A Decomposition-Based Approach for Manufacturing System Design

by

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ABSTRACT

The design of manufacturing systems is a complex task that requires many people to cooperate and communicate at various organizational levels. Companies often change the design of their manufacturing systems by using "off-the-shelf" solutions, such as U-formed manufacturing cells, without relating those solutions to overall system objectives. These ad hoc changes seldom have a formal process to guide them.

This thesis contributes to the development of a manufacturing system design framework that satisfies five objectives: (1) it clearly separates objectives from means of achievement, (2) it relates low-level activities and decisions to high-level goals and requirements, (3) it states interrelationships among different elements of a system design, (4) it provides a common platform to effectively communicate this information across the organization, (5) it guides the designers through all stages of the system design. The framework is based on a recently developed Manufacturing System Design Decomposition (MSDD).

This thesis reports on a multiple case-study research program that validates and modifies the MSDD. This research program led to the creation of a questionnaire that guides the systematic investigation and critical analysis of manufacturing systems. The reliability of this questionnaire has been tested successfully with Cronbach's Alpha factor.

The thesis describes four groups of case studies that show how the MSDD provides a powerful tool to analyze the strengths and weaknesses of existing manufacturing systems. In addition, the thesis uses the MSDD to derive new manufacturing system designs. It shows that the MSDD is equally applicable across industry, manufacturing processes, production volume, and company size. The research in this thesis proves theoretical and literal replication of the premises stated in the MSDD. A database is developed to provide a graphical interface for the use of the MSDD, for documenting system design projects, and for analyzing the questionnaire. Modifications to the MSDD are recommended, based on the case studies. The thesis provides a basis for future research to integrate existing manufacturing system design methodologies with the MSDD.

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Committee Member: Professor Sara Beckman
Committee Member: Professor Stephen Graves
Committee Member: Professor David Hardt

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List of Acronyms

AGV	Automatic Guided Vehicle
AS/RS	Automated Storage and Retrieval System
CIM	Computer Integrated Manufacturing
CIMOSA	CIM Open System Architecture
CNC	Computer Numerical Control
CT	Cycle Time
DM	Design Matrix
DP	Design Parameter
e.g.	Exempli Gratia (for example)
ERP	Enterprise Resource Planning
EWIP	Emergency Work In Process
FMS	Flexible Manufacturing System
FR	Functional Requirement
GIM	GRAI Integrated Method
GRAI	Graphe a Resultats et Activities Interlies
i.e.	Id Est (that is)
ILVS	In Line Vehicle Sequence
JIT	Just In Time
MRP	Material Requirements Planning
MSDD	Manufacturing System Design Decomposition
OM	Operations Management
PERA	Prudue Enterprise Reference Architecture
PM	Performance Measure or Preventive Maintenance
ROI	Return On Investment
SCORE	Structured Company Operational Review & Evaluation
SMED	Single Minutes Exchange of Die
SPC	Statistical Process Control
SWIP	Standard Work In Process
TPM	Total Productive Maintenance
TPS	Toyota Production System
TQM	Total Quality Management
TSSC	Toyota Supplier Support Center
UE	United Electric
VDI	Verein Deutscher Ingenieure
VSM	Value Stream Mapping
WIP	Work In Process

Chapter 1 Introduction

Manufacturing is one of the most important contributors to economic wealth. Even though the service sector tends to steadily grow in Western economies, half of the jobs in the US are still tightly coupled to manufacturing [Hopp and Spearman, 1996]. Global competition forces Western companies to streamline their manufacturing operations. In addition, customer requirements are becoming more demanding in terms of higher product variety, shorter product life cycles, faster delivery times, and better quality. Companies have to design efficient manufacturing systems to meet those customer requirements.

The design of manufacturing systems is an inherently complex task. It starts with the definition of system requirements and ends with operation of the system. Many people from various organizational levels and disciplines have to cooperate to create and operate a successful manufacturing system. However, research studies provide evidence that most manufacturing system design is done in an ad-hoc fashion without applying a design process that supports the achievement of the system requirements. Although numerous tools and methods are available to support the design process, it often is not possible to integrate the various tools into a comprehensive manufacturing system design methodology. This thesis develops a manufacturing system design framework with the potential to combine existing manufacturing system design methodologies.

1.1 Motivation

Several studies find that industry tends to follow loosely defined procedures to carry out the task of manufacturing system design. There is a particular lack in defining and communicating design requirements and objectives across the organization [Hopp & Spearman, 1996, Wu, 2000].

Manufacturing strategy frameworks clarify system requirements at an abstract level. The frameworks define high-level system requirements and provide guidance for the selection of general system configurations such as job shop or manufacturing cells [Hayes &

Wheelwright, 1979, Miltenburg, 1995]. However, the frameworks do not help to break those high-level requirements into more detailed objectives.

Designing a manufacturing system in the absence of defined system requirements often leads to unsatisfactory system performance. A recent trend in industry is to transform the shop floor towards "lean" manufacturing. Companies tend to copy established "lean tools" such as U-form manufacturing cells and kanban systems [e.g., Sekine 1999]. The "lean tools" are often seen as generic solutions to contemporary manufacturing problems [Zipkin, 1991]. Few authors, however, point out the necessity to view these practices in the context of the whole system [Japan Management Association, 1986, p.23]. To address this need, Suzuki of TRW developed a framework relating the "lean tools" to objectives in order to understand the objectives those tools are trying to achieve [Suzuki, 1999].

A large amount of research has been done to understand the Toyota Production System (TPS). Hence, many frameworks attempt to support designers in the design of a manufacturing system that can copy the manufacturing efficiency observed at Toyota. The frameworks focus on operational aspects of a manufacturing system and build upon tools and concepts associated with Toyota. The frameworks often do not relate those tools to system requirements. Conceptual designs are considered as a given based on Toyota's approach. As a result, industry often copies those tools out of system context as discussed above.

Manufacturing system design in industry often starts with a rough layout scheme, which divides the plants into sub-systems such as machining and assembly. The design of the sub-systems is often a replication of existing system designs without a clear definition of system requirements. The advantage of copying existing lines could be that a company gradually improves their systems by incorporating gained knowledge [Kreafle, 2001]. However, many companies lack a formal process to capture such knowledge [Grant, 1996]. As a result, manufacturing engineers often copy existing system designs without knowing the original objectives that led to the existing design.

During more detailed design phases, manufacturing engineers are often assigned to specific tasks such as the selection of a specific machine. The engineers are often not able to relate their design decisions to the overall system. A translation of high-level system requirements to lower-level design decisions and vice versa is often not possible. Consequently, there is a tendency to optimize single operations rather than the system as a whole.

Value Stream Mapping (VSM) has recently become a widely used tool in industry. VSM is a very valuable and useful tool to support manufacturing system design particularly during early design phases, when general relationships between sub-systems are defined. However, VSM does not support the detailed system design and does not consider human aspects of manufacturing systems.

System designers have a large choice among various tools that support the manufacturing system design task. However, those tools are often difficult to link with each other. It would be desirable to develop a manufacturing system design framework that better facilitates the connection of existing tools. Such a framework would guide practitioners through all stages of manufacturing system design and operation without losing the system perspective.

1.2 Problem Statement

To summarize, there is a need to develop a comprehensive framework that can guide practitioners through all stages of manufacturing system design. Starting with the definition of system requirements, the framework must be able to link design decisions at various stages to those requirements. It is desirable that the framework is able to make use of existing tools for manufacturing system design. Those tools should be linked with each other to avoid local optimization.

It is believed that the framework should satisfy the following requirement:

- clearly separate system design objectives from design solutions
- relate low-level activities and decisions to high-level goals and requirements
- state the interrelationships among the different elements of a system design
- provide a common platform to effectively communicate this information across the organization
- integrate existing tools for manufacturing system design

- guide practitioners from system design to operation.

1.3 Scope of Research

This thesis develops a manufacturing system design framework that satisfies the requirements outlined above in three steps.

- Development of the Manufacturing System Design Decomposition (MSDD).
- Validation and modification of the MSDD.
- Outline of an application process based on the MSDD.

The MSDD uses axiomatic design to articulate a general set of objectives and means for manufacturing systems. The MSDD provides a structure for relating the many elements of manufacturing systems and for linking low-level design decisions to high-level system objectives. Four case studies test whether or not the MSDD provides a useful framework for manufacturing system design. The first case study compares three plants producing plastic bumpers for the automotive industry. The study shows how well the MSDD can explain performance differences among observed manufacturing systems. The second case study applies the MSDD in one of the bumper production plants to test how well the MSDD can support system designers. The third study examines two distinctive line designs for the assembly of electronic products within the same company. The strength and weaknesses of both systems are explained with the help of the MSDD. Furthermore, the case study develops improvement suggestions for the two line designs based on the premises stated in the MSDD. The last case study applies the MSDD to analyze a value stream in a medium-sized family owned company that manufactures automatic process controllers for pressure and temperature. The company is known to have a very efficient manufacturing system. Thus, the case study uses the MSDD to see how well it captures the positive aspects of the manufacturing system design.

A data collection tool based on the MSDD is developed to standardize the compilation of observations made during the case studies. A software tool is created to provide a graphical user interface for the use of the MSDD, document system design projects and to support the analysis of the observations.

1.4 Organization of Thesis

This thesis begins with a review of existing approaches to manufacturing system design. The review categorizes the various approaches by relating them to a general systems engineering process. Then follows a discussion of manufacturing system design in practice. Chapter 3 reviews existing research methodologies and defines the applied research framework of this thesis. The fourth chapter describes in detail the MSDD, which builds the basis for the remaining part of the thesis. The research framework outlined in Chapter 3 requires a standard way to evaluate a system relative to the MSDD and to relate observations to the MSDD in a repeatable manner. The chosen means for the data collection is a form of questionnaire based on the MSDD, which is described in chapter 5. Chapter 6 describes the four groups of case studies. Chapter 7 summarizes the findings of the case studies, and makes suggestions for improvements and modifications to the MSDD. Chapter 8 suggests how other manufacturing system design approaches can be linked to the MSDD. Chapter 9 summarizes the work performed and identifies future research areas.

Chapter 2 Literature Review

2.1 Introduction

Reviewing the vast body of literature in manufacturing system design is a daunting challenge. Manufacturing system design incorporates numerous research disciplines ranging from manufacturing strategy to detailed process engineering.

This literature review is based on a belief that manufacturing system design must apply systems engineering methods to manage the complexity of the design task [Wu, 1992, Hitomi, 1996]. The chapter therefore begins with a review of systems engineering and discusses its application to manufacturing system design. Existing frameworks and methodologies of manufacturing system design are then reviewed and related to the systems engineering process. After describing examples of manufacturing system design in practice, the chapter concludes with a summary and motivation for the research in this thesis.

2.2 Systems Engineering

2.2.1 Definition of Systems and Systems Engineering

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

Systems engineering is basically a structured approach to think about and work with systems. Wu describes it as a generic problem solving cycle [Wu, 2000, p. 126]. Hitomi finds four characteristics of systems engineering in the literature [Blanchard and Fabrycky, 1998, p.23]:

(1) A *top-down approach* that examines how individual system elements work together to influence overall system performance. The bottom-up approach is complementary in that it deals with individual elements first and then considers the relationships among the elements. Both, the top-down and bottom-up approaches assume that systems are hierarchical in nature. (2) A *life-cycle* orientation that addresses all phases of a system from conceptualization, rough design, detailed design, and operation to phase out. (3) System design starts with the definition of *system requirements*, relates these requirements to design decisions, and performs system evaluations relative to the requirements. (4) System design requires an *interdisciplinary* approach to understanding and handling the system complexity.

A systems engineering process describes the engineering tasks that support and specify all activities through the phases of a system life cycle. Figure 2-1 illustrates the systems engineering process [Blanchard & Fabrycky, 1998, p.26]. The process moves from left to right in iterative steps, not sequential.

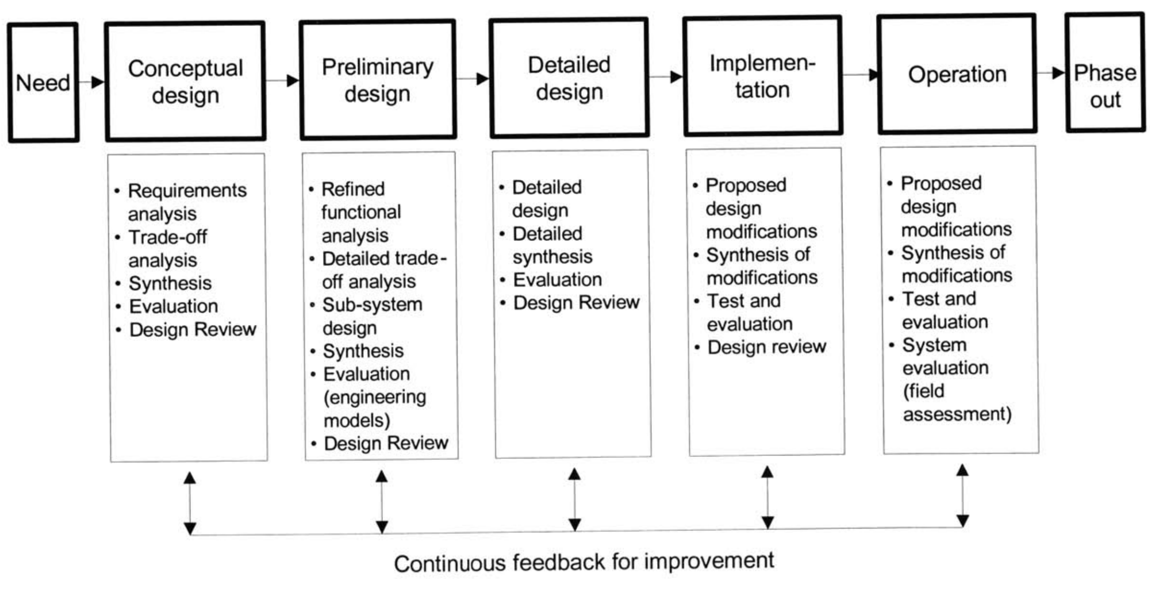


FIGURE 2-1: GENERAL SYSTEMS ENGINEERING PROCESS [ADAPTED FROM BLANCHARD & FABRYCKY, 1998, P.26].

The process highlights several important aspects of systems engineering:

- Systems exist to fulfill a purpose. System requirements must be defined.
- Systems are hierarchical in nature and can be divided into sub-systems.
- Systems are designed and improved over time until the system is phased out.
- Three tools are commonly used throughout the system design process: synthesis, analysis, and evaluation.

Synthesis refers to the selecting and combining of system components in such a way that the defined system requirements can be satisfied [Blanchard, Fabrycky, 1998, p.67]. Synthesis occurs in every phase of the systems engineering process as the system design becomes more and more specific. Synthesis is essentially a creative process to satisfy defined requirements. Analysis develops system requirements, performs feasibility studies, and defines evaluation measures. Evaluation occurs after synthesis and assesses how well system requirements have been satisfied.

System design essentially applies the systems engineering process to create a "useful system (static structure and operating procedure) under a specified evaluation criterion by the use of scientific disciplines" [Hitomi, 1996, p. 30]. Note that the systems engineering process also includes the operation of the system and does not end with implementation.

The following paragraphs discuss the characteristics of manufacturing systems and explain how the systems engineering process can be applied to manufacturing system design.

2.2.2 Definition of Manufacturing System and Manufacturing System Design

Definition of Manufacturing System

There is no generally shared definition of manufacturing systems [see e.g., Arinez, 2000, p. 27]. However, there are common elements among the definitions found in literature: the *purpose* of manufacturing systems is to convert inputs into outputs by processing material. The *elements* of manufacturing systems are *resources* such as people, equipment, material and information. The resources are linked by *relationships* enabling material and information to flow through the system. The relationships represent the *organization* of the system.

The boundary of the manufacturing system is not always included in the definitions. Cochran distinguishes manufacturing systems and production systems. Production systems include the manufacturing system along with functions such as marketing, finance, and product development [Cochran, 1994]. The manufacturing system can therefore be seen as the shop floor of a manufacturing enterprise.

A working definition of manufacturing systems for this thesis is as follows [adapted from Cochran, 1994, Chryssolouris, 1992, Wu, 1992]:

> Manufacturing systems consist of people, machines, tools, material, and information, which are related to each other to produce a value-added product.

Definition of Manufacturing System Design

Manufacturing system design must integrate the many elements of a manufacturing system into a smoothly functioning whole. It starts with the definition of the system requirements and ends with the operation of the system.

Given the broad meaning of manufacturing system and the numerous elements it consists of, it is not surprising to find an even broader understanding of manufacturing system design. Wu and Hitomi emphasize the need to apply systems engineering approaches to design manufacturing systems [Wu, 2000, Hitomi, 1996]. Wu starts with the definition of enterprise objectives, which are then translated into the physical arrangement and the operation of the system. Black focuses on the physical layout of the operations and the material flow [Black, 1991]. Kettner provides a detailed step-by-step procedure from goal definition to detailed physical layout to implementation [Kettner et al., 1984]. The GRAI method concentrates on developing decision support for conceptual and preliminary design phases [Doumeingts et al., 1993].

Arinez [2000] categorizes manufacturing system design definitions found in literature into four types: (1) layout and structural organization of physical elements, (2) procedural design approaches providing a sequence of interrelated design activities, (3) decision process, (4) system control. Each type focuses on particular aspects of the system engineering process by limiting the scope of manufacturing system design (e.g., to layout, control).

As stated in the outset of this chapter, manufacturing system design must apply a systems engineering approach to structure the complexity of the relationships of manufacturing systems. Therefore, a general definition of manufacturing system design should not be limited to a single aspect of system engineering relative to manufacturing, but should include all aspects. Figure 2-2 illustrates activities in each phase of the system engineering process applied to manufacturing system design.

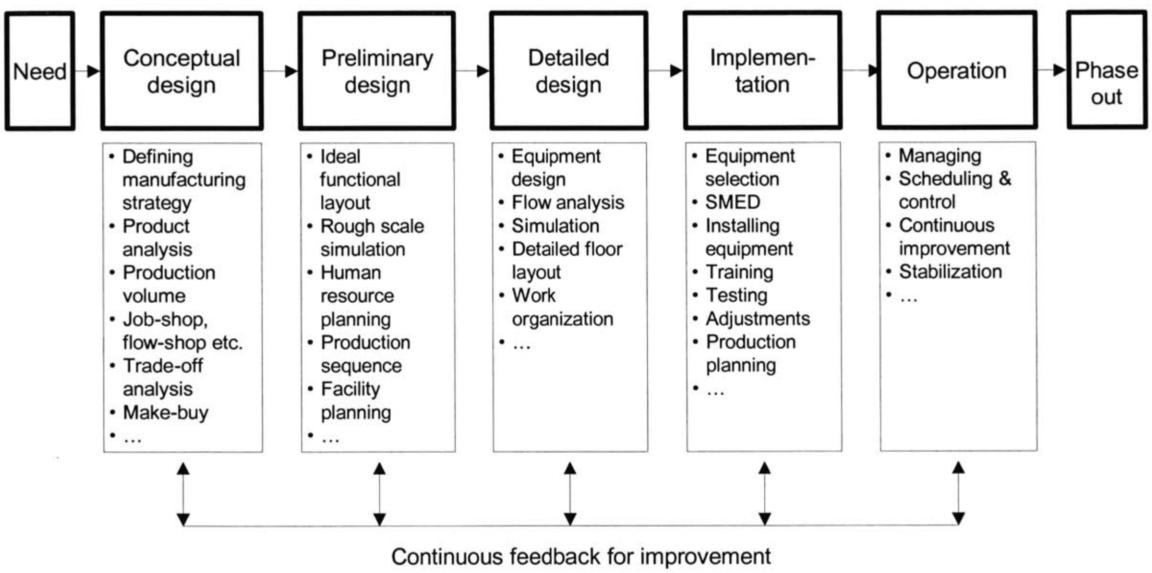


FIGURE 2-2: SYSTEMS ENGINEERING PROCESS APPLIED TO MANUFACTURING SYSTEMS.

A working definition of manufacturing system design for this thesis is as follows:

> Manufacturing system design applies a system engineering process to create and operate a manufacturing system from the definition of the system needs and requirements to the phase out of the system.

With this working definition in mind, the following section reviews existing approaches to manufacturing system design and relates them to the systems engineering process. Approaches can be methods, methodologies, frameworks, or special tools. The goal of the review is to examine the strengths and limitations of existing approaches relative to the task of manufacturing system design.

2.3 Manufacturing System Design Approaches

2.3.1 Manufacturing System Reference Architectures

Within the context of manufacturing systems, a reference architecture is a set of models which describe what a manufacturing system consists of and how it functions [Williams et al., 1993]. Most architectures focus on control aspects and try to systemize decision making in manufacturing systems. This section reviews three reference architectures and relates them to the overall systems engineering process.

PERA

The Purdue Enterprise Reference Architecture (PERA) provides a framework for examining manufacturing system design from the definition of enterprise objectives to the design of individual tasks [Williams, 1993]. PERA, using a process that is similar to the engineering process presented above, distinguishes five phases: concept phase, definition phase, design phase, installation phase, and operations phase. PERA links an information architecture and a manufacturing architecture with a human-organization architecture. Although PERA provides a useful framework to convey the complexity of manufacturing systems, the overall application process remains undefined.

GRAI Method

The Graphe a Resultats et Activites Interlies (GRAI) reference model has been developed to provide a general description of a manufacturing system with the focus on system control [Doumeingts et al., 1993]. The model distinguishes three sub-systems of manufacturing systems: the *physical system* transforms material etc. into output products, the *decision* system ensures that the system objectives are met, the *information system* contains all information the decision system needs. The goal of the GRAI model is to structure the design and analysis of manufacturing systems in the early design phases. The GRAI model uses two main tools: GRAIgrid is a top-down approach to identify decision centers. Decision centers are functional areas (planning, purchasing etc.) that make decisions to coordinate the system. GRAIgrid determines the time horizon in which decisions are made relative to a predefined set of functions. The second tool, GRAInet, is a bottom-up approach to model activities and decisions made in the system. The GRAI model is useful in designing the control structure of systems with the focus on computerized solutions.

A recent extension of GRAI is the GRAI Integrated Method (GIM), which applies existing tools such as IDEF0 to integrate decision, information and physical systems. It is unclear how GRAI can be applied to the physical design aspects of manufacturing systems [Wu, 1992]. It is also unclear whether the model can be applied without the extensive use of computer modeling.

CIMOSA Model

The goal of CIMOSA is to model business processes and enterprise objects of a CIM environment [Vernadat, 1993]. The main function of CIMOSA is to develop an executable model of some part(s) of the enterprise and then use the model to control the CIM system operations. It is focused on the logical (i.e. control) part of manufacturing systems and provides only limited support for the physical design. Tools of the framework are designed to capture system requirements in a structured way. High-level requirements are decomposed into lower-level activities.

Summary of Reference Architectures

The architectures provide a general framework for manufacturing system design and operation. CIMOSA and GRAI are computer oriented and focus primarily on control and decision aspects of manufacturing systems. PERA in contrast is a conceptual framework for applying systems engineering to manufacturing systems, but it does not provide tools for the different systems engineering phases. All three architectures provide a relatively complete view of an enterprise life cycle. However, more detailed tools are needed to accomplish the full challenge of manufacturing system design.

2.3.2 Conceptual Design Frameworks

The purpose of conceptual design frameworks is to clarify system requirements at an abstract level. The frameworks define manufacturing strategy criteria and translate those criteria into requirements for the conceptual and preliminary system design phases. With respect to system engineering, the frameworks support the first two phases as illustrated in Figure 2-3.

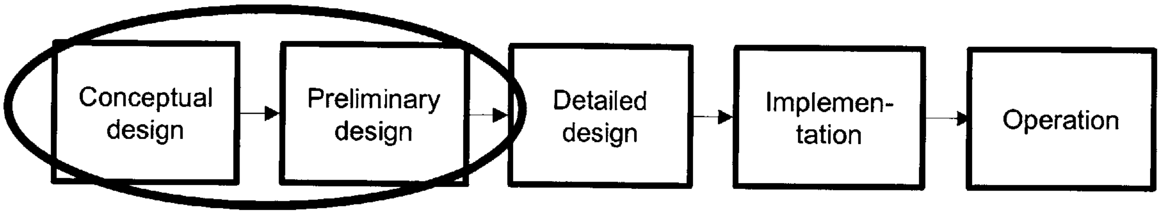


FIGURE 2-3: FOCUS OF CONCEPTUAL DESIGN FRAMEWORKS RELATIVE TO SYSTEMS ENGINEERING PROCESS.

