts should be moved to the next downstream operation in the quantity and time interval determined by pitch.

FR		DP		Intention
FR-115	Meet customer expected lead time	**DP-115**	Mean throughput time reduction	In order to provide customers with products as quickly as the customer demands them, the mean throughput time through the manufacturing system must be reduced.
FR-T1	Reduce information delay	**DP-T1**	Information integrated with work (visual factory, kanban system)	To reduce the delay between information being generated within the manufacturing system and information becoming available, the information should be integrated with work. Examples are a visual factory and use of kanban.
FR-T2	Reduce lot delay	**DP-T2**	Reduction of transfer batch size (single-piece flow)	To reduce the delay between processing lots, batch sizes should be reduced. The ideal batch size is one piece.
FR-T3	Reduce process delay (caused by $r_a > r_s$)	**DP-T3**	Production designed for takt time	To reduce the amount of time products spend waiting for processing, the manufacturing system should be designed to operate at takt time.
FR-T31	Define takt time(s)	**DP-T31**	Definition or grouping of customers to achieve takt times within an ideal range	In order to define takt time(s) within a manufacturing system, customers should be grouped so that the takt times fall within an acceptable range for a range of demand levels.
FR-T32	Ensure that production cycle time equals takt time	**DP-T32**	Subsystem enabled to meet the desired takt time (design and operation)	To ensure that the production cycle time equals takt time, subsystems must all be capable of meeting the takt time.
FR-T321	Ensure that automatic cycle time <= minimum takt time	**DP-T321**	Design of appropriate automatic work content at each station	To ensure that the cycle time of automated operations is less than takt time, the duration of work allocated to automatic operations must be less than or equal to takt time.
FR-T322	Ensure that manual cycle time <= takt time	**DP-T322**	Design of appropriate operator work content/loops	To ensure that the cycle time of manual operations is less than takt time, the duration of work allocated to manual operations must be less than or equal to takt time.
FR-T323	Ensure level cycle time mix	**DP-T323**	Staggered production of parts with different cycle times	Production of parts with different cycle times should be staggered so that the average cycle time is less than or equal to the takt time.

FR		DP		Intention
FR-T4	Reduce run size delay	DP-T4	Production of the desired mix and quantity during each demand interval	To reduce the delay between different product types, the entire mix of product demand should be produced during each demand interval.
FR-T41	Provide knowledge of demanded product mix (part types and quantities)	DP-T41	Information flow from downstream customer	To know what products should be produced in the manufacturing system, production information must be drawn from the downstream customer.
FR-T42	Produce in sufficiently small run sizes	DP-T42	Quick changeover for material handling and equipment	To enable the manufacturing system to produce in small run sizes, equipment and material handling must be capable of quick changeovers.
FR-T5	Reduce transportation delay	DP-T5	Material flow oriented layout design	To reduce the delay associated with material transportation, the manufacturing system should be laid out according to material flow.
FR-T6	Reduce systematic operational delays	DP-T6	Subsystem design to avoid production interruptions	To reduce delays that occur as a result of required operations in the manufacturing system, subsystems should be designed to avoid interruptions.
FR-T61	Ensure that support resources don't interfere with production resources	DP-T61	Subsystems and equipment configured to separate support and production access req'ts	Routine support tasks, such as chip removal, equipment lubrication and material replenishment, should not interfere with production. Access requirements and equipment should be designed to prevent these disruptions.
FR-T62	Ensure that production resources (people/ automation) don't interfere with one another	DP-T62	Coordination and separation of production work patterns	Production activities should be designed and coordinated so that people and equipment do not interfere with one another.
FR-T63	Ensure that support resources (people/ automation) don't interfere with one another	DP-T63	Coordination and separation of support work patterns	Support activities should be designed and coordinated so that people and equipment do not interfere with one another.
FR-12	Minimize manufacturing costs	DP-12	Elimination of non-value adding sources of cost	To minimize manufacturing costs, non-value adding sources of cost must be eliminated.

FR		DP		Intention
FR-121	Reduce wasted processing	**DP-121**	Elimination of non-value adding processing steps	To reduce the amount of unecessary processing, non-value adding processing steps should be eliminated.
FR-122	Reduce wasted use of employees	**DP-122**	Elimination of non-value adding tasks	To improve employee productivity, tasks that do not add value to the product or company should be eliminated.
FR-C1	Eliminate operators' waiting on machines	**DP-C1**	Human-Machine separation	Operators should not waste their time waiting on individual machines.
FR-C11	Reduce time operators spend on non-value added tasks at each station	**DP-C11**	Machines & stations designed to run autonomously	To reduce the amount of time operators spend on non-value adding tasks at each machine, equipment should be designed to run without human supervision once it has been loaded and the cycle begins.
FR-C12	Enable worker to operate more than one machine / station	**DP-C12**	Workers trained to operate multiple stations	Workers should be trained to operate multiple stations so that they are not tied to a single machine.
FR-C2	Eliminate wasted motion of operators	**DP-C2**	Design of workstations / work-loops to facilitate operator tasks	Operator motions should be designed to minimize waste and facilitate required tasks.
FR-C21	Minimize wasted motion of operators between stations	**DP-C21**	Machines / stations configured to reduce walking distance	To limit the amount of time operators waste moving between stations, stations should be located close to each other.
FR-C22	Minimize wasted motion in operators' work preparation	**DP-C22**	Standard tools / equipment located at each station (5S)	To minimize wasted motion when preparing to work, tools and equipment should have standard locations close to the point of use.
FR-C23	Minimize wasted motion in operators' work tasks	**DP-C23**	Ergonomic interface between the worker, machine and fixture	To minimize the wasted motion of operators while they perform tasks, work stations and equipment should be designed with an ergonomic interface.
FR-C3	Eliminate operators' waiting on other operators	**DP-C3**	Balanced work-loops	To prevent operators from waiting for other operators to finish tasks, balanced work-loops should be designed to ensure each operator finishes at the same time.

FR		DP		Intention
FR-C4	Improve effectiveness of production managers	DP-C4	Self directed work teams (horizontal organization)	To improve the effectiveness of managers, self directed work teams should be empowered to resolve a wide variety of common issues.
FR-13	Minimize investment over manufacturing system lifecycle	DP-13	Investment strategy to reduce investment over manufacturing system lifecycle	To minimize the total investment required over a manufacturing system's lifecycle, a long-term investment strategy should be used.
FR-I1	Reduce cost of future investments	DP-I1	Manufacturing system adaptability matched to expected market demands	To reduce the cost of future investments, manufacturing systems should be designed to adapt to the expected market demands over the system lifecycle.
FR-I11	Match adaptability to product design changes to expected market demands	DP-I11	Manufacturing equipment designed to accommodate product design changes	Manufacturing equipment should be designed to accommodate product design changes according to expected market demands.
FR-I12	Match adaptability to new products to expected market demands	DP-I12	Manufacturing system designed to accommodate new products	The manufacturing system should be designed to accommodate new products according to expected market demands.
FR-I13	Match adaptability to production volume changes to expected market demands	DP-I13	Manufacturing system designed to accommodate production volume changes	The manufacturing system should be designed to accommodate changes in production volume that correspond to expected market demands.
FR-I2	Reduce cost of initial investment	DP-I2	Reduction of excess over-capacity	To reduce the initial investment in a manufacturing system, excessive over-capacity in the system should be eliminated.