The literature distinguishes general types of manufacturing system configurations. A manufacturing system configuration may be defined as a manufacturing (sub-)system at a general, conceptual level [Duda, 2000, p.163]. A configuration is the result of general decisions about equipment selection and arrangement, material flow, and control. No decisions regarding work descriptions, tool design etc. are made yet. The most commonly cited configurations are: project shop, job shop, FMS, manufacturing cells, transfer lines, and continuous processing lines [e.g., Hayes and Wheelwright, 1984, Kettner et al., 1984, Black, 1992, Askin, 1993, Miltenburg, 1995].

A *project shop* is used for large immobile parts such as ships, buildings etc. All needed parts and machines are brought to the product. *Job shops* group equipment into departments e.g., drilling department, milling department. Each product produced in a job shop has a unique path through the manufacturing system. Product flexibility is very high, scheduling is often subject to frequent changes, and inventory levels are high. A *flexible manufacturing system* (FMS) is a highly automated configuration of CNC controlled equipment with automated material handling. Direct labor is limited, since routing, machining and material handling is fully automated. FMS usually consists of 3-10 machines. *Manufacturing cells* are designed for a family of similar parts. Group technology is frequently used to determine families. Parts of similar size and shape can often be processed by a similar set of processes. Manufacturing cells are often associated with the Toyota production system [Shingo, 1989]. Manufacturing cells are usually not fully automated. Operators perform material handling and processing. Manufacturing cells are applicable for machining and assembly. *Transfer line* or *flow lines* involve a series of stations often arranged in a straight line, to produce a single part. The configuration is most effective when justified by low product mix and high production volume. Material movement in flow lines is usually automated. *Continuous processing lines* refer to non-discrete manufacturing processes such as in refineries.

The following paragraphs review several frameworks, which help system designers to determine the type of configuration most appropriate in a given context and relates the frameworks to the systems engineering process.

Hayes and Wheelwright [1984] developed the well-known product-process matrix showing how system configurations relate to production volume and mix (see Figure 2-4). Hayes and Wheelwright state that elements on the diagonal are most suitable to satisfy companies' needs.

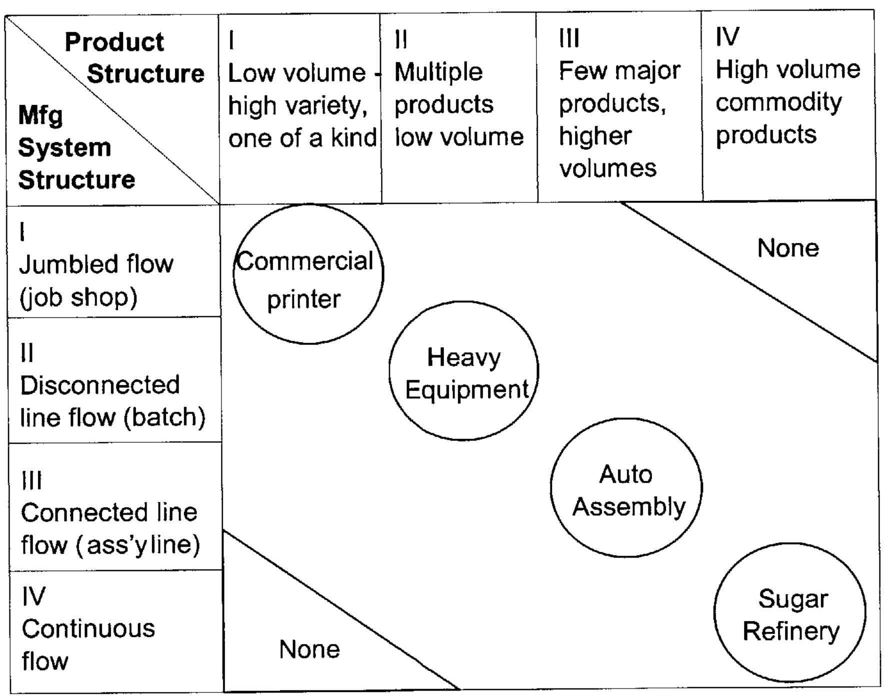


FIGURE 2-4: PRODUCT-PROCESS MATRIX [ADAPTED FROM HAYES AND WHEELWRIGHT, 1984]

Miltenburg [1995] extended the process-product matrix by strategic objectives (delivery, cost, quality etc.) and manufacturing levers (human resources, organization structure etc.) as shown in Figure 2-5.

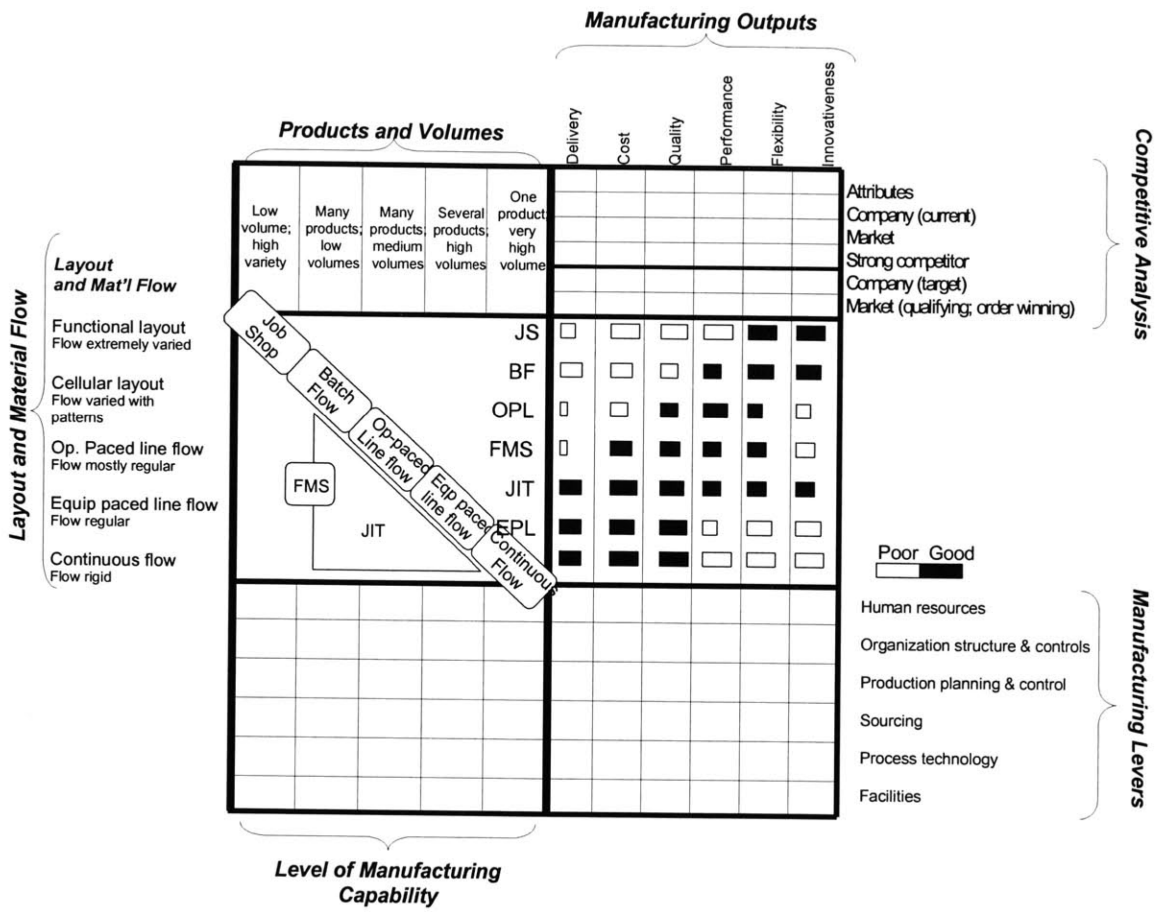


FIGURE 2-5: FRAMEWORK FOR SELECTING A MANUFACTURING STRATEGY [MILTENBURG, 1995]

The framework is very useful in analyzing the present position of a company and deriving an improvement strategy. It shows the impacts on manufacturing systems of strategic decisions such as increasing production volume or changing production technology. A shortcoming of the framework is that it treats the configurations as discrete choices and does not provide guidance on how to combine advantages of different configurations. The framework also does not assist the actual design of the manufacturing system, as it is limited to high-level strategic choices.

Other authors offer similar correlations between production volume and mix and system configuration [e.g., Black, 1991, Reinhardt, 2000]. The relationships, however, are only useful for a very high-level selection of possible configurations. First, there is significant overlap between the different configurations as shown in Figure 2-6. Second, many existing manufacturing systems show characteristics of several configurations. Third, it is assumed that basically two variables (production volume and mix) are the main determinants for the system configuration.

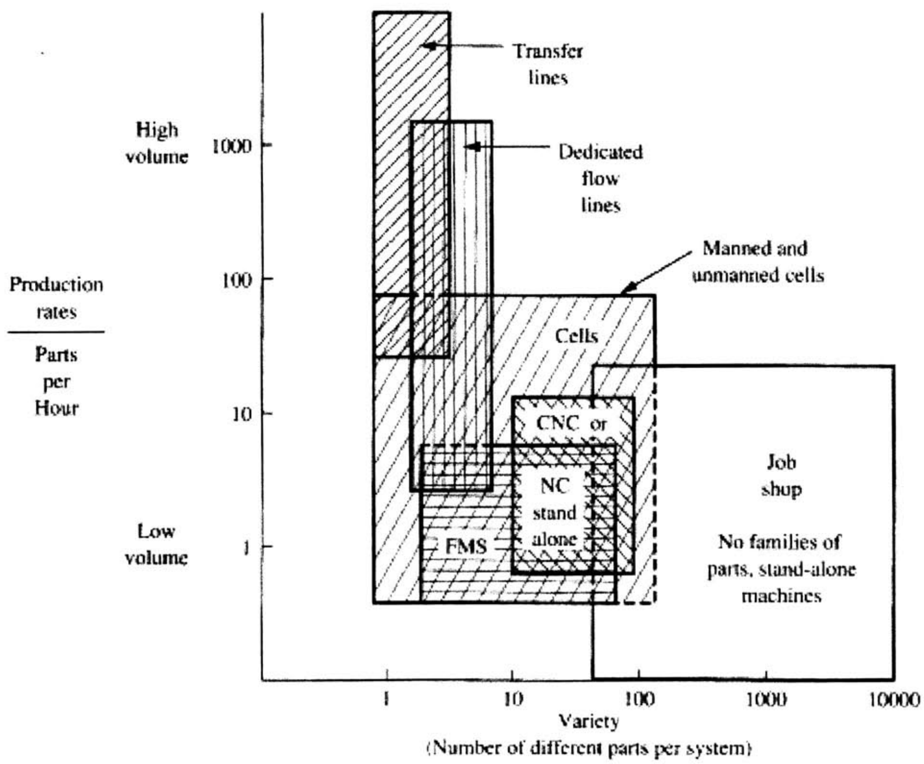


FIGURE 2-6: RELATIONSHIP BETWEEN PRODUCTION RATE / MIX AND SYSTEM CONFIGURATION [BLACK, 1991, P. 46]

2.3.3 Frameworks for Detailed Planning and Operation

2.3.3.1 Toyota Production System

The Toyota Production System (TPS) has greatly influenced the research of manufacturing system design over the last 10 to 20 years. Many books on TPS have been published since the 1980s [e.g., Monden, 1983; Hall, 1983; Japan Management Association, 1986]. However, interest in academia and industry to understand the success of TPS has increased greatly since the publication of "The Machine that Changed the World " [Womack, Jones, Ross, 1990]. The book coined the term "lean production" in describing TPS and made the success of the TPS well known across the world. Another term frequently used to describe TPS is Just-In-Time production [Schonberger, 1982, Sakakibara, 1993].

Lean production describes a broad set of management and manufacturing methods commonly used at Toyota. A tendency is to categorize lean tools into best practices such as Kanban, SMED and U-shaped manufacturing cells [e.g., Sekine 1999]. Few authors, however, point out the necessity to view these practices in the context of the whole system: "One cannot discuss the kanban system out of context. If anyone tries to imitate that system without regard to all the factors contributing to its success, then his efforts will be in vain" [Japan Management Association, 1986, p.23]. Other authors present the means of lean manufacturing as a universally applicable solution to manufacturing problems [Black, 1991, Schonberger, 1990].

Many companies have tried to implement those means with varying degrees of success [e.g., Liker, 1998; Cusumano, 1992]. Academia developed frameworks and design approaches to understand the underlying principles of lean production and to allow transferability within industry [e.g., Monden, 1983; Sakakibara, 1993; Spear & Bowen, 1999].

The following paragraphs review TPS-related research with respect to the systems engineering process.

TPS Framework

Sakakibara et al. [1993] developed a framework for Just-in-Time (JIT) manufacturing. The core Just-In-Time manufacturing framework is shown in Figure 2-7. The framework is based on academic and practitioner literature and provides a valuable summary of research with respect to the Toyota Production System. The upper and lower parts of the framework show how manufacturing strategy, management, and organizational aspects interrelate with each other. The main focus of the framework is on the middle part and deals with continuous improvement and problem solving activities.

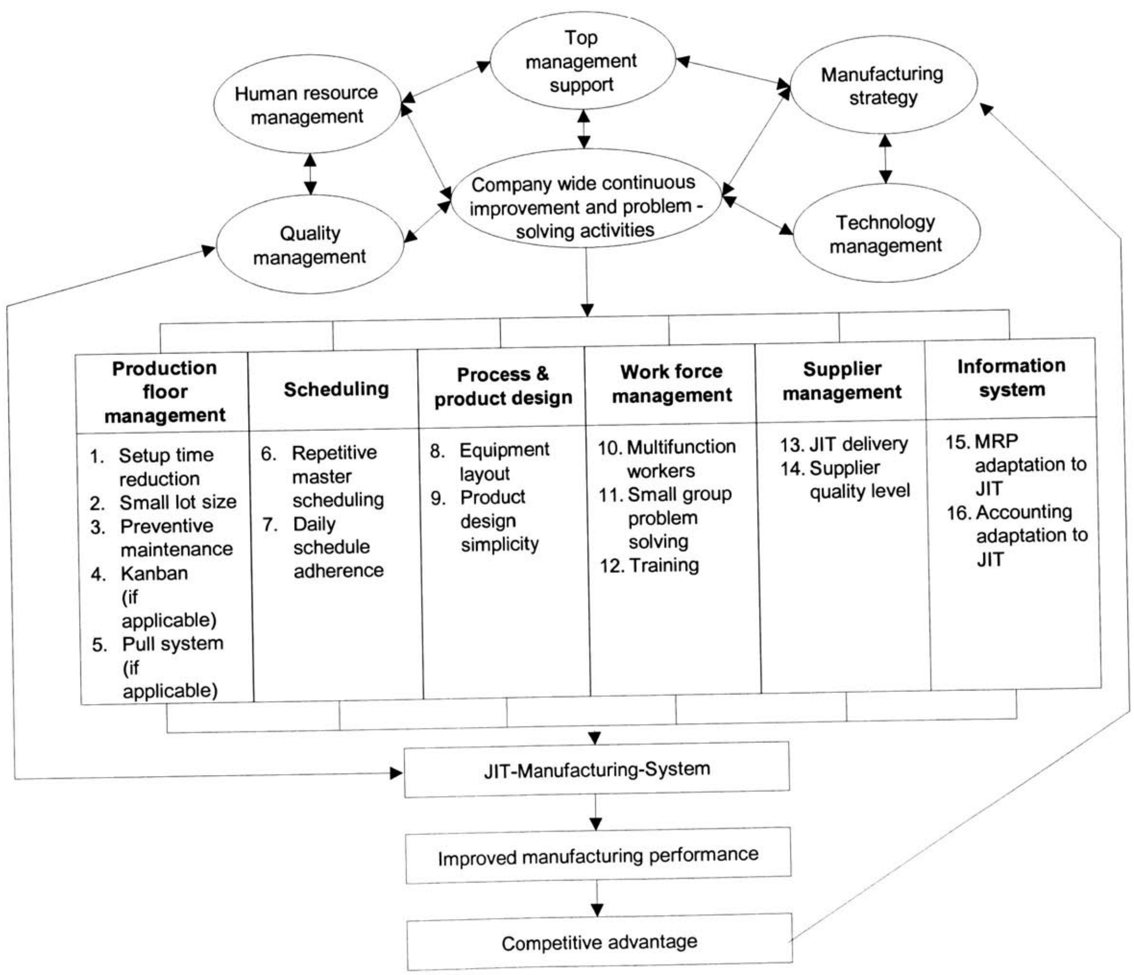


FIGURE 2-7: CORE JUST-IN-TIME MANUFACTURING FRAMEWORK [SAKABIBARA ET AL., 1993].

The framework highlights an important issue: most TPS related research deals with implementation and operational issues of the systems engineering cycle. Very little attention is paid to early phases of systems engineering such as the formulation of requirements, preliminary design synthesis and analysis, and system evaluation. Sakakibara et al. [1993] also note that most research on JIT has been empirical and descriptive.

JIT Measurement Instrument (Sakakibara et al.)

Sakakibara et al. expanded the core JIT manufacturing framework shown in Figure 2-7 to a measurement instrument by formulating 16 practices usually associated with JIT manufacturing. The measurement instrument consists of a questionnaire, which allows companies to evaluate their performance relative to the depicted practices. In terms of the systems engineering process, most practices are related to the implementation and operational phase, except for one scale that measures accounting practices. The questionnaire was sent to 41 plants in three industries. The analysis of the survey determined three underlying factors of the sixteen practices: management of people and schedule, simplified material flow, and supplier management. Those factors could be seen as high-level objectives to be achieved by the manufacturing system.

The JIT research and measurement framework provides a valuable tool to evaluate system performance relative to key factors of TPS. The framework suggests that implementing the depicted 16 practices will eventually lead to a high performing manufacturing system. However, the framework does not show how the practices depend on each other and how the system must be designed to achieve good performance relative to the practices.

Toyota Production System Framework by Monden

Monden developed a framework of the Toyota production system based on detailed studies of Toyota plants in Japan. Monden relates basic methods and concepts observed at Toyota and develops a sequence, in which those elements should be implemented (Figure 2-8). The intent of the framework is to show relationships between system goals and means. The idea is to start with the means at the bottom and to move upward to achieve the ultimate goal of increasing profits.

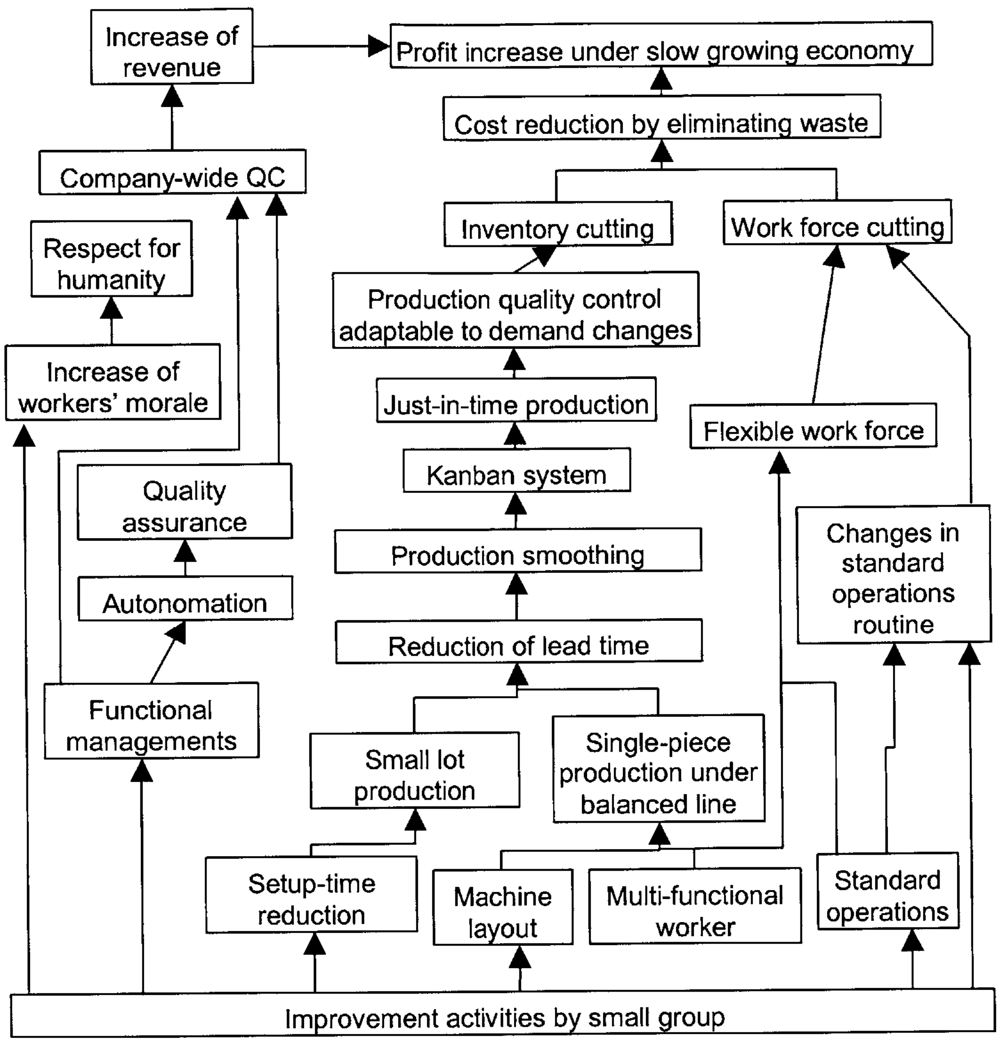


FIGURE 2-8: IMPLEMENTATION STEPS FOR TOYOTA PRODUCTION SYSTEM [MONDEN, 1998, P.328]

The framework shows clearly that single elements cannot be implemented isolated from their prerequisites. For example, a kanban system requires small lot production, which requires short setup times and multi-functional workers. This view is in vast contrast to a statement by Schonberger that a kanban system "can be installed between any successive pair of processes in 15 minutes, using a few containers and masking tape" [Schonberger, 1990].

Monden provides a bottom-up approach for manufacturing system design based on methods and concepts observed at Toyota. The framework is useful in clarifying the interrelationships between those concepts. However, the distinction between means and goals is unclear. It seems that all lower-level elements shown in Figure 2-8 are means to achieve the ultimate goal of increasing profits. In terms of system engineering, Monden's framework focuses on detailed design and operational aspects of system design by taking Toyota's conceptual design as given.

Blanchard et al. point out that bottom-up methodologies are based on known elements, whose physical presence is assured. However, bottom-up methodologies cannot guarantee that high-level system requirements are being met simply because the known elements are implemented [Blanchard, Fabrycky, 1998, p. 28]. That is, following Monden's framework in successively implementing elements of the Toyota production system does not necessarily achieve a profitable manufacturing system. It is therefore unclear how well Monden's framework can support a systemic design of manufacturing systems as it lacks the clear definition of requirements. Cochran classifies objectives and means of TPS and argues that Monden mixes both in his framework [Cochran, 1994].

Lean Production Framework (Suzuki)

Suzuki of TRW Japan faced the challenge to transform his company's plants towards TPS style manufacturing. TRW worked together with the Toyota Supplier Support Center (TSSC). As a result, Suzuki created a lean production framework shown in Figure 2-9 to better understand the relationships between the tools associated with TPS. Suzuki followed a bottom-up approach by categorizing the TPS tools and deriving three higher-level objectives, which are supported by the tools: cost control, delivery control, and quality control.

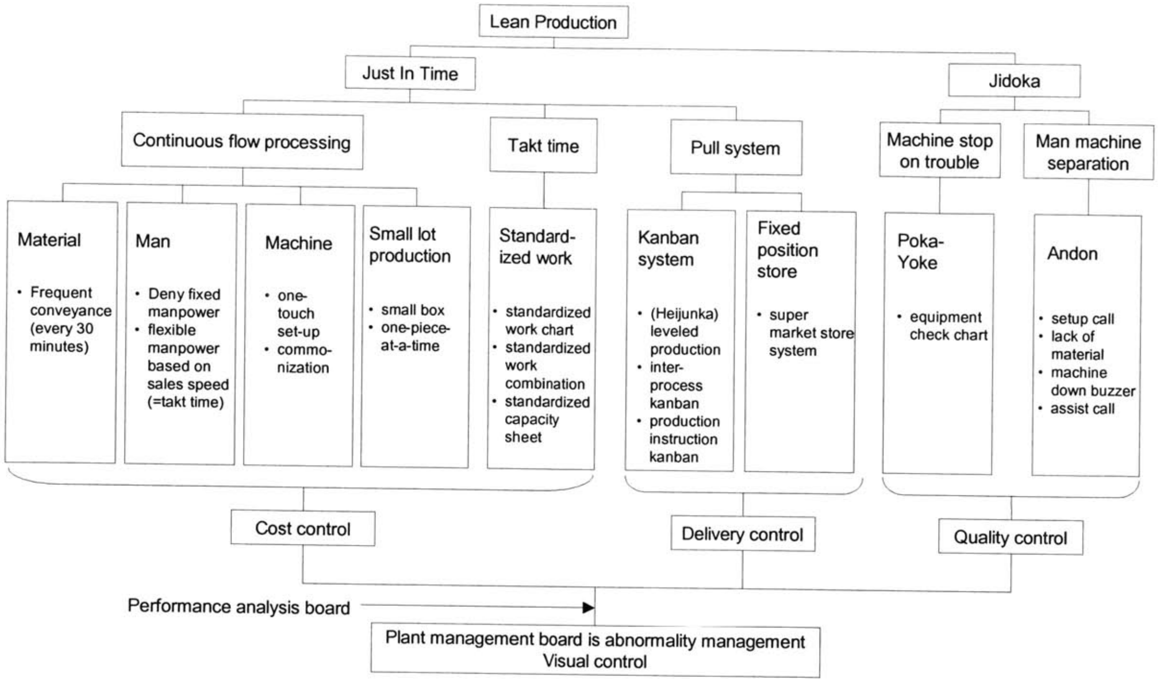


FIGURE 2-9: LEAN PRODUCTION FRAMEWORK [SUZUKI, 1999]

According to discussions with Suzuki, the framework enabled him to understand why particular tools should be used. The approach underlines the need of stating system requirements and the means to achieve the requirements.

TPS as Rule-Based Manufacturing (Spear & Bowen)

In spite of existing frameworks such as Monden's, which explain the mechanics of the Toyota production systems, many companies still struggle in implementing TPS. Spear and Bowen researched Toyota plants from the organizational point of view. They believe that one reason for unsuccessful copying of TPS is that companies do not adapt the overall philosophy [Spear, Bowen, 1999]. Spear concluded that "the Toyota production system can be codified as Rules-in-Use that guide the design, operation, and improvement of activities, connections, and flow paths" [Spear, 1999, p.105]. Spear stated four rules:

Rule 1: All work shall be highly specified as to content, sequence, timing, and outcome.
Rule 2: Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses.
Rule 3: The pathway for every product and service must be simple and direct.

Rule 4: Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.

The elements usually associated with TPS (kanban, manufacturing cells, leveling) are merely visual manifestations of applying the four rules. Spear and Bowen provide examples showing the four rules at work in daily operations. All participants in the system must understand and follow the rules. Knowledgeable people or *Sensei*, who teach the rules through frequent and structured problem solving, are a critical part of the system.

Spear's findings contribute to understanding how Toyota can sustain and further develop the success of its production system. The emphasis on tacit knowledge inherent in the Toyota organizations explains why implementing merely physical design solutions (e.g., manufacturing cells) will not be lead to the same effect as within Toyota.

From the system engineering perspective, the rules are mostly related to the operational phase with limited interaction to earlier phases. The rules do not guide the design of manufacturing systems, but rather provide a framework for continuous improvement once the system is implemented. Furthermore, it is unclear how the tacit knowledge underlying the rules can be established in companies considering the prerequisite of a Sensei.

Summary of TPS Related Frameworks

TPS related research is mostly empirical and descriptive [Sakakibara et al., 1993]. The frameworks discussed here attempt to help system designers create a manufacturing system that can emulate manufacturing efficiency of the system observed at Toyota.

In terms of systems engineering, the focus of the frameworks is on operational aspects of system design including some considerations of detailed planning as illustrated in Figure 2-10. The frameworks build upon tools and concepts associated with Toyota and do not necessarily relate those tools to system requirements. Conceptual designs are considered as a given based on the Toyota's approach.

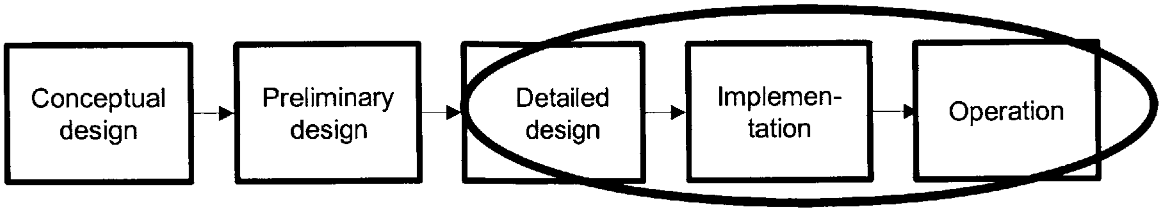


FIGURE 2-10:TPS RELATED RESEARCH AND FRAMEWORKS RELATIVE TO SYSTEMS ENGINEERING PROCESS.

2.3.3.2 Value Stream Mapping

Value Stream Mapping (VSM) has recently become a widely used tool in industry. It consists of set of symbols and steps to illustrate material and information flow in manufacturing systems and to derive improvements. "Value stream mapping is a qualitative tool by which you describe in detail how your facility should operate in order to create flow" [Rother, Shook, 1998, p. 4].

A value stream encompasses all processes and steps - both value added and non-value added - to produce a final product from raw material to the outside customer. The material flow shows all material movements from and to processes, inventories, inspection etc. The information flow illustrates the coordination of the material flow.

The goal of VSM is to look at the whole rather than at individual processes. A standard set of symbols that VSM uses provides a common language for discussions about the system. Creating a value stream map facilitates cross-departmental discussions, since all participants of the value stream must express how their activities tie into the conversion flow.

The main focus is on illustrating relationships between processes in terms of material and information flow. A value stream map shows some limited process information such as cycle time, changeover time, shift pattern etc. Possible improvements are derived from the value stream map to help achieve a smooth material flow.

VSM is a very valuable and useful tool to support manufacturing system design, particularly during the early design phases, when general relationships between sub-systems are defined. In terms of systems engineering, VSM covers a broad range of tasks with the main focus on preliminary design as shown in Figure 2-11. It influences detailed design and operational phases insofar as it is used to derive recommendations and improvements. However, VSM does not provide a formal process for the physical design of manufacturing systems.

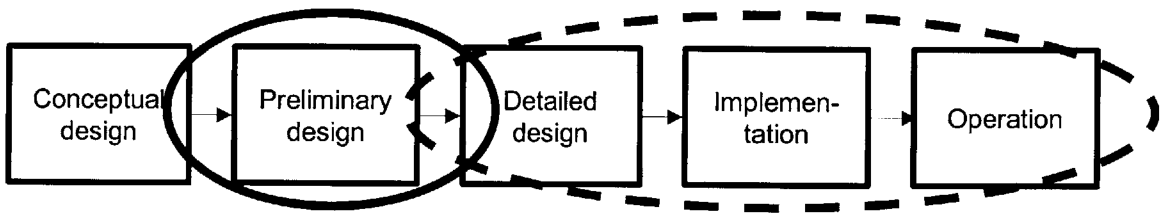


FIGURE 2-11: THE FOCUS OF VALUE STREAM MAPPING IS ON DEFINING RELATIONSHIPS BETWEEN SUBSYSTEMS.

2.3.3.3 Manufacturing Objective Hierarchy (Hopp & Spearman)

Hopp and Spearman generated a hierarchy of manufacturing objectives to achieve high profitability in manufacturing organizations. The hierarchy shown in Figure 2-12 focuses on operational practices such as reduction of variability, utilization considerations, service rate, and inventory. The two high-level goals of low costs and high sales lead to conflicting practices at lower levels. For example: low inventory is desirable to reduce costs, while high inventory ensures meeting delivery demands to achieve high sales; A large number of different products supports high sales, but a low number of different products reduces costs.

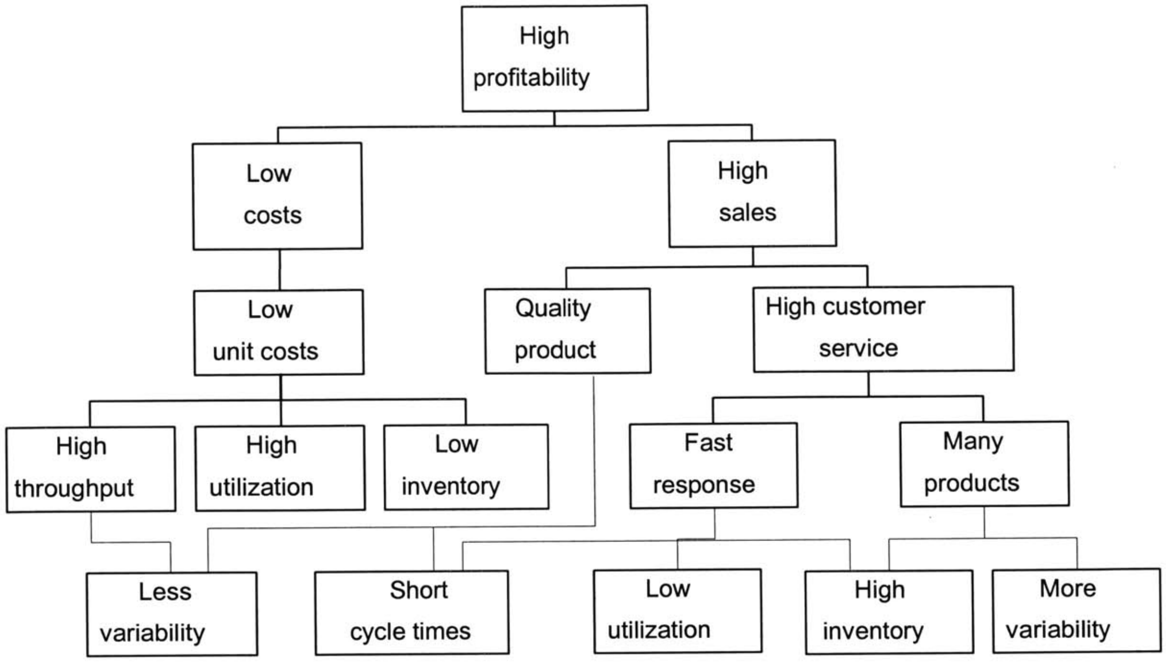


FIGURE 2-12: DECOMPOSITION OF HIGH PROFITABILITY FOR MANUFACTURING SYSTEMS [HOPP & SPEARMAN, 1996, P.200]

The hierarchy is not intended to be a manufacturing system design framework. It illustrates how operations management relates to overall manufacturing system objectives. Furthermore, the hierarchy points out the presence of trade-offs in the operation of manufacturing systems.

2.3.3.4 Factory Design Procedures (Kettner)

System design procedures provide a detailed step-by-step guide for factory design. The approach presented by Kettner is one of the standard procedures in German research and industry [Kettner et al., 1984]. Other similar approaches can be found [Aggteleky, 1970, Felix, 2000].

The goal of the procedure is to provide a logical sequence and time sequence of main planning steps for designing a factory. Kettner subdivides the tasks into six phases as shown in Figure 2-13 and describes supportive tools for each phase such as organization charts, layout planning tools, workstation design.

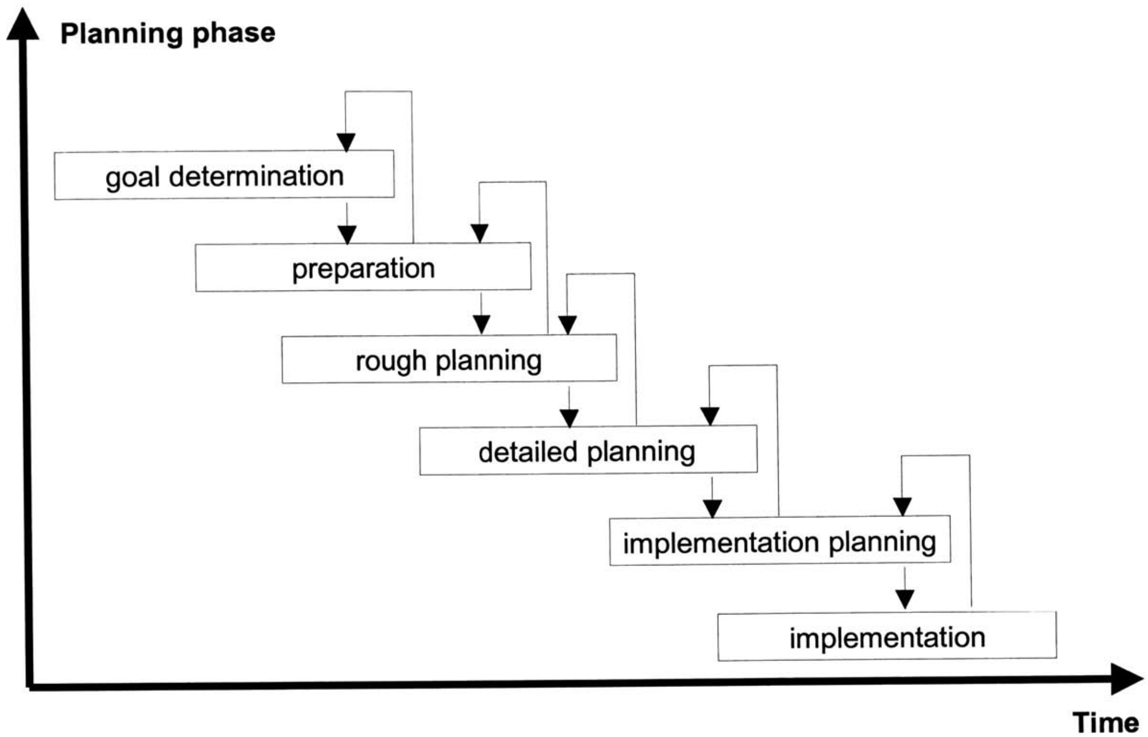


FIGURE 2-13: FACOTRY DESIGN PROCEDURE [KETTNER ET AL., 1984]

The procedure is very comprehensive and covers all systems engineering phases except the operational phase. The general structure is very intuitive in the way that it divides the complex task of factory design into different phases with an increasing level of detail. However, the procedure fails to provide linkages between the phases making it difficult to understand how decisions at later design phases affect the achievement of requirements from earlier phases.

2.3.3.5 Manufacturing and Supply Chain Management (Wu)

Wu developed a framework that attempts to provide a unified approach to the design and operation of manufacturing and supply systems [Wu, 2000]. The overall structure of the framework is shown in Figure 2-14. It consists of three main areas: Manufacturing and supply Strategy Analysis (MSA), Manufacturing and supply System Design (MSD), and Manufacturing and supply System Operation (MSO). The overlap between the three areas represents three additional functions: MSA/MSD interfacing, MS implementation, and MS status monitoring. In addition, Wu defines three layers or architectures that overlay all three areas: physical or manufacturing and supply architecture, human and organizational architecture, and information and control architecture.

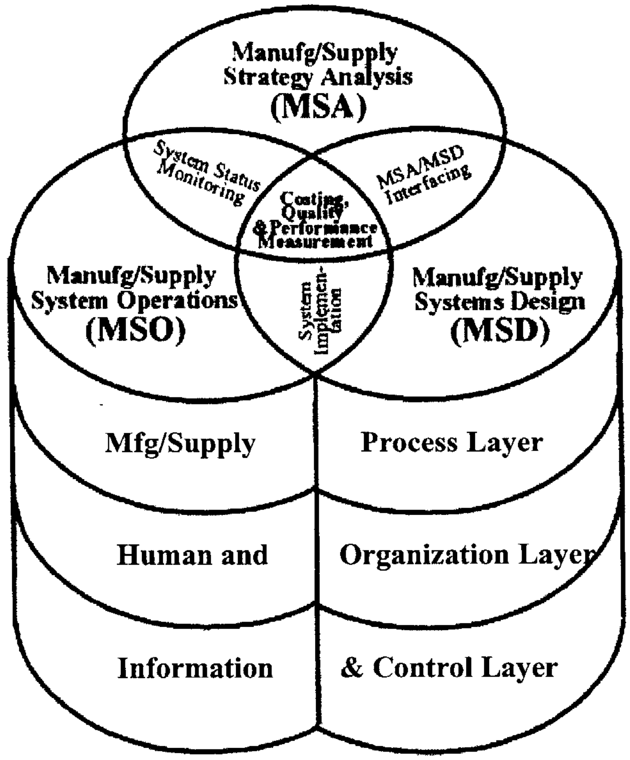


FIGURE 2-14: STRUCTURE OF UNIFIED MANUFACTURING SYSTEM MANAGEMENT FRAMEWORK [WU, 2000, P. 126].

MSA supports the company to analyze its products, market, operation and to determine the strategic positioning of the company. MSD determines the best structure of a manufacturing system in order to support the strategic objectives. MSO performs plan, monitor and control functions and reflects activities normally associated with MRP/ERP systems.

The overall framework represents a comprehensive aggregation of manufacturing system design approaches drawing from various sources. The three areas and three intersections are compatible with the systems engineering phases. The three layers are equivalent to the ones defined by PERA. Wu also applies numerous tools and methods to the tasks of each area, which is similar to Kettner's approach. For example, he applies the manufacturing strategy categories defined by Hayes et al. [1988] to determine the strategic position of the company [Wu, 2000, p. 139]. The approach also provides numerous checklists and documents to capture milestones and knowledge along the design and operation of manufacturing systems. Wu states that the overlapping regions shown in Figure 2-14 still represent areas where further research is needed to achieve an integrated manufacturing system management framework.

2.3.3.6 Other Approaches and Tools for Manufacturing System Design

Numerous other tools support manufacturing system design at various stages. Operations management (OM) assists quantitative evaluation and analysis of systems ranging from broad applications, such as supply chain management, to detailed job sequencing. OM defines close boundaries in order to express problems mathematically. Due to the quantitative nature of OM, its application is most beneficial during later phases of system design when design constraints become better defined. From the manufacturing system design perspective, OM provides tools for well-defined sub-problems.

Simulation and analytical modeling evaluate potential designs in terms of performance and feasibility. Various simulation packages are available to assess potential system configurations (Quest, witness, ProModel etc.). They enable an intuitive understanding of the system's dynamic behavior. Industrial engineering software can simulate manual work to determine work cycles before installing the system (AutoMat).

Facility layout planning determines the physical organization of a production system. The objective is to minimize material handling costs considering two constraints: floor area requirements and physical building restrictions. Facility planning is mainly a combinatorial optimization problem with well-defined boundaries to enable the formulation of algorithms. It is used during preliminary and detailed planning phases. Meller and Gau provide a comprehensive literature review of facility layout planning [Meller, Gau, 1996]. They point out that the optimization of material handling can cause sub-optimality from the system perspective. They conclude that future research must concurrently address facility layout and manufacturing system design issues.

KOMPASS is a recently developed method, which supports the consideration of human aspects in the design of manufacturing systems [Grote et al., 2000]. The method consists of an analysis and design tool and is based on criteria derived from the field of work psychology. The analysis tool evaluates an existing system with respect to the work system, the individual work tasks, and the human-machine interaction. The method supports all five phases of the system engineering process, but is limited to human considerations.

2.3.4 Manufacturing System Design in Practice

Several studies have been undertaken to determine how manufacturing system design is done in industry. Hopp and Spearman found that system designers tend to follow a loosely defined sequence of steps starting with a rough layout scheme with little consideration of product flow [Hopp & Spearman, 1996, p. 605]. A recent workshop with companies of the aerospace industry also confirmed that companies did not have a procedure for the design of the shop floor [LAI workshop, 2001]. Grant observed that most companies somewhat formalize in-house procedures, but do not use formal processes [Grant, 1996]. Knowledge capturing was generally low. Most methodologies were project management driven rather than tailored to manufacturing system design. Only one company applied a formal procedure, which was based on Parnaby [1986]. Wu summarizes five main problems of manufacturing system design in practice:

1. Awareness: most manufacturing engineers are not aware of formal manufacturing system design methodologies. As a result, manufacturing system design is often ad hoc, "firefighting" to solve immediate problems and lacks consideration of problem root causes and strategic issues.
2. Generic vs. specific: the overall approach to manufacturing system design may follow a generic methodology, but it must be possible to tailor the approach to the company at the detailed levels.
3. Consistency: most methodologies provide their respective approaches at high levels of abstraction leading to confusion in practice and loss of consistency.
4. Documentation: lack of documentation hinders consistent communications among system designers. Assumptions are often not documented. Learning from previous system problems is difficult due to ill-structured documentation.
5. Implementation: many companies failed to apply existing design methodologies due to faulty execution of the implementation process. Main areas of concern are short lead-times of design projects and insufficient

coordination of tasks. Furthermore, objectives were not communicated consistently across the organization.

Observations made during industrial projects for this research confirm the findings mentioned above. No company had a formal procedure to be followed. One automotive component supplier had a detailed procedure for product design, which also contained interfaces with manufacturing. Every step in the product design was accompanied by a report to capture milestones, drawing specifications etc. Besides guiding the design process, the procedure also provided a base for knowledge capturing. However, the design of the manufacturing system was reduced to a single step in the procedure. The company did not have any additional procedures for the manufacturing system design.

Most system design projects started with a new product launch or capacity extensions. A critical first step in those projects was the determination of an investment plan for financial approval. This plan included equipment to be purchased, rough layout planning, floor space requirements, direct labor costs and potential savings for replacement investments. The system was often laid out to meet a fixed forecasted demand in spite of past demand fluctuations. System requirements with respect to human-machine interfaces, material supplies, or relationships between processes, were often not considered in early design phases. Therefore, preliminary designs were basically driven by investment costs and direct labor costs. Strategic considerations and an explicit statement of system objectives were mostly missing.

Layout configurations were often replications of existing system designs or driven by political decisions. One company producing fuel tanks for the automotive industry, had to design an additional fuel tank line for a new product. The initial system configuration was a one-to-one replication of existing lines. There was no-root cause analysis of problems with the existing lines as it was assumed that those problems were independent of the large-scale configuration. A review of the line revealed structural issues, which were to be considered in future projects.

A company that assembles electronic goods traditionally built the complete unit with one or two operators at one location. Assembly time was between six and twelve minutes (see Chapter 6 for more detail). A newly appointed manager decided to implement a drastically new line approach based on his previous work experience. The new layout distributed the assembly to 28 stations along a progressive assembly line. One operator at each station had a cycle time between 25 and 35 seconds. It is still unclear which line design better supports the company's strategy. The new line design was not a result of defining system requirements and translating them into a line configuration. Instead, the new configuration was the starting point of the system design project. High-level system requirements and conceptual design considerations were not considered.

Some companies outsourced the system layout to equipment vendors. Various vendors created system configurations based on a common set of specifications e.g., capacity requirements, quality, and process plans. Alternatively, one vendor might be asked to design a transfer line, while another vendor might be asked to design a flexible manufacturing system. The vendor suggestions were then evaluated and one configuration was selected [see also Duda, 2000, p. 55].

During more detailed design phases, manufacturing engineers were often assigned to specific tasks for example the selection of a specific machine. Those engineers often worked in isolation from the overall project not knowing how their tasks interacted with the whole system. A translation of high-level system requirements – if stated at all – to lower-level design decisions was very rare.

A frequently observed tendency in industry is the desire to become lean. Design decisions are reviewed and evaluated on criteria that supposedly capture the thinking behind lean manufacturing. It is common to use established lean tools such as U-shaped manufacturing cells and kanban. However, there is often no common understanding of lean manufacturing. As a result, project evaluations differ depending on the evaluator.

Even Toyota does not follow a formal process when designing a new line or making system design decisions, but uses detailed process and equipment specifications. The system design is mainly based on consensus and the inherent understanding of the Toyota production system. Spear calls this Rule-In-Use [Spear and Bowen, 1999].

In summary, industry usually does not apply formalized approaches for the design of manufacturing systems. There is particular lack of defining and communicating design requirements from early design phases to the operation of the system. Detailed design often tends to be done isolated from the whole system leading to local optimization of processes. Direct labor reduction is often a major driving force for new system layouts.

2.4 Chapter Summary

This chapter defined manufacturing system design within the context of systems engineering. Existing approaches (methodologies, tools, and frameworks) for manufacturing system design were reviewed and classified using a systems engineering process. Figure 2-15 groups the reviewed approaches into three groups:

The first group deals with manufacturing strategy related issues. Approaches are mainly concerned with the early phases of manufacturing system design. Miltenburg and Duda provide valuable extensions to translate strategy requirements to more detailed system design activities.

Approaches in the second group cover all five aspects of the systems engineering process. However, the approaches are either very general and not applicable for a specific system design project (PERA), they provide tools for each phase without linking the tools (Kettner), or they focus on a particular aspect of manufacturing systems (KOMPASS).

In the third group, approaches concentrate on detailed design and operational issues. Lean manufacturing related research and design approaches usually fall into this category. High-level system decisions are taken as a given as the system attempts to copy configurations associated with the Toyota production system. Furthermore, design requirements are often not defined. As a result, it is difficult to evaluate whether detailed design decisions support system objectives.

Approach / Author	conceptual design	preliminary design	detailed design	implemen-tation	operation
Hayes and Wheelwright (1979)	x	x			
GRAI (1992)	x	x	(x)		
Miltenburg (1995)	x	x	(x)		
Duda (2000)	x	x	(x)		
CIMOSA (1993)	x	x	x	x	x
PERA (1993)	x	x	x	x	x
Wu (2000)	x	x	x	x	x
Kettner (1984)	x	x	x	x	x
KOMPASS (2000)	(x)	(x)	x	x	x
Value Stream Mapping (1998)		x	(x)	(x)	(x)
Facility planning		x	x		
Suzuki (1999)		(x)	x	x	x
TPS frameworks			x	x	x
Monden (1989)			x	x	x
Sakakibara (1993)			x	x	x
Black (1991)			(x)	x	x
Hopp & Spearman (1996)			(x)	x	x
Spear (1999)			(x)	x	x
Shingo (1989)				x	x

x = focus of approach
(x) = partially considered

FIGURE 2-15: EXISTING MANUFACTURING SYSTEM DESIGN METHODOLOGIES, TOOLS AND FRAMEWORKS RELATIVE TO SYSTEMS ENGINEERING PROCESS.

Manufacturing system design in practice is characterized by a lack of formal processes. System requirements are often not defined. Detailed design activities are often not related to the whole system and lead to local optimizations. The desire to become lean often results in implementing off-the-shelf solutions, which repeatedly do not achieve the expected results. One reason for the failure may be the fact that existing solutions are used without understanding the objectives those solutions help to achieve. The example of Suzuki illustrated the need to relate solutions to system requirements to make them applicable in industry.

Recently, several authors emphasize the need for better integration among various disciplines to create a comprehensive manufacturing system design methodology [Meller, Gau, 1996; Wu, 2000; Hopp & Spearman, 1996, Hitomi, 1996]. Wu's framework is the most comprehensive among the reviewed approaches and provides possible ways for further integration.

The review pointed out several key points relative to the field of manufacturing system design:

- Very few approaches provide a complete coverage of all five systems engineering phases.
- Each approach provides valuable support for manufacturing system design, but it is often difficult (or unknown) to integrate with other approaches.
- Lean manufacturing is mainly focused on system operation and improvement without formally stating system requirements.
- There is a general lack of distinguishing system requirements and design solutions.
- Manufacturing system design in practice usually does not apply a formal design process. It is often done ad hoc or based on predefined off-the-shelf-solutions.

A comprehensive manufacturing system design methodology should

- be able to use existing approaches
- foster the definition of design requirements and relate design solutions to requirements.
- help to communicate requirements and design solutions throughout the organization.
- be able to show how low-level decisions affect the achievement of high-level requirements.
- facilitate the integration of existing tools for manufacturing system design.
- support a structured step-by-step design process.

The decomposition-based approach for manufacturing system design attempts to achieve the stated prerequisites. That approach builds the theoretical framework for the remaining part of this thesis and is introduced in the next chapter.

Chapter 3 Manufacturing System Design Decomposition

3.1 Introduction

This chapter introduces the development of the Manufacturing System Design Decomposition (MSDD). The motivation for developing MSDD is the desire to (1) clearly separate objectives from the means of achievement, (2) relate low-level activities and decisions to high-level goals and requirements, (3) state the interrelationships among the different elements of a system design, (4) provide a common platform to effectively communicate this information across the organization.

The design methodology of axiomatic design was used for the development of the MSDD and is briefly introduced before describing the MSDD in detail.

3.2 Axiomatic Design

The following paragraphs provide a brief introduction to the axiomatic design methodology and terminology. The focus is on those aspects of axiomatic design that were used to develop the MSDD. For more detail on the axiomatic design methodology, please refer to [Suh, 1990; Tate, 1999].

3.2.1 Basics of Axiomatic Design

Axiomatic design consists of two axioms, the independence axiom and the information axiom. The two axioms are defined as follows [Suh, 1990, p.47]:

> **Independence Axiom**:
>
> Maintain the independence of the functional requirements.
>
> Alternate statement: In an acceptable design, the design parameters and the functional requirements are related in such a way that specific design parameter can be adjusted to satisfy its corresponding functional requirement without affecting other functional requirements.

Information Axiom:

Minimize the information content of the design.

Alternate statement: The best design is a functionally uncoupled design that has the minimum information content.

The functional requirements (FRs) represent the goals of the design or what needs to be achieved. The design parameters (DPs) express how the FRs are satisfied. The FRs and DPs can be described mathematically as a vector. The relationship between the FRs and the DPs can be stated as a matrix. This matrix is called the Design Matrix (DM).

$$\{FRs\} = [A]\{DPs\} \tag{4-1}$$

The elements of the design matrix, A, indicate the effects of changes of the DPs on the FRs. As an example, consider the design equation shown below:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{4-2}$$

The binary elements of the design matrix, expressed as X's and 0's, indicate the presence or absence of a relationship between a DP and the associated FR. X's should always be present along the diagonal, meaning that each DP affects its associated FR (e.g., A_{11}=X indicates that DP_1 affects FR_1). The X at A_{21} shows that DP_1 also affects FR_2. This design matrix information can also be represented graphically as shown in Figure 3-1. An arrow from a DP to an FR indicates the presence of a non-zero, off-diagonal element in the design matrix.

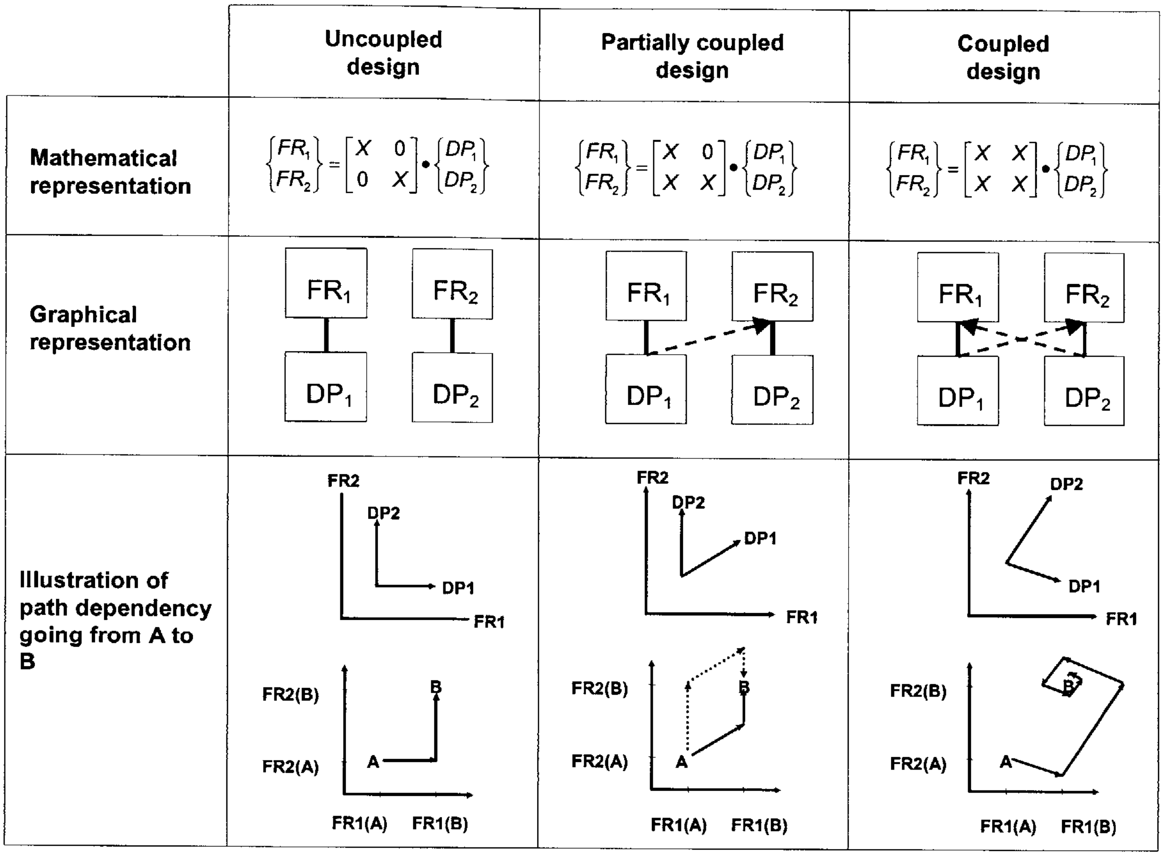


FIGURE 3-1: THE MATHEMATICAL AND GRAPHICAL REPRESENTATION OF UNCOUPLED, PARTIALLY COUPLED AND COUPLED DESIGN.

Figure 3-1 illustrates three types of design: uncoupled design, partially coupled design and coupled design[1]. In an uncoupled design, each DP affects only its associated FR. In a partially coupled design, at least one DP affects more than one FR, but the design matrix is triangular i.e. there are no non-zero elements above the diagonal. Adjusting DPs in a partially coupled design is path dependent. In the partially coupled design in Figure 3-1, for example, it is best to go from A to B by adjusting DP1 first, and then DP2, as that path avoids one iteration. A coupled design is one in which the design matrix has non-

[1] Axiomatic design uses the term "decoupled" instead of "partially coupled". However, since "decoupled" may associate that the design was previously coupled, the term "partially coupled" is used instead throughout this thesis.

zero elements above and below the diagonal. The adjustment of DPs to achieve a new design target is iterative.

The independence axiom determines if the design is an uncoupled, decoupled or coupled design. The axiom can be used to select the best design, if several alternatives have been developed. It is required to achieve an uncoupled design or at least a decoupled design, as their outcomes are inherently more robust. Coupled designs are not acceptable and should be eliminated. Furthermore, the design matrix highlights path dependencies, which have to be considered during the implementation.

The use of the information axiom requires expressing the relationships between FRs and DPs in the form of equations. Since FRs and DPs in the MSDD are mostly conceptual, it was not possible to quantify the relationships. Therefore, the information axiom was not used in creating the MSDD and will not be discussed further herein.

3.2.2 Application of Axiomatic Design for the Development of the MSDD

The overall axiomatic design process is shown in Figure 3-2:

1. Determination of the functional requirements (FRs).
2. Determination of the design parameters (DPs).
3. Clarification of the relationship between the DPs and FRs to determine the design matrix.
4. Further decomposition if necessary.

Axiomatic design provides a tool to structure the design thought process and to document design steps. Axiomatic design does not eliminate the need for creativity, since the formulation of FRs and DPs is essentially a creative process. The need to rigorously state FRs and DPs before decomposing further made it necessary to carefully phrase FRs and DPs in order to avoid ambiguity. This was particularly important considering the broad context of manufacturing system design.

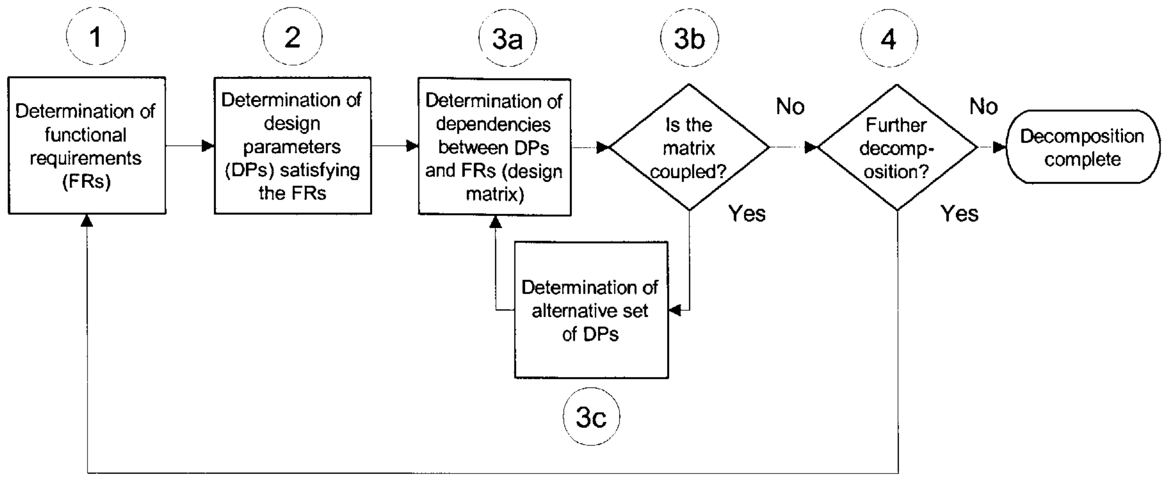


FIGURE 3-2: THE AXIOMATIC DESIGN DECOMPOSITION PROCESS CONSISTS OF FOUR STEPS: DETERMINATION OF FRS, DPS, DESIGN MATRIX, AND FURTHER DECOMPOSITION IF NECESSARY.

The following questions were used to determine the appropriate value of an element A_{ij} of the design matrix: Does the realization of DP_j affect the achievement of FR_i? Would failing to implement DP_j affect the system's ability to achieve FR_i ? If the answer to either of the questions was yes, the element of the design matrix A_{ij} became "X". For example: consider the relationship between DP-112 "Throughput time variation reduction" and FR-111 "Manufacture products to target design specifications" shown in Figure 3-4. The element in the design matrix $A_{112-111}$ is 0. Variation in throughput time (e.g., due to fluctuating inventory levels) should not affect the ability of individual processes to produce to target specifications. Therefore, reducing throughput time variation (DP-112) does not affect the system's ability to produce to target specification (FR-111).

The dependencies represent an "ideal" design. It could be argued for example that reduction of variability (DP-112) affects the ability to manufacture products to target specifications (FR-111), since time pressure may lead to a lower level of accuracy [see e.g., McKay et al., 1995]. While existing systems may show such dependencies, it should be possible to achieve the FRs in the order expressed in the design matrix.

Coupled designs were disentangled by choosing different DPs or restating the DPs. The meaning of the DPs may have been too broad, thus affecting more than one FR. Sometimes an FR-DP-pair was misplaced and became part of a lower level of the decomposition. After resolving all coupling problems, the FRs and DPs were arranged in such a way that the FR-DP pair whose DP affects the most FRs was organized first. As a result, the MSDD shows path dependence when reading from left to right.

The next step in the design process was to decide if further decomposition is necessary. Decomposition proceeded to a level that was specific enough to support design decisions without limiting the general applicability of the MSDD. For example: FR-P121 "Service equipment regularly" with the corresponding DP-P121 "Regular preventative maintenance program" was not decomposed any further, since preventive maintenance programs are tailored to the company's needs and numerous existing methods are available to design a preventive maintenance program.

3.3 Manufacturing System Design Decomposition

The development of the MSDD draws from a variety of sources and experiences: literature on manufacturing system design; frameworks described in the literature review; industrial engineering; Toyota production system; and industrial projects in a variety of industries including automotive, consumer goods, aircraft, and food processing. The desire was to make the MSDD applicable to a wide range of repetitive, discrete part manufacturing environments.

The decomposition process resulted in six main areas: quality, identifying and resolving problems, predictable output, delay reduction, operational costs, and investment as shown in Figure 3-3. The following section derives the general structure of the MSDD before describing each area in detail. The complete version of the MSDD is shown in Appendix A.

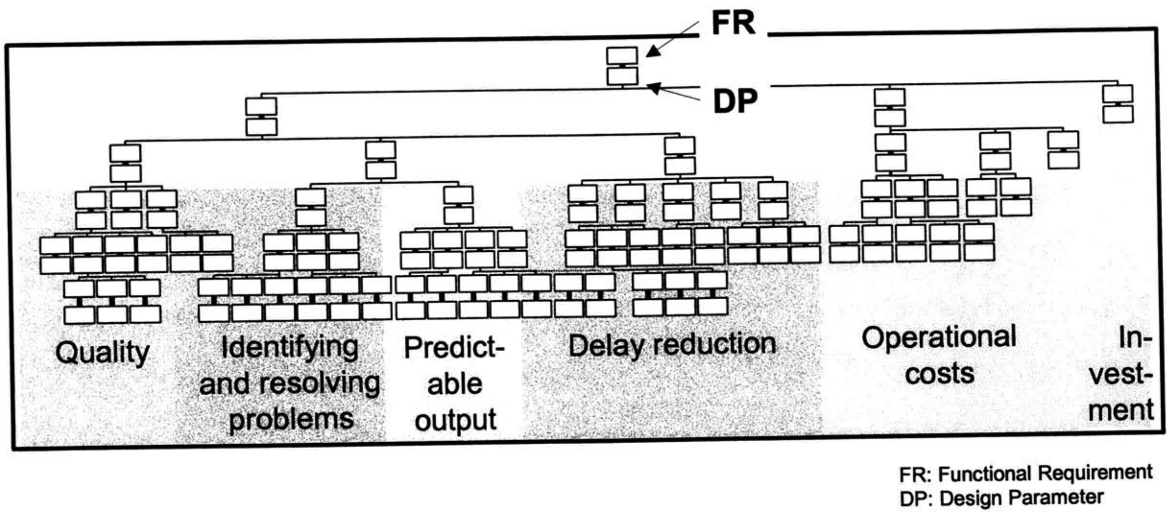


FIGURE 3-3: THE MSDD DISTINGUISHES SIX GENERAL FUNCTIONS OF MANUFACTURING SYSTEMS: QUALITY, IDENTIFYING AND RESOLVING PROBLEMS, PREDICTABLE OUTPUT, DELAY REDUCTION, OPERATIONAL COSTS, AND INVESTMENT. EACH FUNCTION IS DECOMPOSED INTO A SEPARATE BRANCH FOLLOWING THE RULES OF AXIOMATIC DESIGN.

3.3.1 General structure

The first FR of the decomposition must express the general goal of manufacturing systems. Hopp and Spearman [1996, p.199] formulate such a goal as follows: "The fundamental objective of a manufacturing firm is to increase the well-being of its stakeholders by making a good return on investment over the long term". The highest-level functional requirement in the MSDD was stated as FR-1 "Maximize long-term return on investment" with the associated DP-1 "Manufacturing system design". Note that the focus of the DP and subsequently of the whole decomposition is on the *manufacturing* aspects of an enterprise. While other areas such as marketing and product development certainly influence return on investment of the enterprise, the MSDD limits attention to core aspects of manufacturing. Quality, delivery, and cost are well established core manufacturing competencies in the literature [e.g., Corbett and Van Wassenhove, 1993]. Further decomposition illustrates how those competencies are considered in the MSDD.

The second level of the MSDD is derived from the ROI formula: FR-11 "Maximize sales revenue", FR-12 "Minimize production costs", FR-12 "Minimize investment over the production system life cycle" with the associated DP-11 "Production to maximize customer satisfaction", DP-12 "Elimination of non-value adding sources of cost", and DP-13 "Investment based on a long term system strategy." The design matrix is as follows:

$$\begin{Bmatrix} FR-11 \\ FR-12 \\ FR-13 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \bullet \begin{Bmatrix} DP-11 \\ DP-12 \\ DP-13 \end{Bmatrix} \tag{4-3}$$

The rationale behind the design matrix is that if the products produced by the manufacturing system do not meet customer expectations and are not sold, it results in unnecessary costs and investment. Thus, DP-11 affects all FR-1x. The elimination of non-value adding sources of costs may require a particular type of investment (e.g., style of equipment) and thus DP-12 affects investment decisions (FR-13). However, it is possible to produce products that meet customer expectations, even though the production costs are high. Therefore, DP-12 does not affect FR-11.

The decomposition of DP-11 "Production to maximize customer satisfaction" considers three aspects of how manufacturing contributes to customer satisfaction: FR-111 "Manufacture products to target design specifications", FR-112 "Deliver products on time", and FR-113 "Meet customer expected lead time."

DP-111 "Production processes with minimal variation from the target" concentrates on selecting and controlling manufacturing processes. It is assumed that product design has specified nominal targets and tolerances to ensure proper functioning of the product. The manufacturing system must then be designed to manufacture to the given product specifications.

On-time delivery (FR-112) refers to the ability of a manufacturing system to meet the quoted delivery dates. The chosen means is DP-112 "Throughput time variation reduction". Throughput time is the sum of all activities necessary in a manufacturing system to produce a given product. Variation in throughput time is caused by disruptions such as machine downtime and material unavailability.

Customers ask for ever shorter lead times. Meeting those lead times (FR-113) forces a supplier to shorten the mean throughput time (DP-113), which is achieved by reducing various sources of delays such as lot sizing, transportation, or batching (FR-T1 – T5). It is important to note that the sources of delays are a predictable consequence of the design and operation of the system, in contrast to production disruptions that occur randomly. The design matrix for DP-111 – 113 and FR-111 – 113 is as follows:

$$\begin{Bmatrix} FR-111 \\ FR-112 \\ FR-113 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \bullet \begin{Bmatrix} DP-111 \\ DP-112 \\ DP-113 \end{Bmatrix} \tag{4-4}$$

The design matrix shows that producing high quality products (DP-111) is a prerequisite for accomplishing customer satisfaction. Producing defective parts and allowing variation in the quality of output adversely affects the ability to deliver products on-time and makes it difficult to meet expected lead times (A_{21} and A_{31} in equation 4-4). A reduction of throughput time variation (DP-112) also leads to shorter mean throughput times (FR-113). Thus, DP-112 positively affects FR-113.

The decomposition of throughput time variation leads to the remaining areas shown in the general structure of the MSDD: FR-R1 "Respond rapidly to production disruptions" deals with the fact manufacturing experiences disruptions and must be able to resolve them. FR-P2 "Minimize production disruptions" forces the organization to reduce the disruptions as much as possible. Since disruptions must first be recognized and responded to before being eliminated all together, the dependencies are as follows:

$$\begin{Bmatrix} FR-R1 \\ FR-P1 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \bullet \begin{Bmatrix} DP-R1 \\ DP-P1 \end{Bmatrix} \tag{4-5}$$

Figure 3-4 summarizes the MSDD up to the stage discussed so far and shows the six branches of the decomposition. The dependencies are indicated as arrows. The FRs and DPs are still very general. While it is not possible to implement a particular DP at this level, the FR-DP-pairs express the general objectives of manufacturing systems. The arrangement of the FR-DP-pair is such that the MSDD shows a path dependency from left to right.

Figure 3-4 shows that the MSDD treats customer satisfaction as a prerequisite for a successful manufacturing system design. Two of the three core manufacturing competencies – quality and delivery – mentioned earlier fall under this branch. The MSDD interrelationships emphasize that maximizing customer satisfaction determines the basis for minimizing operational costs and investment decisions. This line of thinking is supported by empirical and theoretical research. Ferdows and De Meyer [1990] propose a "sand cone model" for system improvement, which starts with quality, then reliability and finally efficiency and costs. Filippini et al. [1998, p. 3400] performed an analysis of 45 manufacturers in Italy and found that "compatibility between punctuality and economic performance has been found only in the presence of high values of quality consistency and delivery time."

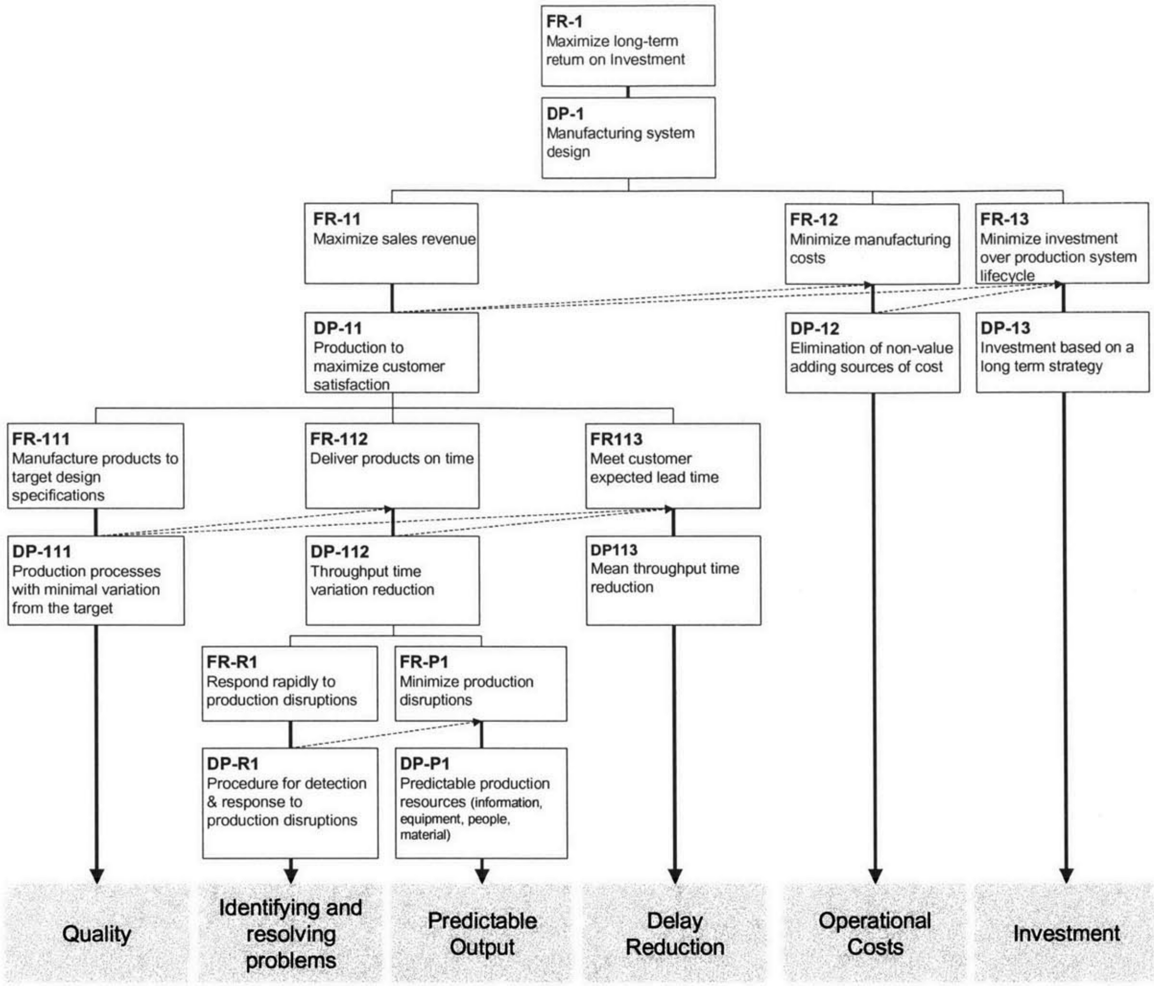


FIGURE 3-4: GENERAL STRUCTURE OF THE MSDD WITH SIX DISTINCTIVE DECOMPOSITION BRANCHES.

The following paragraphs describe each of the branches in detail. Note that the names of the FRs and DPs become different to simplify reading. The letter following the hyphen indicates the branch: Q stands for quality, R for responding to disruptions, P for predictable output, T for throughput time reduction, D for direct labor, I for indirect labor.

3.3.2 Quality

The quality branch focuses on individual processes. Each process must be able to consistently produce output according to product specifications. The complete decomposition of the quality branch of the MSDD is shown in Figure 3-5.

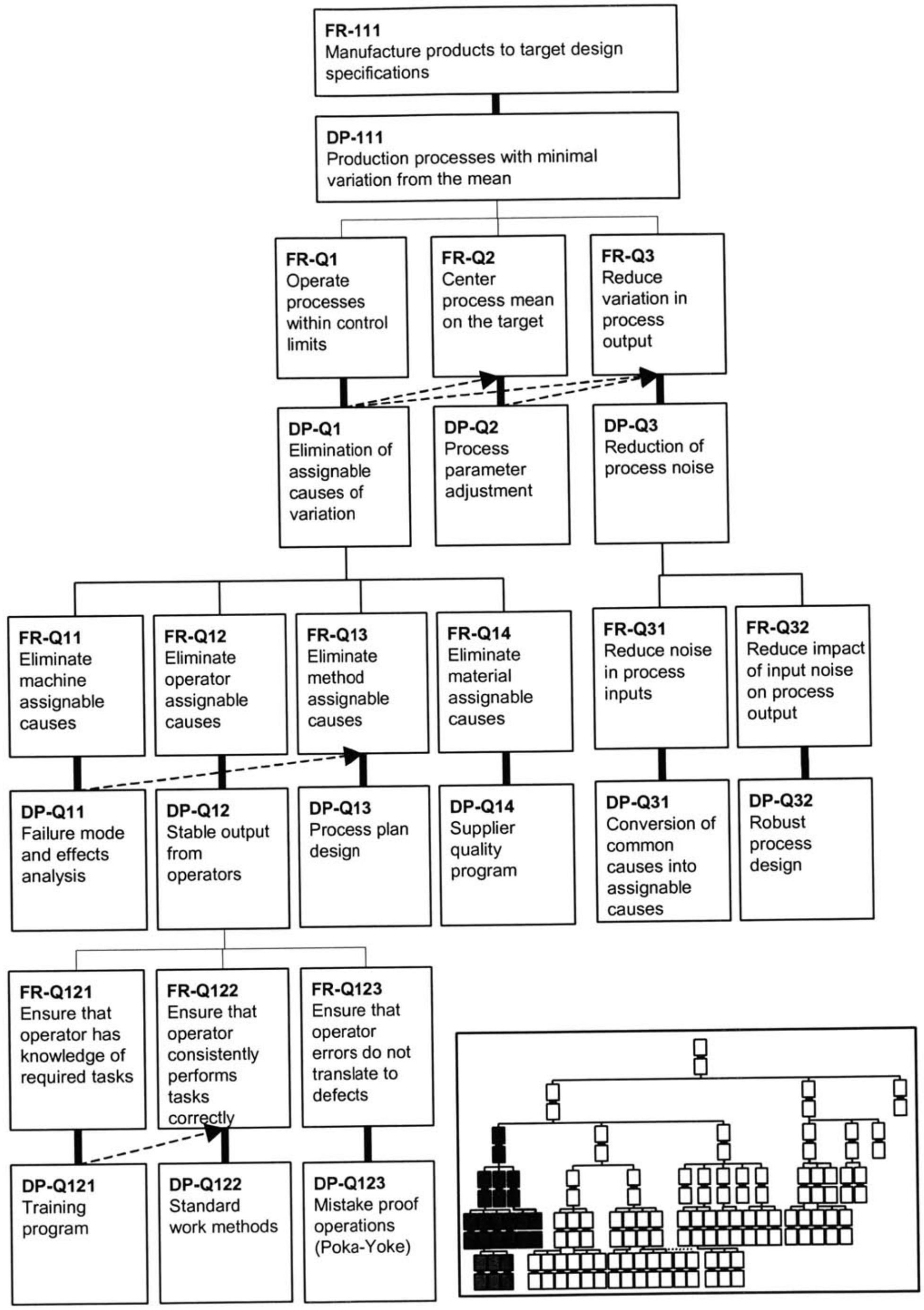


FIGURE 3-5: QUALITY BRANCH OF THE MSDD.

The first requirement for high quality output is process stability. A process is said to be under control when no assignable causes of variation are present and, instead, only common causes of variation occur [Montgomery, 1985]. Assignable causes are non-random events that, when eliminated or corrected, result in the process returning to a state of control. The chosen FR-DP-pair is FR-Q1 "Operate processes within control limits" and DP-Q1 "Elimination of assignable causes of variation." The elimination of assignable causes includes the selection and design of equipment, operator capabilities, methods, and material (FR-DP Q11 – Q14). The second quality requirement stems from the fact that a process capable of producing according to product specifications and operated in a stable manner may still produce out-of-tolerance parts, if the process is operated off target. FR-Q2 "Center process mean on the target" and DP-Q2 "Process parameter adjustment" enforces the need to operate with the process mean at the specified value. The last high-level quality requirement is to reduce variation in process output (FR-Q3) by reducing process noise (DP-Q3).

The design matrix for quality is decoupled and it highlights the importance of having processes that are capable of producing according to product specifications. Some processes may be difficult to adjust without affecting their robustness, which may lead to coupling between FR-DP-Q2 and Q3. It is then necessary to determine process parameters, which simultaneously shift process means and reduce variation [Arinez, 2000].

$$\begin{Bmatrix} FR-Q1 \\ FR-Q2 \\ FR-Q3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \bullet \begin{Bmatrix} DP-Q1 \\ DP-Q2 \\ DP-Q3 \end{Bmatrix} \tag{4-6}$$

The elimination of process variation starts with the appropriate selection of production resources: Equipment must be selected that is capable of producing to target specifications (FR-DP-Q11); operators must be trained properly and the work performed so that the operator's output is consistent (FR-DP-Q12); process plans must ensure effective conversion of raw material to planned products (FR-DP-Q13); the material used must be defect free and compatible with product specifications. After the resources are in place, the elimination of assignable causes is an ongoing effort during the operation of the system.

Stable operator output (DP-Q12) is further decomposed into three elements: the first prerequisite is to ensure that operators have knowledge of the required tasks (FR-Q121). The chosen means is training (DP-Q121). Monden [1998, p.158] calls training a "key to implementing a successful system." Secondly, it is necessary to ensure that operators consistently perform the tasks correctly (FR-Q122) by defining and enforcing standard operator work methods (DP-Q122). The third requirement "Ensure that operator human errors do not translate into defects" accounts for the fact that in spite of thorough training and work standards, operators do make errors. A suggested means to achieve FR-Q123 is the use of Poka-Yoke devices [Hirano, 1988].

3.3.3 Identifying and Resolving Problems

The main goal of the identifying and resolving problems branch is to achieve a manufacturing system that can be improved by being able to recognize and eliminate disruptions. Identifying and resolving problems reduces throughput time variation caused by unplanned production disruptions. Disruptions as indicated by the MSDD are problems that lead to a loss in system availability. The decomposition of DP-112 "Throughput time variation reduction" only considers disruptions that do not result from quality problems. Quality problems, though disruptive to a manufacturing system, are treated separately under the previously described quality branch.

The decomposition of FR-R1 "Respond rapidly to production disruptions" and its corresponding DP-R1 "Procedure for detection and response to production disruptions" is shown in Figure 3-6. In order to accomplish DP-R1, disruptions must be recognized (FR-R11), communicated to the right resource (FR-R12), and eventually be solved (FR-R13). The associated DP's are conceptual and refer to sub-system configurations (DP-R11), feedback procedures (DP-R12), and standard improvement methods (DP-R13). The dependencies follow the logic that disruptions must first be recognized, then communicated and then resolved.

Technology can be helpful in recognizing disruptions by providing instantaneous feedback about the state of the manufacturing system. However, the perspective taken here is that the operator is the ultimate source in dealing with disruptions, which is expressed in the wording of DP-R11 and DP-R12.

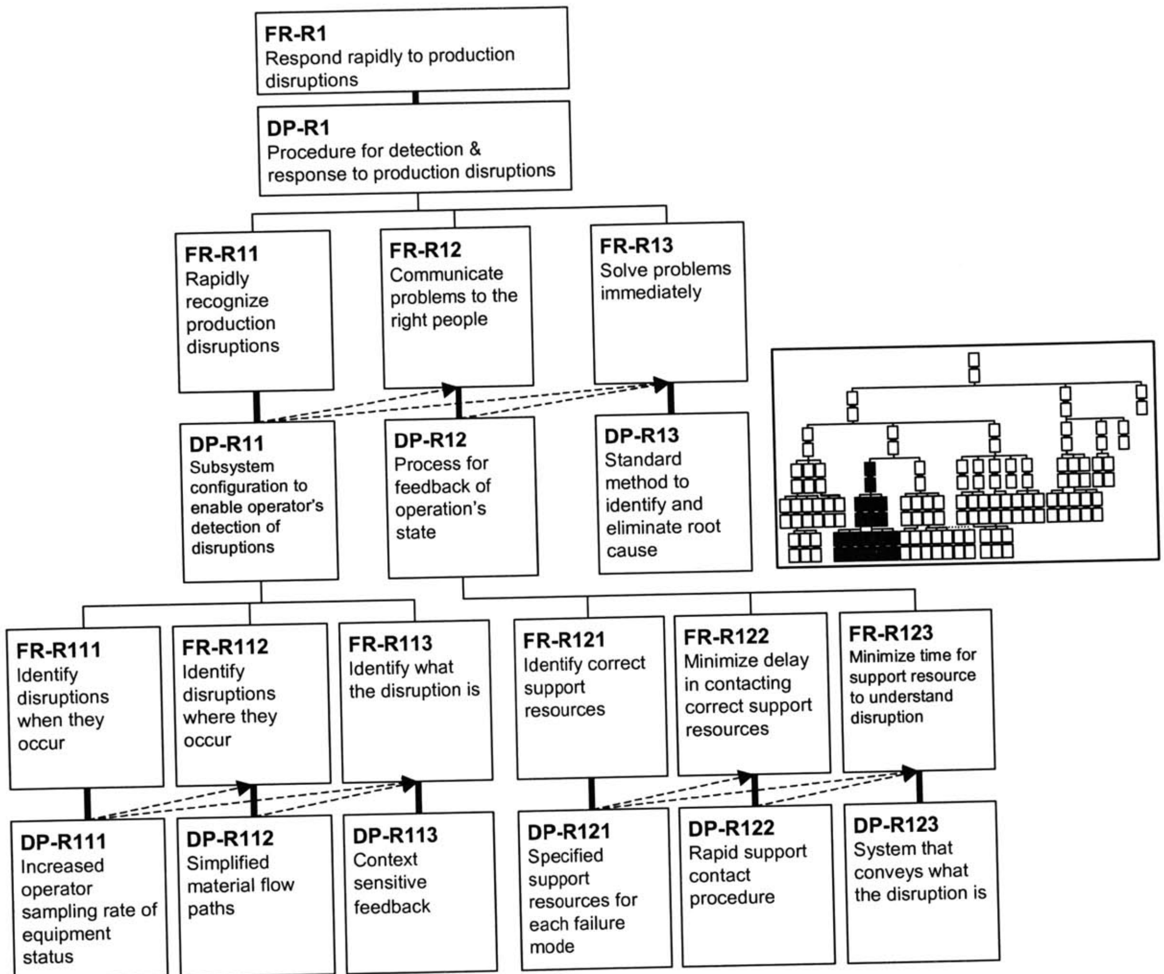


FIGURE 3-6: IDENTIFYING AND RESOLVING PROBLEMS BRANCH OF THE MSDD. THERE ARE THREE MAIN ELEMENTS IN THE BRANCH: DISRUPTIONS MUST BE RECOGNIZED (WHEN, WHERE, WHAT), COMMUNICATED, AND EVENTUALLY SOLVED.

The underlying thinking of the decomposition of DP-R11 is that the sub-system configuration (design and operation) supports the operator in recognizing disruptions (when, where and what). The design of the work tasks and the integration of the human into the overall system are critical aspects. For example, if an operator repeatedly cannot finish a cycle in the predefined time, she should signal a problem. The system should expose abnormal situations.

The "Process for feedback of operation's state" (DP-R12) stresses the importance of establishing standard communication paths between participants of a manufacturing system. Support resources must be defined (FR-DP R121) and quick correspondence must be possible (FR-DP R122). Furthermore, the system should support the diagnosis of problems (FR-DP R123). This could be done, for example, by having machine panels that display the root cause of a disruption. In any case, the diagnosis and elimination of disruptions should follow a defined and standard procedure (FR-DP R13).

3.3.4 Predictable Output

Rapidly responding to and resolving production disruptions is the basis for eliminating production disruptions. To minimize production disruptions (FR-P1), predictable production resources are required (DP-P1). Four types of production resources must be predictable: information (FR-P11), operator (FR-P12), equipment (FR-P13), and material (FR-P14), as shown in Figure 3-7.

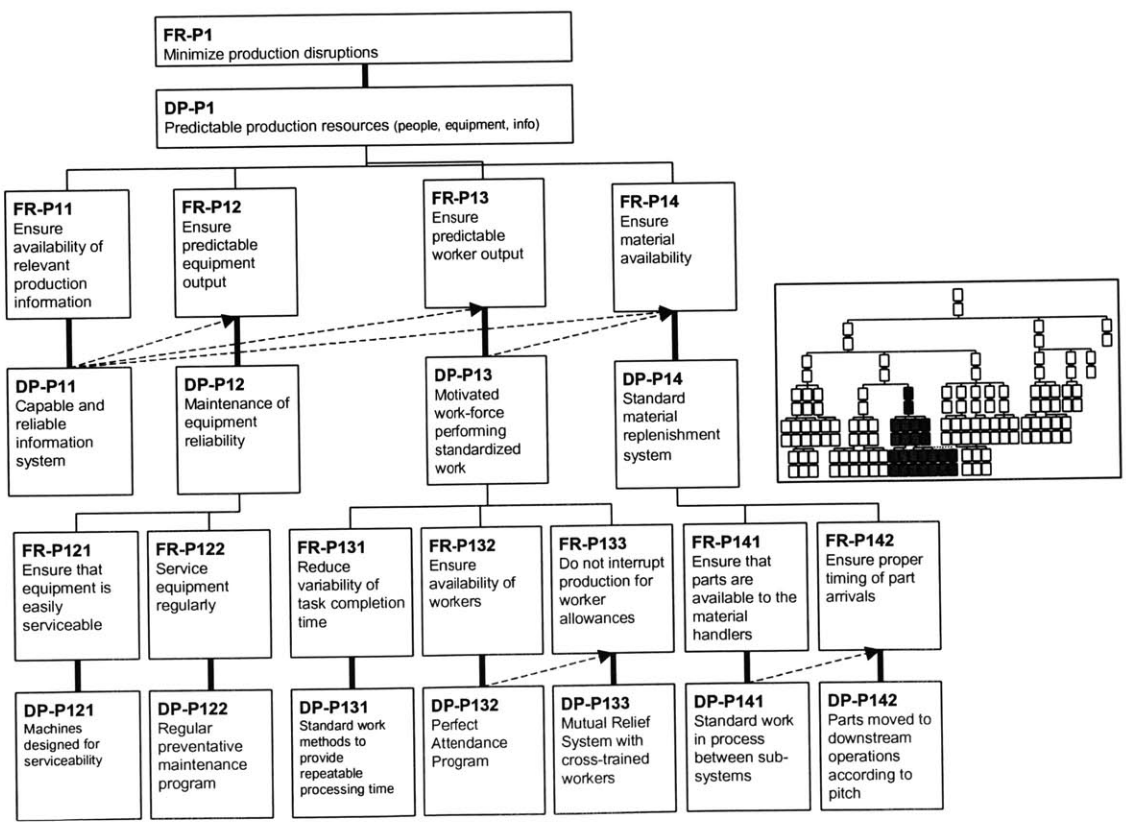


FIGURE 3-7: THE DECOMPOSITION OF PREDICTABLE RESOURCES DISTINGUISHES FOUR PRODUCTION RESOURCES: INFORMATION, EQUIPMENT, PEOPLE, AND MATERIAL.

DP-P12 "Maintenance of equipment reliability" includes all hardware of the manufacturing system, e.g., machines, tools, material handling. The first step towards predictable equipment output is the consideration of serviceability during the design and selection of the hardware (FR-DP P121). VDI Norm 4004 [Blatt 3 p.5] gives an overview what aspects of equipment enable serviceability. Once the system is installed and operated, regular maintenance is required to ensure proper equipment functionality (FR-DP P122). Further details about equipment maintenance can be found in the literature of total productive maintenance e.g., [Nakajima 1989].

Three requirements are defined to achieve stable time output from operators as shown in Figure 3-7: reducing variation of task completion time (FR-P131) by defining standard work methods (DP-P131); ensuring that operators are available when tasks need to be performed (FR-P132); and avoiding production disruptions due to worker allowances (FR-P133) by mutual relief (DP-P133). The MSDD views stable operator output as a prerequisite for material availability, particularly for the frequent and predictable delivery of material. Thus, DP-P13 affects FR-P14 "Ensure material availability" (see arrow between DP-P13 and FR-P14 in Figure 3-7). More detailed information about the design of work systems from the ergonomic and psychological point of view can be found for example at [Strohm, Ulich, 1997, Grote et al., 2000].

The last aspect of predictable output is material availability. Variability increases inventory levels in order to ensure production. The MSDD expresses this relationship through higher-level dependencies, since predictable output (FR-P1) is affected by time variation (DP-R1) and variation of process output (DP-111) as shown in Figure 3-4. Other reasons for inventory are operational settings (batch size, transportation lot size etc.), which are discussed in the delay reduction branch.

The decomposition of FR-P14 "Ensure material availability" with the corresponding DP-P14 "Standard material replenishment system" requires having standard levels of inventory to enable stable production. The decomposition of FR-DP P14 focuses on two objectives of material replenishment: (1) ensuring that material is available when needed (FR-P141), and (2) delivering material to the downstream process when needed (FR-P142).

DP-P141 "Standard material replenishment system" does not prescribe any particular inventory control policy. The emphasis is on having defined levels of inventory and not random uncontrolled levels. FR-DP-142 "Ensure proper timing of part arrivals" with DP-P142 "Parts moved to downstream operations according to pitch" links the delivery of material with material consumption. The DP-expresses a very advanced stage of material control in medium to high volume repetitive manufacturing by requiring to deliver material in synchronization with the consumption rate. It describes a "milk-route" replenishment system, in which a person has a defined route through the shop floor and replenishes consumed material on a regular basis.

3.3.5 Delay Reduction

The decomposition of DP-113, "Mean throughput time reduction," encompasses several components of throughput time that reflect operational settings or time inefficiencies in the system. Inventories, which buffer against variation, were considered previously under FR-DP P1, "Predictable material availability."

The delay reduction branch of the MSDD considers five delays that affect throughput time: *Lot delay* (FR-T1) occurs when parts are transported between operations; *Process delay* (FR-T2) occurs when the arrival rate of parts is higher than the service rate; *Run size delay* (FR-T3) arises when parts wait before or after processes due to chosen run sizes (Run size is the number of parts produced before changing over to the next part); *Transportation delay* (FR-T4) is the time parts spend being transported within the plant; *Systematic operational delays* (FR-T5) occur when production resources interfere with each other.

The first four delays lead directly to WIP or inventory, while the fifth delay reduces the efficiency of production time. The objective is to reduce each of the five delays as much as possible, which leads to five FRs. The complete delay reduction branch is shown in Figure 3-8. Each delay and its dependency with the other delays are discussed below in a separate paragraph.

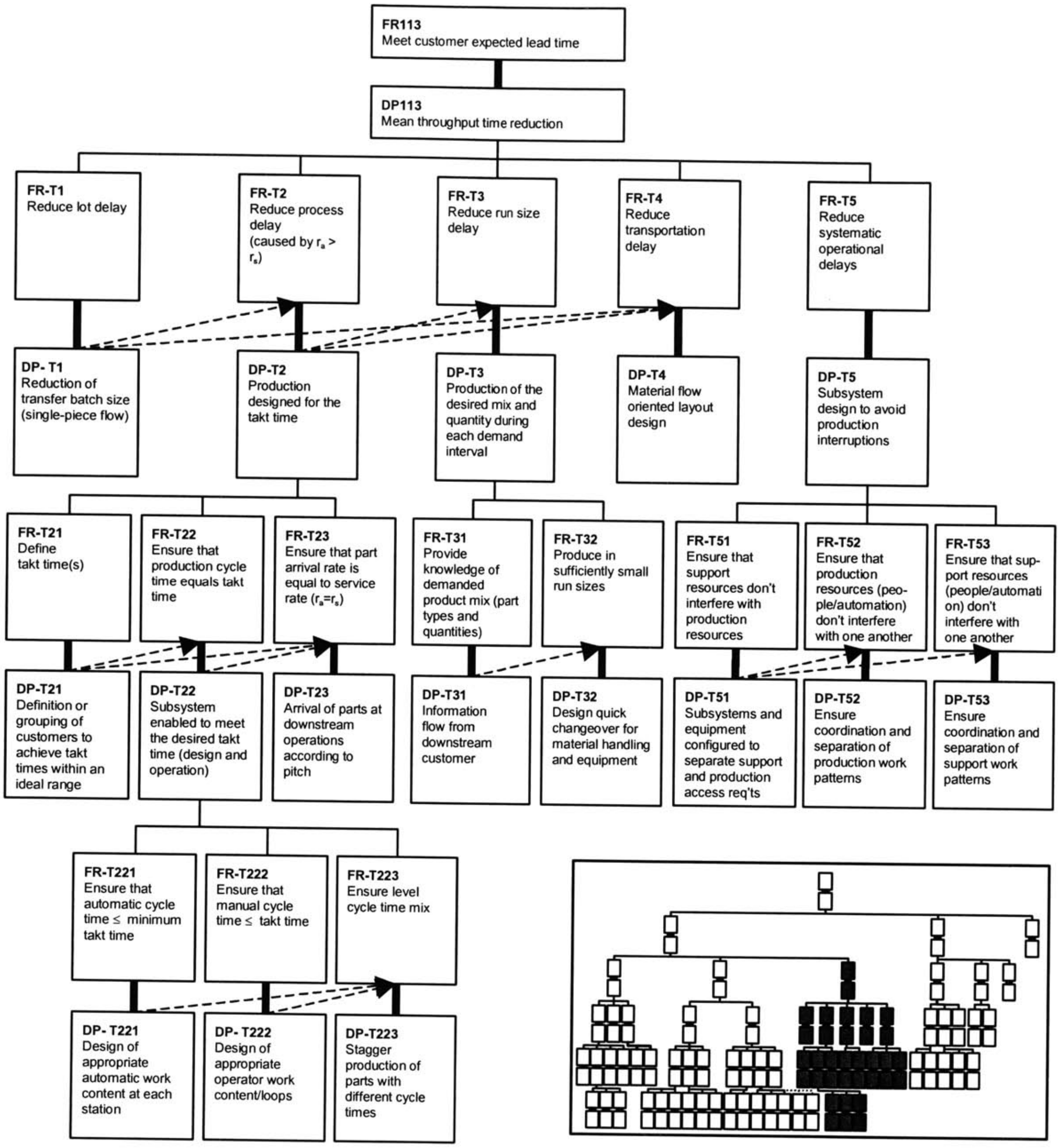


FIGURE 3-8: THE MSDD DISTINGUISHES FIVE TYPES OF DELAYS: LOT DELAY, PROCESS DELAY, RUN SIZE DELAY, TRANSPORTATION DELAY, AND SYSTEMATIC OPERATIONAL DELAYS.

Lot delay reduction

Lot delay occurs, when parts are transported between operations in batches greater than one. The means to reduce lot delay is simply to transport smaller quantities (DP-T1). DP-T1 affects FR-T2 "Reduce process delay caused by arrival rate > service rate", since transfer frequency influences arrival rate of parts. Smaller transfer batches require more transfers, which increases transportation delay. Thus, DP-T1 adversely affects FR-T4 "Reduce transportation delay". DP-T4 "Material flow oriented layout" must compensate for those losses. The ultimate achievement of DP-T1 "Reduction of transfer batch" is single-piece flow, which will influences the way manufacturing resources are arranged e.g., in the form of manufacturing cells. Note that transfer batch sizes also depend on material handling equipment (size of bins, ability to move parts manually or with fork lifts).

Process delay reduction

When the arrival rate of parts, r_a, is greater than the service rate, r_s, parts accumulate in front of the downstream operation. The time parts wait in front of the downstream process is defined as process delay. Assuming that the long-term average arrival rate is equal to the average service rate, process delay occurs only during shorter time intervals in which $r_a > r_s$ Otherwise, an infinite number of parts would accumulate in front of the downstream process. The goal of eliminating process delay is to pace all operations according to takt time and to achieve a smooth flow of material through the system. Such a system is often called balanced [Monden, 1998, p. 145; Hopp & Spearman, 1996, p. 226].

Pacing a system according to takt time has significant influences on the design and the operation of the system [Linck, Cochran, 1999]. Sub-systems must be defined in such a way that they can operate according to takt time (FR-DP T21). Equipment and work loops must be designed so that takt time can be achieved (FR-DP T221 – T222). The scheduling of the system must consider takt time to achieve a leveled production schedule (FR-DP T223).

Balancing production may require smaller run sizes. In that sense, DP-T2 "Production balanced according to takt time" requires FR-T3 "Reduce run size delay". Realizing DP-T2 also requires proper timing of material deliveries, which might increase transportation activities (FR-T4 "Reduce transportation delay").

Run size delay reduction

Run size is the number of parts produced before changing over to the next part. The chosen means to reduce run size delay is "production of desired mix and quantity during each demand interval" DP-T3. There are two prerequisites to achieve DP-T3: order mix and quantity must be known on the shop floor (FR-DP T31), and resources must be able to perform quick changeovers (FR-DP T32).

DP-T31 "Information flow from downstream customer" suggests the use of, e.g., a kanban system. Other alternatives such as CONWIP [Hopp & Spearman, 1996] or hybrid systems [Bonvik, 1998] combine downstream and upstream information. DP-T31 may not be the only way to satisfy FR-T31. While pull manufacturing is considered a very stable and efficient way to operate a system [Benton, Shin, 1998], it is not always applicable. Many job-shops cannot afford to have intermediate buffers between operations when producing one-of-a-kind parts. The important point is to provide clear information about the product mix and quantity.

Transportation delay reduction

Transportation delay (FR-T4) is defined as the total time parts spend in transport including time waiting for transport. "Material flow oriented layout" (DP-T4) is a chosen means to reduce transportation delay by elminating the need for transport all together. An alternative could be to speed up the means of transportation. However, that solution does not address the root cause of the delay: transportation distances. Literature on facility planning provides valuable tools to achieve DP-T4. (See e.g., [Meller, Gau, 1996] for a comprehensive review of facility planning literature.)

Systematic operational delays reduction

Systematic delays, resulting from production resources interfering with each other, lead to loss of production time. Unlike the other four delays of the delay branch, systematic operational delays do not directly lead to WIP. The MSDD distinguishes production resources (operators and equipment, which add value to the part) and support resources (e.g., material supply, chip removal, inspection). Delays occur when one resource hinders the ability of another resource to perform its required task. Avoiding such delays (FR-DP

T5) requires detailed design of the system layout and operation (FR-DP T51 – T53). A common delay is the interference of material supply with the value added work. Operators often have to leave their workstations to pick up new material or to make space for material delivery equipment.

3.3.6 Operational costs

Son [1991] proposes the cost system for advanced manufacturing systems shown in Figure 3-9. The operational cost branch of the MSDD does not decompose according to a cost system as suggested by Son, since most of the cost elements he identifies have been attended to in previous branches of the MSDD. The dependencies shown in the general structure of the MSDD (see Figure 3-4) show that decisions in the quality, identifying and resolving problems, predictable output, and delay branch all help to remove causes of operational costs and investment. The operational costs branch focuses on three remaining sources of costs: direct labor (FR-DP 121), indirect labor (FR-DP 122) and facility costs (FR-DP 123). Depreciation and other investment costs fall under the investment branch.

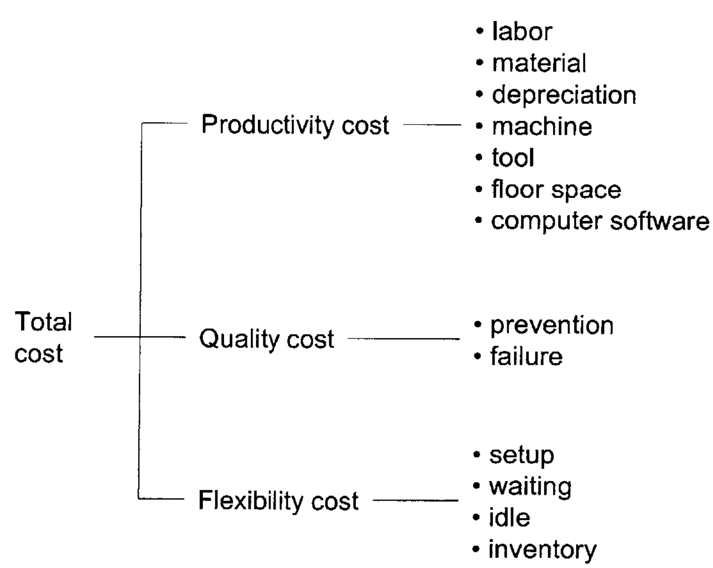


FIGURE 3-9: COST SYSTEM FOR ADVANCED MANUFACTURING SYSTEMS [SON, 1991]

The decomposition of DP-121 "Elimination of non-value adding manual tasks" distinguishes three sources of waste: waiting while the machine operates (FR-D1), wasted motions (FR-D2), and waiting of operators on other operators (FR-D3). The chosen means to satisfy the FRs are human-machine separation (DP-D1), workstation and work loops design (DP-D2), and balanced work loops (DP-D3). The complete decomposition of the operational costs branch is shown in Figure 3-10.

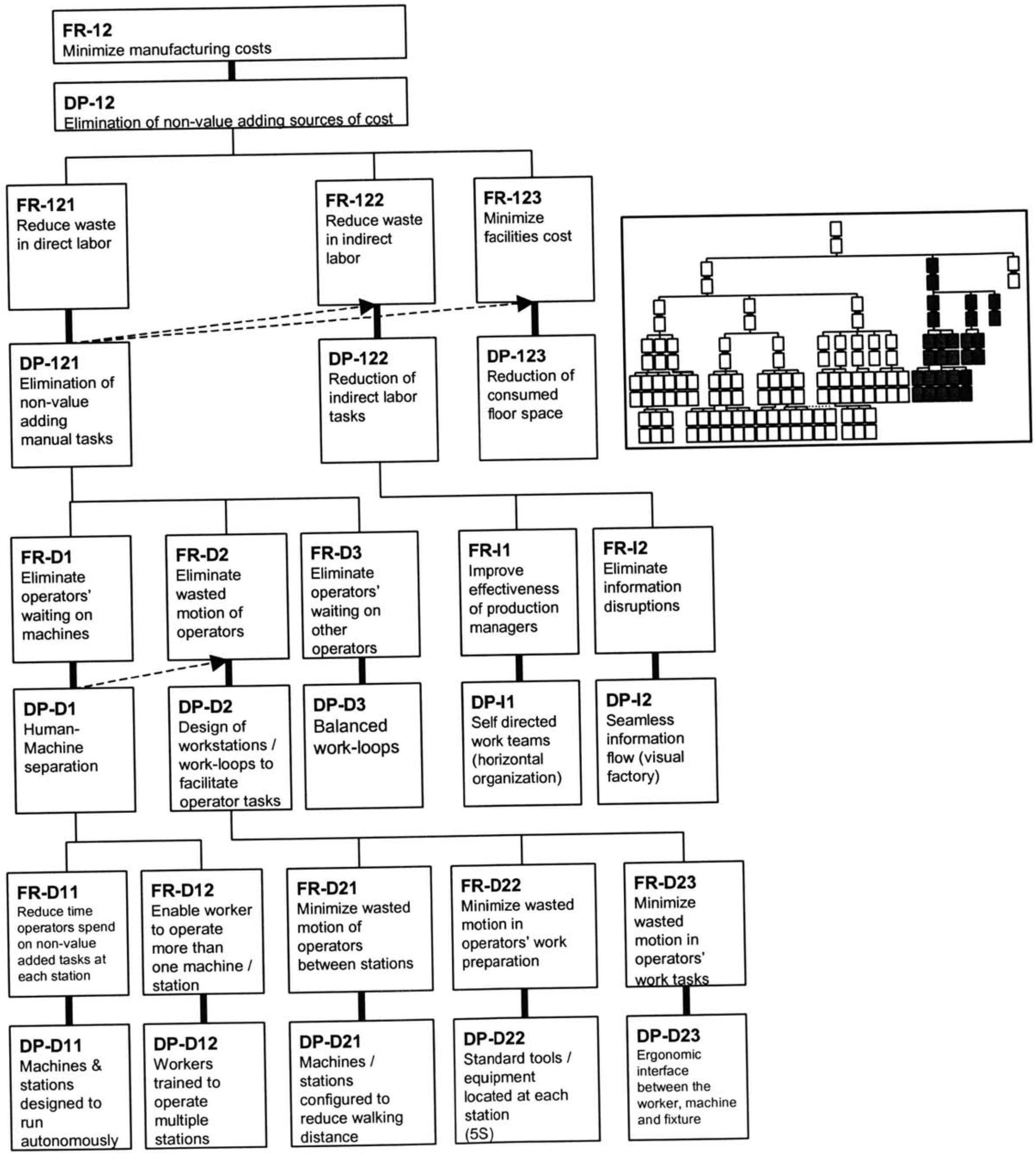


FIGURE 3-10: THE OPERATIONAL COSTS BRANCH FOCUSES ON THE ELIMINATION OF NON-VALUE ADDING SOURCES OF COSTS (DP-12). THREE SOURCES OF COSTS ARE CONSIDERED: DIRECT LABOR (FR-DP 121), INDIRECT LABOR (FR -DP 122) AND FACILITY COSTS (FR-DP 123).

Human-machine separation requires appropriate equipment selection. It should not be necessary for operators to just watch the machine cycle. Machines should be able to perform each cycle autonomously (FR-DP D11). Another aspect of human-machine separation is the ability of the worker to operate several machines - possibly of different processes (FR-DP D12).

The elimination of wasted motions (FR-DP-D2) places additional requirements on the equipment design and facility layout to minimize walking distances and to provide ergonomic interfaces (FR-DP-D21 and D23). FR-DP D22 refers to clean and orderly work places to avoid wasted time and motion in work preparation.

Balanced work loop design (DP-D3) requires synchronization of the work loops, when several operators work in one team. The objective is to combine work tasks in such a way that idle times of operators are eliminated. Work loop design interacts with equipment selection and shop floor layout. Often companies select equipment and layout the shop floor without considering the human interface. As a result, operators are idle for part of the cycle.

Note that elimination of direct labor costs should not be a system design objective at the outset of a project. The MSDD emphasizes the role of operators to achieve the production of right quality, right mix, at the right time. Reducing direct labor costs at the expense of quality or delivery performance is counterproductive for the overall system objective. There is nothing wrong with reducing costs in manufacturing systems – as long as the objectives stated to the left are satisfied.

3.3.7 Investment

As discussed in section 3.3.1, the MSDD does not decompose the investment branch, because it was found that investment decisions are too dependent on the particular company circumstances. However, there are some general considerations for investment decisions, which are derived from the MSDD.

The basic idea of the MSDD with respect to investment is: let the system drive the investment decisions, not the investment decision the system [Cochran et al., 2000]. Consider the selection of machines: at the outset of a system design project, there may be many machines available capable of producing a given product. The MSDD places several requirements on the equipment: operators must be able to operate them (FR-DP Q121), the equipment must be serviceable (FR-DP P121), machine cycle time must be conform with the overall production pace (FR-DP T221), quick changeover may be required if several products are produced (FR-DP T32), ergonomic interfaces (FR-DP D23), etc. Satisfying those requirements may reduce the number of available machines. The idea of the MSDD is that the final investment decision selects from a set of machines, which can satisfy the requirements stated in the MSDD.

Son [1991] points out how financial measurement systems can hinder achievements of system improvements, since qualitative benefits can often not be translated into financial measurements. The path dependency in the MSDD states that investment decisions should be based on the objectives and decisions made in the left branches of the decomposition.

3.4 Review of Use of Axiomatic Design

The following section discusses strengths and weaknesses of applying axiomatic design to manufacturing system design. (See also [Duda, 2000, pp. 78] and [Arinez, 2000, pp. 86].)

Separation of objectives and means

There exist numerous predefined solutions for manufacturing system design, such as manufacturing cells, kanban etc. Axiomatic design does not start with tools. It stipulates the need to state an objective first and then determine a design solution to satisfy the objective. This is entirely different than using predefined off-the-shelf solutions that fail to specify which design objective is satisfied. The MSDD only mentions tools when the tool satisfies a single objective. For example, Poka-Yoke devices are referred to in the MSDD as a means to prevent human errors from occurring (FR-DP Q123).

During the development of the MSDD, existing tools were thoroughly analyzed to determine which manufacturing system objectives they satisfied. This clarified the benefits and limitations of existing tools and showed how the tools helped to achieve a good system design. Sometimes the development team considered a design solution to be an important aspect of manufacturing system design before defining the underlying requirement it satisfied. It often turned out that the design solution was a conglomerate of several things spread out across different branches of the MSDD. For example, U-shaped manufacturing cells are a frequently cited tool for effective manufacturing system design. Such cells as designed and operated at Toyota satisfy numerous objectives rather than one single functional requirement. A manufacturing cell therefore represents a "physical integration" of several FRs and DPs (corollary 3 of axiomatic design [Suh, 1990, p. 52]). The advantage of explicitly stating the objectives and solutions is that system designers can relate how their activities help to achieve system goals.

Axiomatic design prevented an unreflected application of predefined design solutions. Rather than recommending a U-shaped cell, the MSDD spells out objectives and means that are satisfied by a U-shaped cell. Simply building U-form cells may lead to poor system design, if the cells cannot satisfy any objective.

Formulating FRs and DPs

The distinction of FRs and DPs may sometimes seem arbitrary. Is an FR really an FR and not a DP or vice versa? Suh [1990] suggests using verb-noun combinations for FRs and noun-verb combinations for DPs. While this suggestions helped to state FRs and DPs, there is still some arbitrariness left when formulating FRs and DPs, particularly at the high levels of the MSDD.

One to one relationship between FRs and DPs

Axiomatic design requires that one and only one DP for each FR. Multiple DPs for one FR would lead to either redundant or coupled designs [Suh, 1990, p.392]. Clausing criticized the strict one-to-one ratio arguing that it is possible to think of several sub-solutions for one FR [Clausing, 1989]. It was sometimes difficult to keep the one-to-one relation between FRs and DPs during the development of the MSDD. For example, there are several ways to satisfy FR-P1 "Minimize production disruptions": through capable information systems, equipment maintenance, standard work methods, standard material replenishment systems. The MSDD summarized all four solutions by stating a "summary"-DP "Predictable production resources", which was then further decomposed into information systems, equipment, people, and material. While the effort to state a "summary" DP seems to be artificial and cumbersome, it forced one to think about the objective for each stated design solution. If no objective could be determined, the design solution was abandoned.

Determining Dependencies

The need to state the dependencies among FRs and DPs at each level of the hierarchy is another valuable characteristic of axiomatic design. The development of the MSDD required careful thought about the dependencies. Since the FRs and DPs are often qualitative and broad, it was necessary to elaborate all possible facets of their meaning in order to define the dependencies. The discussions often lead to reformulations of FRs and DPs to avoid ambiguity and led to a common understanding of broad qualitative terms. The subsequent decomposition became crisper and more focused.

Creative process

The development of the MSDD was not a straightforward process of starting with the highest level FR and decomposing to the lowest level DP. Several iterations were necessary, which sometimes led to restating complete branches of the decomposition.

Ideas and inputs for the development of the MSDD came from various sources as mentioned before. Those inputs helped to define system requirements and design solutions. Pre-defined system design solutions such as manufacturing cells, were analyzed in terms of objectives and means.

3.5 Chapter Summary

This chapter presented the MSDD. Axiomatic design was applied to guide the development of the MSDD and was briefly discussed. The decomposition process resulted in the distinction of six main objectives for manufacturing systems: quality, identifying and resolving problems, predictable output, delay reduction, reduction of operational costs, and investment efficiency. The first five objectives were further decomposed into more specific objectives and means. The decomposition proceeded to a level that was specific enough to support design decisions without limiting the general applicability of the MSDD.

The chapter concluded with a review of axiomatic design, which proved to be a powerful tool to structure the thought process and development process of the MSDD. It was particularly useful for separating design objectives from solutions. While the axiomatic design terminology is sometimes not intuitive, it provided a common language among the development team.

Chapter 4 Research Framework

4.1 Introduction

This chapter outlines the research framework[2] applied in this thesis. Manufacturing system design lacks a unifying research framework [Wu, 2000; Hitomi, 1996, Hopp and Spearman, 1996]. The span and breadth of the field makes it difficult to apply a standard research framework. In order to perform the research of this thesis, it is therefore necessary to define a framework tailored to the specific needs of this research.

The research goal of the Production System Design laboratory is to develop a manufacturing system design approach that (1) clearly separates objectives from means of achievement, (2) relates low-level activities and decisions to high-level goals and requirements, (3) states the interrelationships among the different elements of a system design, (4) provides a common platform to effectively communicate this information across the organization, and (5) guides the designers throughout the system design.

This thesis contributes to that goal and consists of three steps as shown in Figure 4-1. The result of the first step is a framework for manufacturing system design. The Production System Design Laboratory has developed a Manufacturing System Design Decomposition (MSDD), which is used as this framework. The research of this thesis was part of the MSDD development. The second step validates and modifies the MSDD. The last step provides an outlook of how the MSDD can be applied in industry and derives future research activities.

[2] A framework is a set of ideas, conditions, or assumptions that determine how something will be approached, perceived, or understood [Webster dictionary].

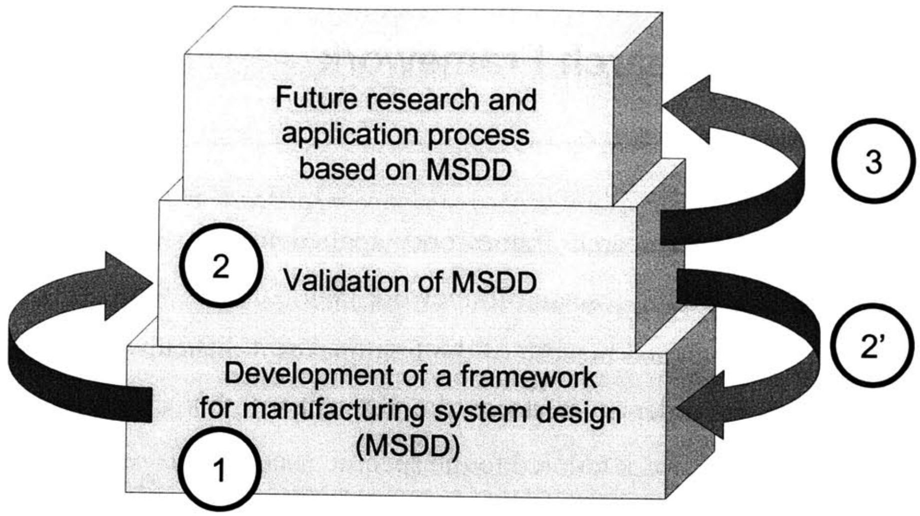


FIGURE 4-1: OVERALL RESEARCH STEPS OF THIS THESIS.

The following paragraphs review existing research methods and justify the choice of framework made for executing this research.

4.2 Review and Selection of Research Methods

Among the different types of research methods one might use, this thesis focuses on two that Leedy categorizes as quantitative and qualitative methods [Leedy, 1997]. Table 4-1 states characteristics of those two methods and indicates the relationship of each to the research area of the thesis. The table shows that qualitative research methods are more suitable for the given research area in most cases. However, there is no clear separation of qualitative and quantitative research methods which is reflected in the fact that the table also highlights quantitative aspects.

TABLE 4-1: CHARACTERISTICS OF QUANTITATIVE AND QUALITATIVE RESEARCH METHODS [LEEDY, 1997]. THE SHADED BOXES INDICATE THE RELATIONSHIP TO THE RESEARCH AREA OF THE THESIS.

	Two classes of research methods	
Question	**Quantitative**	**Qualitative**
What is the purpose of the research?	to explain and predict	to describe and explain
	to confirm and validate	to explore and interpret
	to test theory	to build theory
	outcome oriented	process oriented
What is the nature of the research process?	focused	holistic
	known variables	unknown variables
	established guidelines	flexible guidelines
	static design	emergent design
	context free	context-bound
	detached view	personal view
What are the methods of data collection?	representative, large sample	informative, small sample
	standardized instruments	observations, interviews
What is the form of reasoning used in analysis?	deductive analysis	inductive analysis
How are the findings communicated?	numbers	words
	statistics, aggregated data	narrative, individual quotes
	formal voice, scientific style	personal voice, literary style
Starting point	hypotheses	more general questions
	collect standardized data from large number of participants	collect an extensive amount of verbal data from a smaller # of participants
	analyze data in such a way that hypotheses can be supported or not	findings accurately reflect the situation under study

Leedy differentiates four different approaches to qualitative research: case study, ethnography, phenomenology, and grounded theory. Table 3-2 shows characteristic research questions for each of these approaches and indicates that ethnography and phenomenology are not appropriate for the development of a manufacturing system design methodology.

TABLE 4-2: APPROACHES AND TYPICAL RESEARCH QUESTIONS FOR QUALITATIVE RESEARCH [LEEDY, 1997]

Research Design	Central Question
Case Study	What are the characteristics of the phenomenon?
Ethnography	What is the culture of this group of people?
Phenomenology	What is the meaning of this experience for these people?
Grounded theory	What theoretical constructs, themes, and patterns are evidenced in the data?

An important distinction between grounded theory and case study based research is the role of theory development. Grounded theory avoids building a theory prior to data collection, since the goal is to form a theory based on gathered data. Case study, in contrast, encourages the development of a theoretical framework prior to data collection. Yin argues that successful performance of case studies requires a theoretical framework [Yin, 1994, p. 32]. The research of this thesis aims at validating and further developing the MSDD. Because the MSDD serves as a theoretical framework to guide the case study design and data collection, the research in this thesis does not rely on grounded theory.

Yin distinguishes multiple-case study and single-case study research. Developing a framework for manufacturing system design would be very subjective by studying only one company. The validity of the findings and the ability to generalize are much better in the multiple-case study approach, which was therefore chosen as the appropriate approach.

Yin shows in Figure 3-5 how to develop a theoretical framework for multi-case research [Yin, 1994, p.49] In this approach, cross case analysis leads to a modification and refinement of the theoretical framework. The dotted line in Figure 4-2 illustrates that the case studies reveal new insights, which may require a redesign of the data and case collection.

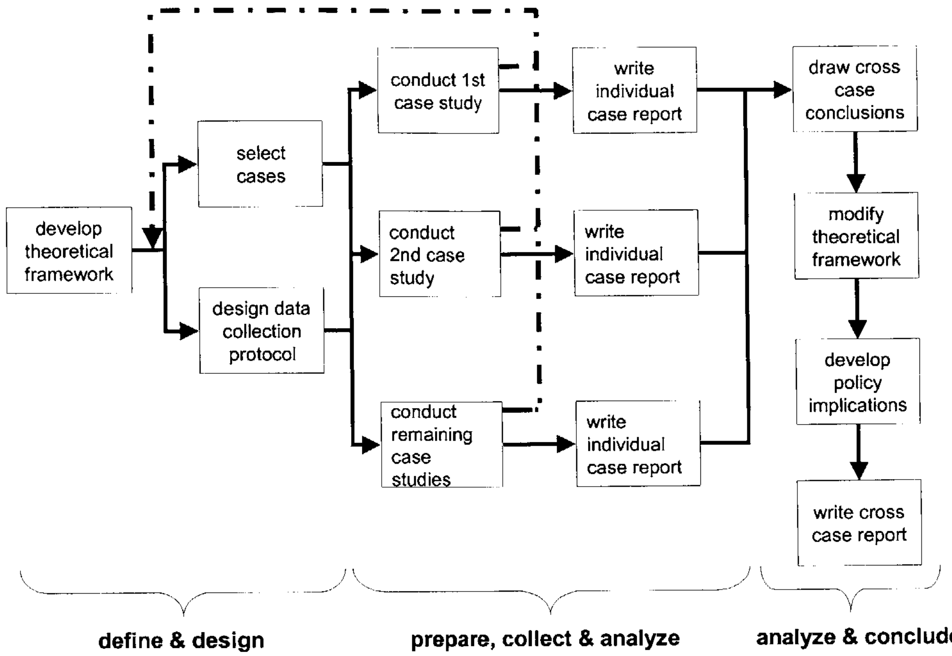


FIGURE 4-2: FRAMEWORK FOR MULTIPLE-CASE STUDY RESEARCH (ADAPTED FROM [YIN, 1994, P.49])

The following section describes how the multi-case study framework has been applied to the work in this thesis.

4.3 Applied Research Framework

A modified case study framework shown in Figure 4-3 integrates the three research steps illustrated in Figure 4-1. as described in more detail in the following paragraphs. The MSDD is the theoretical framework that is in place at the start of the case studies. The case selection and design of the data collection is based on the MSDD for the validation step. The findings of the case studies give rise to modifications of the MSDD that are incorporated into the application process and the future research paths. The following paragraphs describe the framework in more detail.

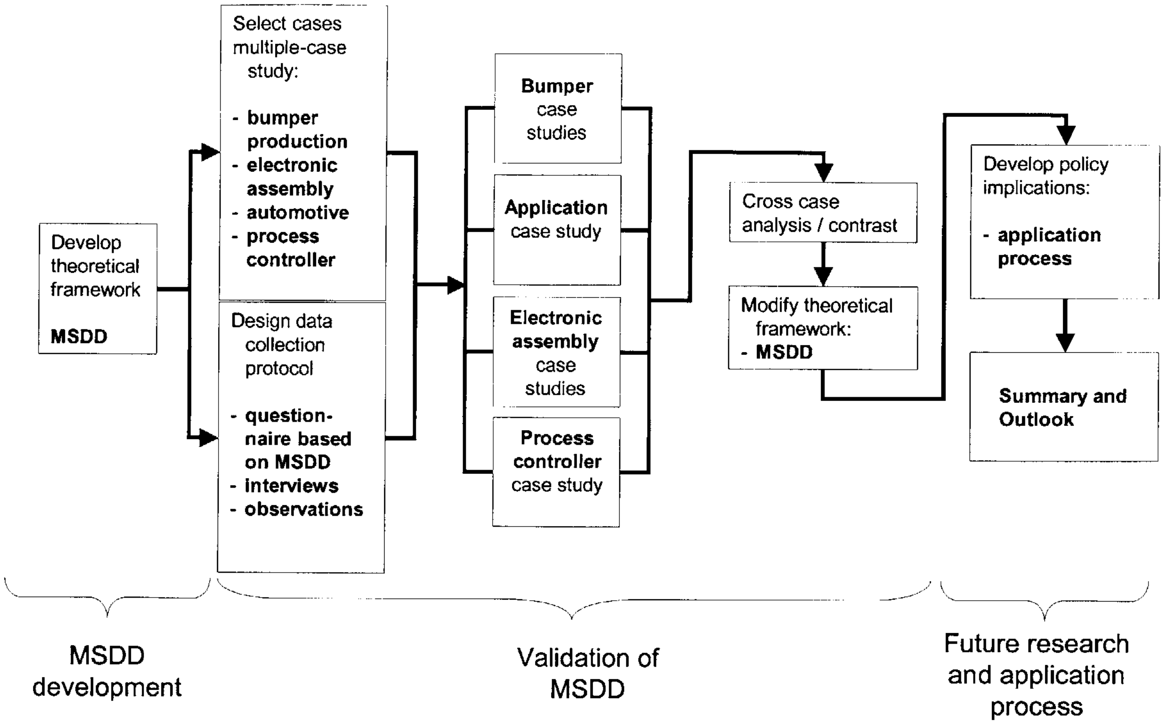


FIGURE 4-3: APPLIED CASE STUDY FRAMEWORK

4.3.1 MSDD Development

The development of the MSDD, illustrated in Figure 4-4, is based on a variety of sources, including the literature on manufacturing system design, studies of the Toyota Production System, and several research projects with industrial partners involving the actual design of manufacturing systems. The manufacturing system design decomposition (MSDD) synthesizes the findings into a resulting theoretical framework for the research of this thesis. Chapter 4 describes the MSDD in detail.

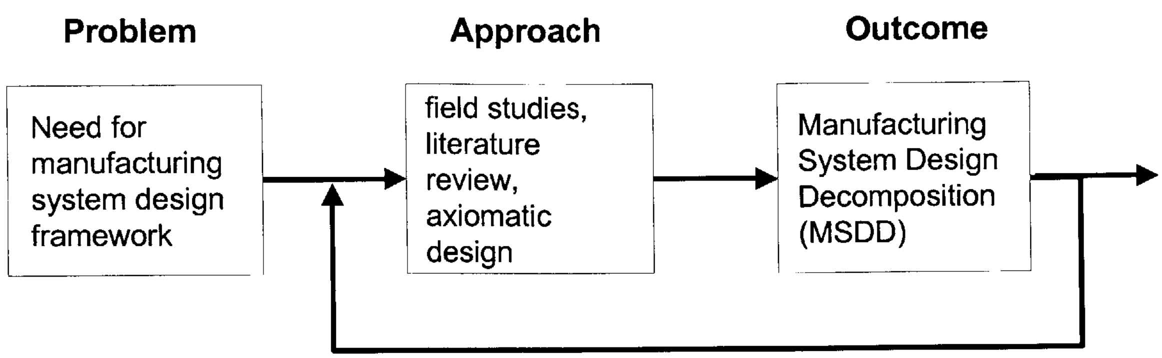


FIGURE 4-4: DEVELOPMENT OF MSDD.

4.3.2 Validation of MSDD

Validation in social science is a confirmation process for gathering evidence to test hypotheses [Krathwohl, 1998, p.4]. Validation of the MSDD means making the MSDD well grounded, making correct inferences from the premises provided by the MSDD. The purpose of the validation is to show that the MSDD provides a useful framework for manufacturing system design. One hypothesis in this study might be that using the MSDD to design a manufacturing system leads to an effective and well-performing manufacturing system. Another hypothesis might be that the MSDD can be used to assess how differences in system design contribute to strengths and weaknesses of different manufacturing systems. The validation of the MSDD lends support to inferences that one may draw from the premises provided by the MSDD.

Figure 4-5 summarizes the validation process. The original problem was to establish the usefulness of the MSDD with the help of a multiple-case study approach. Based on the findings of the validation, the MSDD will be modified. Furthermore, the validation process establishes a framework for future research with the MSDD.

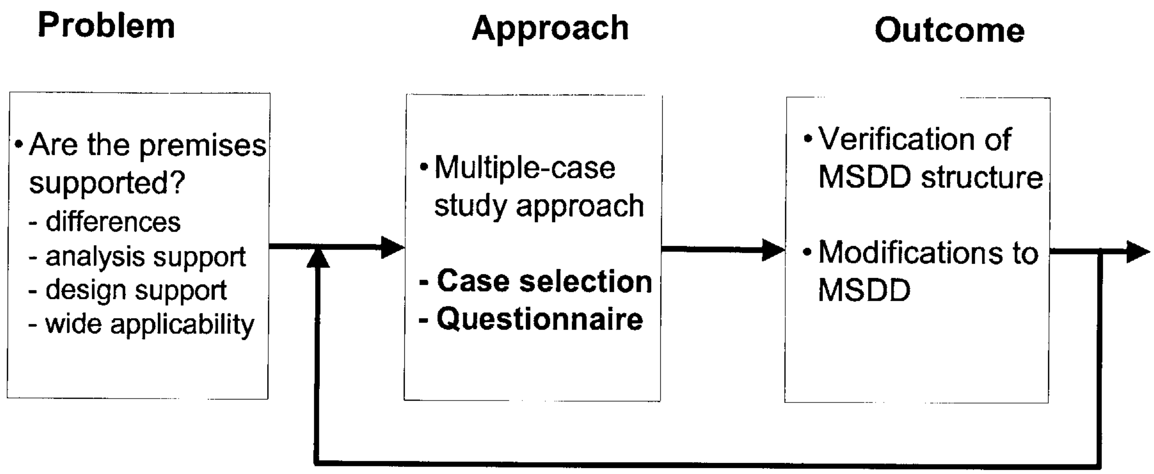


FIGURE 4-5: VALIDATION PROCESS

4.3.2.1 Selection of Companies

The selection of the companies must support the wide applicability of the MSDD. Four criteria were most important. Companies should:

(1) represent more than one industry. Selected companies in this study belong to automotive, electronic assembly, and consumer goods industries. The research found that the MSDD is not biased towards any of the three industries.

(2) show drastically different manufacturing system designs. Within the same industry, Rouse suggests selecting companies with distinctive different performance [Rouse et al., 1996]. Among several companies of the automotive industry that participated in this research, three sites produced plastic auto bumpers with significantly different system designs. The studies showed that the MSDD could explain the reasons for and the performance consequences of these different system designs.

(3) have different company size. Some companies in the study were part of a large corporation with multi-billion revenues, while others were small family owned businesses. The research showed no direct influence of company size on the applicability of the MSDD.

(4) should apply various processes and have various production volumes. The case studies involved machining and assembly processes in the automotive industry. Another company assembled electronic goods. Production volume ranged from 7,500 bumpers per day to 500 units per day.

Taken together, the four groups of case studies shown in Figure 4-3 satisfy the criteria mentioned above. The bumper case studies compare three plants producing plastic bumpers for the automotive industry. Two of the plants belong to the same cooperation and have drastically different system design than the third company. The system design of the third plant is very effective, while the design of the other two plants is medium to poor. The application case study mentioned in Figure 4-3 applies the MSDD for the design project in one of the bumper production plants. It is tested how the MSDD can be applied support system designers.

The electronic assembly case studies examine two distinctive line designs for the assembly of electronic products within the same company. The strength and weaknesses of both systems are explained with the help of the MSDD. Furthermore, the case studies suggest opportunities for future system designs. The process controller case study applies the MSDD for the analysis of a medium sized family owned company, which manufactures automatic process controllers for pressure and temperature. The company has a very efficient manufacturing system. It is examined if the MSDD captures the positive aspects of the manufacturing system design.

Theoretical and logical replication is a desired characteristic of multiple case studies [Yin, 1994, p.48]. Theoretical replication means that different results should be expected based on predictably different circumstances. Theoretical replication is achieved with the three bumper case studies. Two of the three plants show a medium to poor performance relative to the MSDD, while the third shows a strong performance. The third plant belongs to a company who is a worldwide benchmark for manufacturing efficiency. It was therefore expected that the plant would show a strong performance relative to the MSDD. The other two plants belong to an automotive supplier group that has initiated major redesign efforts in both plants in order to improve their performance. It was therefore expected that those two plants would not show a strong performance relative to the MSDD. Both expectations have been confirmed by the case studies.

Logical replication means that case studies based on the same prerequisites show similar results. That is, companies with a good manufacturing system design should show good performance relative to the MSDD and vice versa. One of the bumper production plants and the medium sized company are well known for their effective manufacturing systems. The case studies also showed a high performance relative to the MSDD. In contrast, it was expected that the other two bumper production plants would show a low performance which has been confirmed in the case studies. The research reveals that logical replication is achieved across industries and company sizes.

4.3.2.2 Data Capturing

The requirement of the data collection is to gather repeatable and comparable data with respect to the MSDD. For that purpose, a questionnaire is developed, which expresses the thought process behind the MSDD. Up to 8 people at each site filled out the questionnaire. The questionnaire asks specific questions related to the FR-DP pairs of the MSDD. The questionnaire and its role are described in detail in Chapter 5 after the MSDD has been presented. Furthermore, the data collection included observations, interviews, and discussions with a variety of people across the organization of the plants.

4.3.2.3 Analysis Strategy

The goal of the case studies is to verify if the MSDD reflects efficient manufacturing system design and can support the design process of manufacturing systems. The analysis of the data follows essentially two approaches as illustrated in Figure 4-6.

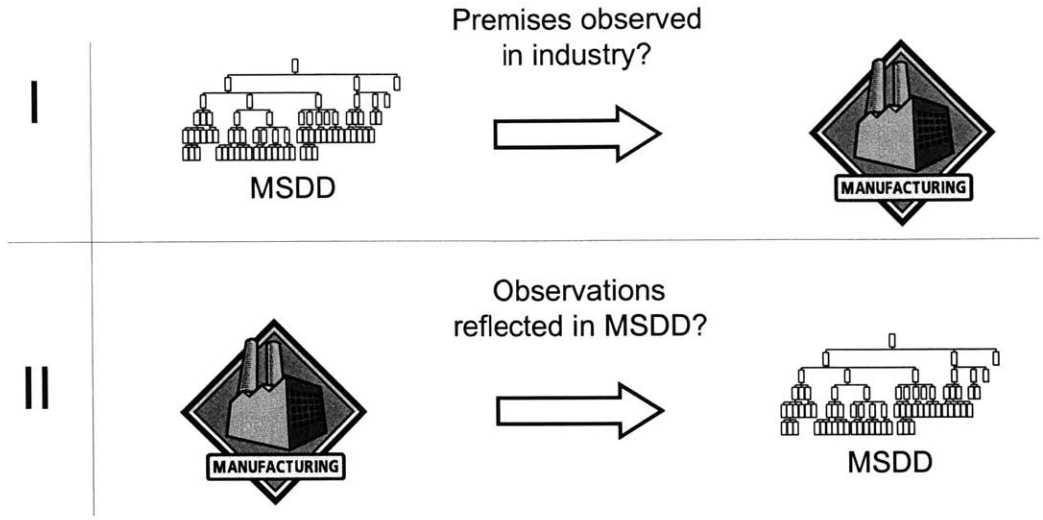


FIGURE 4-6: TWO APPROACHES FOR DATA ANALYSIS.

The first approach tests if the premises and propositions made by the MSDD are observed in industry. The premise is that a company achieving the requirements stated in the MSDD should show a superior system design than a company which does not achieve the requirements. For example, the MSDD states requirements and means to identify and resolve problems in manufacturing systems. The research then asks if a company, when following the described means, is able to identify and resolve problems. Standardized and comparable data capturing is essential for this type of analysis, which is facilitated by the questionnaire.

Furthermore, the MSDD makes the assumption that satisfying a particular objective can depend on the achievement of other objectives. For example, it is assumed that standardized work is required to achieve predictable operator output, which subsequently affects predictable material availability (see Chapter 4 "Predicable Output" for more details). The case studies examine if dependencies stated in the MSDD can be observed in industry.

The second approach relates observations to the MSDD and checks if the MSDD can explain the observations. For example, one company had a paint system for plastic bumpers, which finished one bumper every five seconds. Five operators were necessary to keep up with the paint system. The work of the operators was poorly balanced and showed several inefficiencies. The research then checked to see if the MSDD reflected the shortcoming of the system design.

In addition, the PSD lab was involved in system redesign projects in some companies. In those cases, the MSDD was used to derive improvement suggestions and to relate all performed design steps to the MSDD. The goal was to assess how the MSDD supports the design of manufacturing systems. This procedure was essential to derive an application process for the MSDD.

The questionnaire also provides a starting point for statistical analysis of the dependencies stated in the MSDD. So far, the MSDD does not contain information about the strengths of the dependencies. The questionnaire can be used to statistically support the stated dependencies. However, such an undertaking is a long-term research project. The work of this thesis establishes, however, a framework for statistical applications to further enhance the MSDD.

Conclusions about the strengths and weaknesses of the MSDD were a result of continuously relating all observations to the MSDD. The process allowed the detailed analysis of the structure and applicability of the MSDD and it derived modifications and recommendations.

4.3.3 Application Process

The final step of the overall research framework is the development of an application process as shown in Figure 4-7. One case study applies the MSDD in a system design project. The findings of the application provide a basis for future integration of the MSDD with an existing procedural design approach [e.g., Kettner, 1984]. Further research is necessary to fully develop an application process.

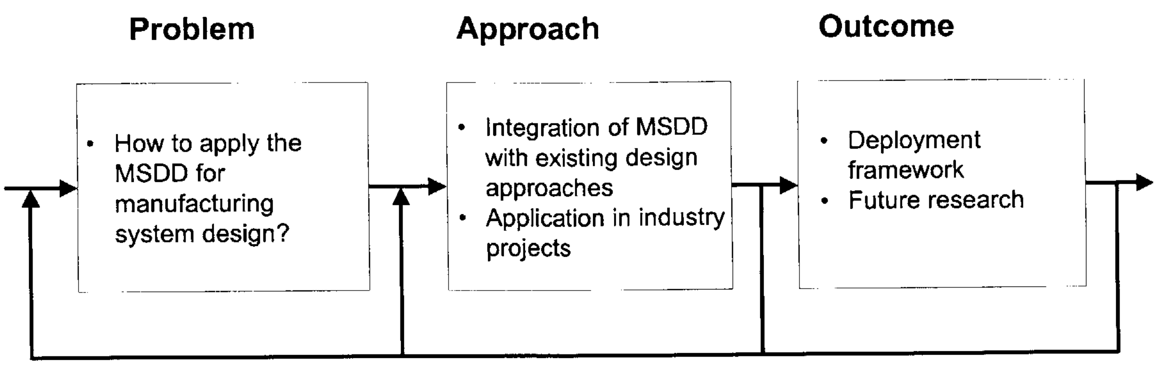


FIGURE 4-7: DEVELOPMENT OF APPLICATION PROCESS FOR MSDD.

4.4 Chapter Summary

This chapter described three steps, in which the research of this thesis contributes to the development of an integrative manufacturing system design. The first step is the development of the MSDD. The second step attempts to validate the usefulness of the MSDD. The third step outlines an application process for the MSDD in industry.

The chapter then developed a research framework in order to perform the three steps outline above. Existing research methodologies were reviewed. The chosen research framework to execute this research is based on a multiple-case study approach presented by Yin. Four groups of case studies were defined in order to examine if the MSDD provides a useful framework for manufacturing system design. The case studies are designed to support logical and theoretical replication. Data analysis consistently related all observations to the MSDD and led to modifications of the MSDD and to future research recommendations. The following chapter describes the data collection tool in detail.

Chapter 5 Design of Data Collection Tool

5.1 Introduction

The analysis approach outlined in Chapter 3 requires a standard way to evaluate a manufacturing system relative to the MSDD and to relate observations to the MSDD in a repeatable manner. It is necessary to standardize observations, interviews, and shop floor tours with respect to the MSDD.

This section describes the development of standardized data collection tool. The tool is a questionnaire with associated questions for each leaf-FR-DP pair. First, the requirements for such a tool are discussed. It follows a review of existing measurement tools for the MSDD before the development of the questionnaire is discussed.

5.2 Requirements for Data Collection Tool

The goal of the data collection tool is to enable the evaluation of companies relative to the MSDD. The data collection tool must support the gathering and interpretation of observations made during the case studies. The development of such a tool poses several questions:

1. Should the FR-DP pairs be measured quantitatively or qualitatively?
2. Is it enough to assess only those FR-DP pairs which are not decomposed any further, or should every FR-DP pair be assessed?
3. Is it necessary to evaluate the FR and DP together, or only the FR, or only the DP?
4. How to ensure comparability between data collections at different sites be ensured?

The following paragraphs discuss the questions to clarify the requirements for the data collection tool.

Evaluating FR-DP, only FR, only DP?

It is not the intention of the MSDD to prescribe design solutions. Therefore, the design parameters should not be seen as the only way to satisfy a stated objective. This suggests that measuring the achievement of an FR is sufficient and the DP would not have to be included in the evaluation process. However, the DPs stated in the MSDD are believed to be a reasonable way to satisfy the stated objectives and it was desirable to confirm if companies applied the suggested means. The consideration of both the FR and DP allowed one to verify if the stated DPs were too narrow, too broad, or perhaps wrong. Therefore, the data collection protocol for the case studies had to consider both FRs and DPs.

Only FRs that are not further decomposed

Is it enough to assess only the FR-DP pairs of the MSDD that are not decomposed any further (leaf FR-DP pairs) and to aggregate the measurements to the top level? That would assume that the higher-level FR-DP pair is the sum and only the sum of the lower-level FR-DP pairs. However, there is a common understanding in system design engineering that the system is more than the sum of the individual elements [Blanchard and Fabrycky, 1998]. Suh [2001, Chapter 4] describes this circumstance as "information associated with the assembly of modules". This suggests that measuring the leaf FR-DP pairs alone is not sufficient to determine the performance of a system relative to the MSDD. It is necessary to include additional information from higher levels of the decomposition.

Quantitative vs. Qualitative

Some FR-DP pairs express a process or procedure, which is difficult to assess using only quantitative data. For example, FR-P121 "Ensure that equipment is easily serviceable" and DP-P121 "Machines designed for serviceability" express the need to consider serviceability during the selection of equipment. The evaluation had to consider to what degree a company considers serviceability of equipment and how servicing equipment affects production.

Every plant uses metrics to measure its system. It would be advantageous to use existing data, since they are easy to obtain and could provide insight into the operation of the manufacturing system. However, the metrics are not necessarily compatible with the structure of the MSDD. For example, the MSDD distinguishes work in process due to process delay, run size, transportation etc. Those distinctions are usually not made in companies and would require converting company data to the specifics of the MSDD.

Furthermore, it is not always clearly defined how metrics are calculated. One company involved in the case studies used a metric "units per man hour" as a measurement for labor performance. However, two plants of the same company calculated the metric differently: one company included material supply personnel while the other did not.

Nevertheless, available data were considered during the case studies to back up observations. Conclusions were not solely based on those data but also were confirmed by first-hand observations or discussions.

Qualitative evaluation allows for a better consideration of the broad meaning of the MSDD. However, it is still required to standardize qualitative measures to ensure consistency of data capturing and analysis.

Comparability

The research is performed in various companies as described in Chapter 3. It is therefore necessary to ensure that observations can be compared with each other. The data collection should be applicable not only for the researcher, but should be transferable, i.e. employees of the companies and other researchers should also be able to use and understand the tool. This will ensure that future research can build on the results of this thesis.

In summary, in order to support the evaluation of companies relative to the MSDD, the data collection tool has to satisfy the following requirements:

- it must consider both the FR and the DP
- it must consider the meaning of not only the leaf FR-DP pairs, but also of the higher-level FR-DP pairs.
- it must be able to capture the full meaning of the FR-DP pairs. Evaluating only with quantitative measures is not sufficient.
- it must ensure comparability of data gathered at different companies.

5.3 Existing Measurements and Evaluation Tools for MSDD

5.3.1 Performance Measures

Each FR-DP pair of the MSDD has an associated performance measure (PM). Duda [2000, pp. 126] provides a detailed description of the measures. The following paragraphs discuss the applicability of the PMs for this research.

The development of the PMs starts with the highest level FR and follow the decomposition to the leaf FRs. The goal of the PMs is to quantify how well an FR has been satisfied rather than to evaluate how well a particular design parameter has been implemented. Table 5-1 shows the performance measures for the "identifying and resolving problems" branch of the MSDD (R-branch) and some other selected FRs, which will be discussed below. For example, FR-T4 "Reduce transportation delay" has the associated measure PM-T4 "Inventory due to transport delay". Some PMs simply measure, if an FR is satisfied or not, e.g., FR-T21 "Define takt time" has the associated PM-T21 "Has takt time been defined yes/no".

There are some obstacles in applying the PMs in industry. Several PMs are very detailed and almost impossible to assess in plants. PM-R112 "Time between identification of where disruption occurred and identification of what the disruption is" requires recording a time span that is very specific to single events. It would be very tedious to measure a whole system at this level of detail. In fact, attempts to apply the PMs during one pilot study quickly made it evident that the required level of detail was impossible to obtain.

Moreover, the general nature of most FRs makes it very difficult to assess the achievement of an FR with a single number. Even the lowest level of the MSDD is still very general in keeping with the desire to make the MSDD applicable to a wide range of companies, as discussed in Chapter 4. For example, FR-DP Q122 "Ensure that operators consistently perform tasks correctly" – "Standard work methods" stresses the importance of defining standard work methods, improving them over time, and ensuring that operators actually follow the standards. It points toward a process rather than a single event in time. The chosen performance measure, PM-Q122 "Number of defects per n parts caused by non-standard methods," focuses on a discrete outcome – number of defects. However, the intent of the MSDD is that work be performed according to a predefined procedure whether or not it results in a defect.

TABLE 5-1: EXAMPLES OF PERFORMANCE MEASURES FOR FUNCTIONAL REQUIREMENTS

Functional Requirement (FR)		Performance Measure (PM)	
FR-Q122	Ensure that operator consistently performs tasks correctly.	PM-Q122	Number of defects per n parts caused by non-standard methods.
FR-T21	Define takt time(s).	PM-T21	Has takt time been defined? (Yes / No).
FR-T4	Reduce transportation delay.	PM-T4	Inventory due to transportation delay.
FR-R1	Respond rapidly to production disruptions.	PM-R1	Time between occurrence and resolution of disruptions
FR-R11	Rapidly recognize production disruptions.	PM-R11	Time between occurrence of disruption and identification of what the disruption is.
FR-R111	Identify disruptions when they occur.	PM-R111	Time between identification of disruption and identification of where the disruption occurred.
FR-R112	Identify disruptions where they occur.	PM-R112	Time between occurrence and recognition that 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-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-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.
FR-R13	Solve problems immediately.	PM-R13	Time between support resource understanding what the disruption is and problem resolution.

While the PMs intend to measure the achievement of an FR, it is not obvious what magnitudes of a PM indicate a desirable achievement of an FR, and which do not. It is perhaps necessary to define company-specific or benchmarked target values for each PM [Duda, 2000, p. 136]. However, the determination of such specific values is beyond the scope of this thesis.

It would not be possible using the current PMs to reveal any inconsistencies between FRs and DPs. Inconsistencies may occur when a DP has a broader meaning than the FR or when the decomposition of a DP covers a wider spectrum than the decomposed DP. The PMs, though, only consider the FRs.

5.3.2 Evaluation Tool

A qualitative approach to assessing a company's system design relative to the MSDD is the evaluation tool shown in Figure 5-1 [Wang, 1999]. The tool measures 16 FR-DP pairs from various levels of the MSDD. The evaluation tool assesses how well a system satisfies each of the sixteen FRs in six levels with level 1 being the worst and level 6 being the best conformance with the FR. A description for each level of the DP helps the analyst to decide to what degree a system belongs to a particular level. Figure 5-2 shows the descriptions for FR-DP R1 "Respond rapidly to production disruptions." The pies indicate that the evaluated company's system shows at least some achievement of the DP at several levels. Similar approaches have been developed for equipment evaluation [Gomez et al., 2000].

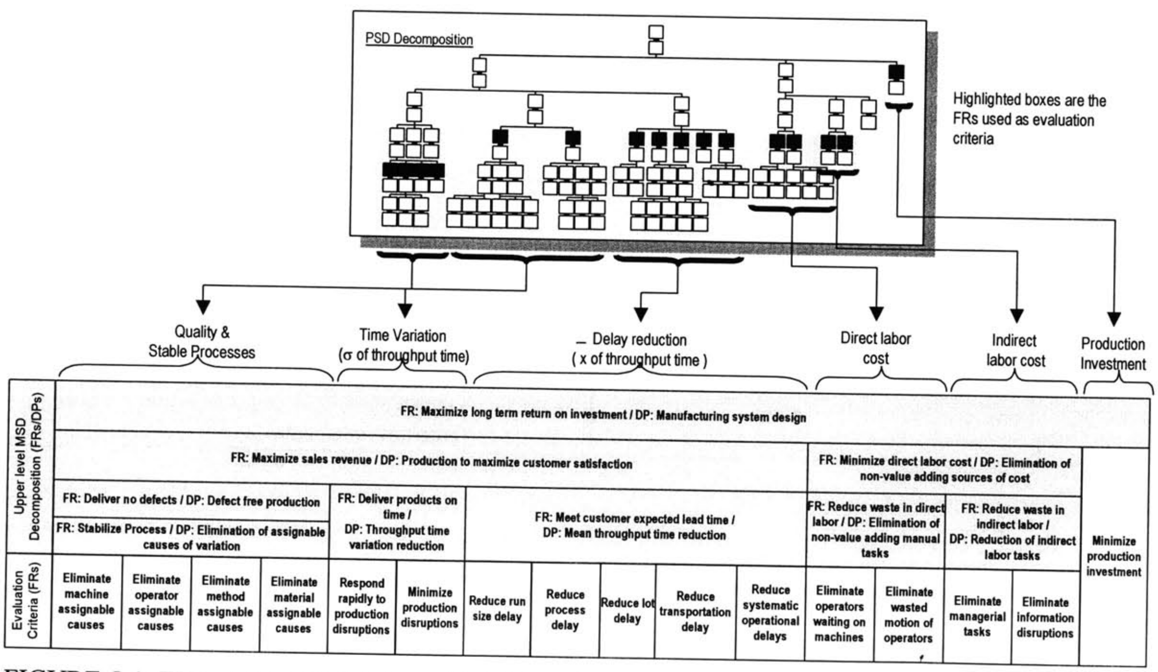


FIGURE 5-1: EVALUATION TOOL ASSESSES HOW WELL A SYSTEM SATISFIES 16 FR-DP PAIRS OF MSDD [WANG, 1999, P. 104].

The descriptions in the evaluation tool express the FR-DP pairs in terms of physical examples, which can be observed on the shop floor. The descriptions are more intuitive than the often abstract wording of the FRs and DPs found in the MSDD, thereby helping the analyst to associate an observed system with the MSDD. In that sense, the evaluation tool is better able to capture the thought process behind the MSDD than the performance measures discussed before.

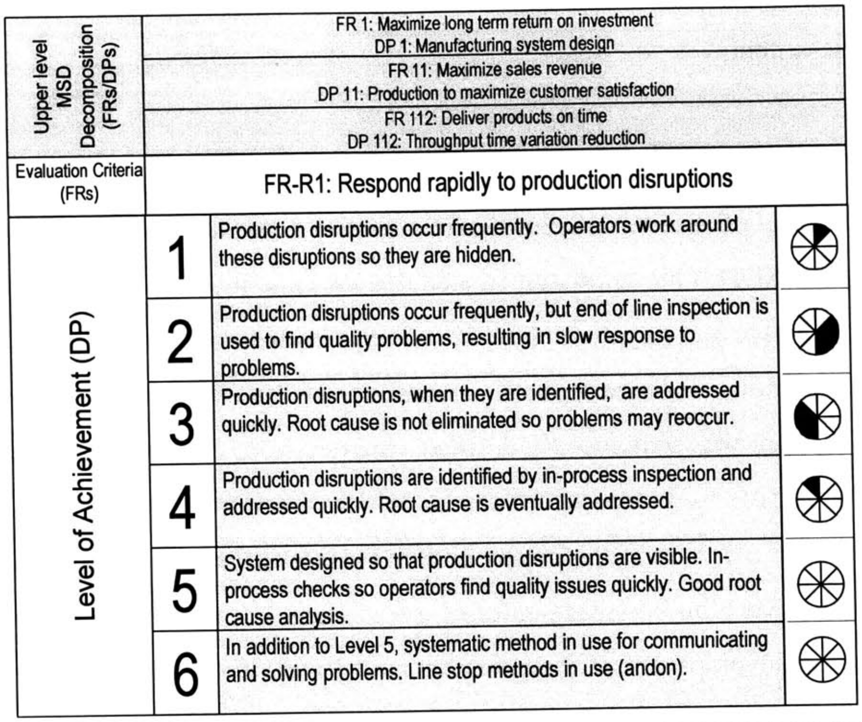


FIGURE 5-2: DETAIL OF EVALUATION TOOL SHOWING THE DESCRIPTION OF SIX LEVELS OF ACHIEVEMENT FOR FR-DP R1. THE PIE CHARTS ILLUSTRATE TO WHAT DEGREE A SYSTEM BELONGS TO A PARTICULAR LEVEL.

The sixteen FRs are selected at a level where the DPs can be physically observed in the manufacturing system. However, the "identifying and resolving problems" branch and the "predictable output" branch are evaluated by only a single FR, which, given the details of those two branches, seems inappropriate. In contrast, four FRs belong to the "quality" branch and 5 FRs to the "delay reduction" branch. Thus, the evaluation of the system design is heavily influenced by those latter two branches, an assumption that is not made in the MSDD.

The evaluation tool was applied to a medium sized company that specializes in metal deep drawing. The plant was evaluated during a two day visit. The goal was to assess the current situation of the company and to derive recommendations for future actions. The visit consisted of shop floor observations and interviews with employees across the organization. At the end of the visit, the evaluation tool was filled out to summarize the findings. It was found that the evaluation tool provided a good basis for categorizing the observations. However, the descriptions were not detailed enough to capture the full meaning of the MSDD. It was necessary to refer to lower level FR-DP pairs to make a complete assessment.

5.3.3 Other Approaches

There were several other attempts during field studies to evaluate a manufacturing system relative to the MSDD. One approach related discussions, interviews and observations to all leaf FRs. Positive and negative elements of the system eventually determined if an FR was achieved or not. A comparison of companies was based on the number of satisfied FRs. The procedure was only loosely defined. The decision, if an FR was satisfied or not, was fairly subjective as it was not clear on which data and observations the decision should be made. Furthermore, the binary coding was not very helpful to evaluate systems that were neither very bad nor very good. Nevertheless, the procedure was an important step towards the development of the questionnaire. Extensive discussions among the case study participants helped clarify the meaning of each FR-DP. Furthermore, it became more evident what kind of information was necessary to gather during case studies to evaluate a system relative to the MSDD.

These pilot field studies also considered how to relate standard performance metrics such as VDI (Verein Deutsche Ingineure) Norm 4004 to the MSDD [VDI Norm 4004]. The advantage of using such measures would be to establish a set of measures that could be used together with the MSDD. However, the MSDD provides a unique view of a manufacturing system by distinguishing six objective branches and, therefore, requires a unique set of measures. For example, the measures in the delay branch do not consider buffers due to unreliable resources or quality problems. Thus, measuring the overall WIP is not an appropriate measure for the MSDD. As a result, established measures were at best applicable at high-levels of the MSDD, but could not be used for the evaluation of lower levels, as they do not reflect the FR-DP relationships stated by the MSDD.

5.3.4 Summary

The performance measures presently included in the MSDD are not considered part of the data collection for this research for four reasons. First, it would require a tremendous amount of time to collect them; second, hard numbers cannot express the thought process of the MSDD; third, measures for different companies would not be comparable as it is not obvious what magnitudes of a PM indicate a desirable achievement of an FR; and fourth, the measures focus only on the FR and do not include the DP.

The evaluation tool described in Figures 5-1 and 5-2 assesses the broader meaning of the FR-DP pairs better than the PMs do. The evaluation tool qualitatively evaluates the performance of a system relative to 16 high-level FR-DP pairs. However, the tool is not detailed enough to be used for a general validation of the MSDD. It is therefore necessary to develop a more detailed assessment tool for the data collection during the case studies.

5.4 Standard Data Collection Tool (Questionnaire)

The chosen data collection tool is a questionnaire based on the MSDD. The questionnaire contains specific questions about the FR-DP pairs stated in the MSDD. The questions use a five-point Likert scale (also known as summated scales). Each scale measures a specific content i.e. the content of a particular FR-DP pair.

Likert scales are a commonly used tool in social science [Krathwohl, 1998]. Sakakibara et al. [1993] developed the JIT measurement framework presented in Chapter 2 based on Likert scales. Questions are answered with one of the following choices: (1) strongly disagree, (2) disagree, (3) neither agree nor disagree, (4) agree, (5) strongly agree, and (0) not applicable.

It is widely accepted in social science to use a 5- or 7-point scale to capture opinions from people [Flynn et al., 1990]. The answers to Likert scales form interval data, which allows the researcher to aggregate data and to apply statistics for making useful generalizations and determining relationships between scale items.

Respondents find Likert scales easy to use. Open-ended questions force the respondent to answer in his own words and can lead to a deeper coverage of the system. However, the wide scope of the MSDD would lead to many open ended questions requiring excessive time for respondents to fill out the questionnaire. Therefore, the questionnaire developed for this research uses mainly Likert scales), supplemented by open-ended questions when it is felt that additional information is necessary, e.g., asking for the amount of time spent on equipment maintenance.

The questionnaire format enables the researcher to express the thinking behind each FR-DP pair by asking several questions instead of using a single question. For example, the following questions are asked about FR-DP P122 "Service equipment regularly." – "Regular preventative maintenance program":

- We dedicate a portion of every day solely to preventive maintenance and follow the preventive maintenance schedule.
- We are usually behind production schedule and have no time for preventive maintenance. Repair is our maintenance.
- We emphasize proper maintenance as a strategy for achieving schedule compliance.
- Our equipment and tools are in a high state of readiness at all times.
- What percentage of time do you dedicate for preventive maintenance? (time for preventive maintenance / available production time).
- What percentage of time is lost due to unscheduled maintenance? (unscheduled maintenance / available production time)

Ideas for questions came from a variety of sources, including auditing handbooks (e.g., SCORE [Poschmann, 1985], [Chambers, Rand, 1997], [Cook et al., 1981]), existing questionnaire and surveys (e.g., [Sakakibara et al. 1993]; A.T. Kearney, 2000]), and manufacturing system design methods ([Spear, 1999]; [Grote et al., 2000]).

Using parts of existing reliable and valid questionnaires has the advantage that the questions can be considered being applicable for research without further testing their reliability. However, it is not always possible to use the existing questions as they have to comply with the meaning and structure of the MSDD. Several questions were originally included in the questionnaire, but later either modified or eliminated. For example, ideas from the KOMPASS method (see review in Chapter 2) provide useful ideas for formulating questions on operator related issues. It is not possible, though, to directly apply the questions of the KOMPASS method, as they are not formulated in Likert scale format [Grote et al., 2000].

The questions evaluate how well an FR-DP pair has been satisfied. The answers on the scale of 1 to 5 are translated into a measure of "goodness" of the system design. A "good" system design would be one that satisfies the FR-DP pairs as stated in the MSDD. In general, "strongly agree" means that the system design satisfies the FR-DP pair very well and vice versa for reverse scales. 25% of the questions are reverse, as recommended by [Alreck and Settle, 1985].

5.4.1 Development of Questionnaire

The formulation of the questions considered both the FR and the DP. It was found that some DPs unnecessarily limit the scope of the FR, while other DPs are broader than the FR. For example, FR-R111 "Identify disruptions when they occur" has the associated DP- R111 "Increased operator sampling rate of equipment status." The DP only focuses on disruptions due to equipment failures and excludes manual assembly operations. Another example is FR-D1 "Eliminate operators' waiting on machines" with DP-D1 "Human-Machine separation." The chosen DP reduces the purpose of human-machine separation to the elimination of waiting time. However, human-machine separation is a broad concept in manufacturing system design that includes aspects such as human flexibility, decision authority, and process transparency [Grote et al, 2000]. The decomposition of DP-D1 does not cover the full meaning of human-machine separation.

The development of the questionnaire first formulated questions only for the leaf FR-DP pairs. It was then asked whether or not the stated questions captured the full meaning of the higher-level FR-DP pair as well. If that was not the case, additional questions were formulated for those FR-DP pairs. If additional questions are necessary to capture the meaning of the higher-level FR-DP pairs, it might indicate an incomplete decomposition of the higher-level DP.

The consideration of the higher-level FR-DP pairs also revealed if the decomposition of a DP was actually broader than the DP itself. Consider the decomposition of DP-P12 "Maintenance of equipment reliability". The DP refers only to the maintenance of the equipment, while the decomposition includes requirements for the design of the equipment (FR-P121 "Ensure that equipment is easily serviceable" – DP-P121 "Machines designed to serviceability").

Similarity of some FR-DP pairs caused redundant questions when the questionnaire was first developed. For example, several FR-DP pairs relate to work standards: Q121, R111, P131. Since the original questions were formulated only with respect to one particular FR-DP pair, it was possible that similar questions were formulated for different FR-DP pairs. The questions were eventually removed, after analyzing if respondents answered the questions consistently. Redundant questions indicated a close relationship of FR-DP pairs.

The questionnaire was continuously modified and improved during the case studies. Additional questions captured new insights, initial reliability tests lead to removal or changing questions, and some questions were moved from one scale to another.

The process of developing the questionnaire provided a good check of the consistency and completeness of the decomposition. Findings were documented for future modifications of the MSDD and are discussed in Chapter 7.

Note: The four rightmost FR-DP pairs of the MSDD are not considered in the questionnaire and are not evaluated in the case studies for the reasons given below. The four FR-DP pairs are the following:

- FR-DP I1 "Improve effectiveness of production managers" – "Self directed work teams (horizontal organization)" and FR-DP I2 "Eliminate information disruptions" – "Seamless information flow (visual factory)" form the decomposition of FR-DP 12 "Reduce waste in indirect labor" – "Reduction of indirect labor tasks." It is believed that the decomposition is not sufficient to achieve a reduction of indirect labor costs. It would have to consider the overall organizational structure of a company, work organization, engineering etc. Capturing that meaning requires further development of the MSDD. Therefore, the two FR-DP pairs were not considered.

- The third FR-DP pair not considered is FR-DP 113 "Minimize facilities cost" – "Reduction of consumed floor space." The DP is much too narrow to capture the meaning of the FR. A meaningful consideration of facility costs in the MSDD requires a much broader decomposition.

- Finally, FR-DP 13 "Minimize investment over production system lifecycle" – "Investment based on a long term system strategy" was not decomposed as it was found that investment strategies are too dependent on the specific companies' needs. For the same reason, it was not possible to state generally applicable questions, which indicate good or bad investment decisions.

5.4.2 Reliability and Validity

There are several tools available to examine reliability and validity of surveys. Reliability examines the consistency and repeatability of the result for each scale. Establishing validity determines how well an instrument measures what it is intended to measure.

5.4.2.1 Reliability

Reliability measures the extent to which a questionnaire, summated scale, or item given to the same people will yield the same results. Reliability therefore measures the ability to replicate a study. The most widely accepted measure for reliability in empirical research is Cronbach's Alpha [Cronbach & Meehl, 1955]. The formula that determines Alpha uses the number of items per scale (k) and the average correlation between pairs of items (r) as expressed in equation (5.1):

$$\alpha = \frac{kr}{1+(k-1)r} \tag{5.1}$$

Alpha ranges from zero to one with one being the highest possible reliability. The literature suggests a minimum acceptable Alpha value of 0.70 for internal consistency. Nunnally [1978] suggests allowing values as low as 0.60 for newly developed scales, which was also used by Sakakibara et al. [1993] for the JIT measurement instrument. Therefore, in this research the lower boundary for Alpha is set at 0.60.

It was desirable to have between 3 and 5 questions for each scale. Some scales of the MSDD, however, consist of only one or two questions, since there would have been too much overlap with questions of other scales. For example, detailed questions for each of the three FR-DP pairs, which build the decomposition of FR-DP R12 "Communicate problems to the right people" – "Process for feedback of operation's state", would inflate the number of questions without providing additional insights. This is particularly true for very specific FR-DP pairs such as FR-DP R121 "Identify correct support resources" – "Specified support resources for each failure mode", which has only one associated question. The reliability test was then performed on the higher level FR-DP.

The software SPSS v. 10.0 provides an easy calculation of the Alpha values. The analysis did not consider answers with 0 values, i.e. if a respondent marked "not-applicable" at one question within a scale, the analysis did not consider any answer of that respondent within that scale.

Table 5-2 shows the results of the reliability test using 67 questionnaires from 49 respondents evaluating 17 different value streams in 10 different companies. Some people filled out several questionnaires both within the same company and across companies.

TABLE 5-2: RESULTS OF RELIABILITY TEST ANALYSIS

FR-DP Name	# questions	Alpha
Q11	3	0.74
Q121	4	0.62
Q122	5	0.81
Q123	3	0.84
Q13	2	0.60
Q14	3	0.69
Q2*	3	0.25
Q31	3	0.76
Q32	2	0.61
R111	4	0.88
R112	3	0.63
R113	3	0.71
R122	2	0.60
R123*	2	0.22
R13	4	0.71
P11	4	0.85
P121	4	0.69
P122	4	0.80
P131	5	0.80
P132	3	0.79
P133*	2	0.39

FR-DP Name	# questions	Alpha
P141	3	0.80
P142	3	0.65
T1	3	0.72
T21*	2	0.57
T221*	3	0.44
T222	2	0.82
T223	3	0.63
T23	2	0.63
T3	3	0.76
T31	4	0.67
T32	4	0.68
T4*	2	0.12
T51	5	0.81
T52	2	0.79
T53	2	0.63
D11*	3	0.43
D12	4	0.62
D21	4	0.72
D22	3	0.79
D23	3	0.79
D3*	3	0.53

FR-DP Name	# questions	Alpha
Q12 - Sum	12	0.90
Q3 - Sum	5	0.82
R11 - Sum	10	0.90
R12 - Sum	5	0.75
P12 - Sum	8	0.77
P13 - Sum	10	0.82
P14 - Sum	6	0.80
T2 - Sum	10	0.84
T3 - Sum	11	0.84
T5 - Sum	9	0.89
D1 - Sum	7	0.74
D2 - Sum	10	0.90

* Alpha values below 0.6

Overall, the reliability was good with only 7 out of 43 scales showing Alpha values below 0.6. Reliability was often low when a scale had only 2 associated questions (see R123, P133, T21, T4). The alpha value of T221 would improve from 0.44 to 0.85 when eliminating question number 3 "We usually try to minimize the number of machines by decreasing the cycle time per machine regardless of takt time." The table also shows Alpha values for aggregated scales in the right column. For example, if all questions for FR-DP R121, R122, and R123 were taken together (R12 – Sum in Table 5-2), the Alpha value is 0. 75. Note, that no value is shown for FR-DP R121, as there is only one question associated to that FR-DP pair.

FR-DP Q2 "Center process mean on the target" – "Process parameter adjustment" has three associated questions: (1) Process mean is only set within tolerances, but not necessarily on target. (2) We continuously monitor processes to check whether they are staying within tolerance specifications (e.g., through SPC). (3) We operate processes on target. Respondents were often not sure how process control was done in the value stream. As a result, the Alpha value of the scale is very low. This suggests that only people knowledgeable about quality control should fill out those questions.

The following example illustrates evidence of reliability outside statistical calculations. Two respondents in different companies accidentally filled out the questionnaire twice for the same value stream using the developed Access database. Neither had access to the first answers. One of the respondents checked the exact same answer 128 times, 2 answers differed by one scale point, and 2 questions were not answered the first time. In another case, a respondent had the exact same value 56 times, a difference of one scale point 46 times, a difference of two scale points 4 times, and 26 questions were not answered the first time.

Considering that this was the first time that scales have been developed for the MSDD and used in field research, the reliability of the questionnaire is quite acceptable. The questionnaire allows researchers to reliably gather data related to the MSDD, which greatly supports plant visits. Future research could also use the questionnaire to perform surveys and apply statistical analyses after gathering data from a large number of plants.

5.4.2.2 Validity

Validity establishes how well the questions for a given scale measure the scale. For example, it is important to know how well the questions for FR-DP P121 measure the meaning of that FR-DP pair. Three main types of validity are content validity, construct validity, and criterion-related validity and are discussed below.

Content validity

Content validity requires the researcher to judge to what extent a summated scale truly measures the concept it intended to measure. The scale content is defined by the MSDD, as every scale is associated with one FR-DP pair. In fact, the ability to express the full meaning of an FR-DP pair through a scale consisting of several questions was one of the motivations to use the questionnaire format. As a result, there is a high degree of content validity in the questionnaire. However, content validity is subjective and should be supported by a quantitative evaluation tool.

Construct Validity and Criterion Related Validity

Construct validity and criterion-related validity require a relatively large number of data points. All questionnaires filled out relative to one value stream would provide one data point. So far, there are only 17 value streams for which questionnaires are available. However, it is recommended to use about 10 times as many data points as items in a scale [Flynn et al., 1990]. Most scales of the questionnaire consist of 3 to 5 questions, which would require 30-50 data points. Thus, the present state of the research does not allow one to perform statistical validity tests yet.

Validity tests offer the possibility to examine hypothetical linkages between scales. Flynn et al. [1990] suggests to build a "nomological network" or framework to illustrate proposed linkages. The MSDD represents such a framework and validity tests could be used to confirm and possibly quantify the dependencies stated in the MSDD.

5.4.3 Limitations

The purpose of the questionnaire was to provide a standard set of data to be collected during the case studies and to enable comparison of observations. It is not intended to ask detailed questions about specific programs such as TPM or TQM, even though those programs are sometimes mentioned as a DP in the MSDD (e.g., DP-P122 "Regular preventive maintenance program"). One could design a whole questionnaire designated to preventive maintenance alone.

The intent of this research is not to develop a questionnaire that evaluates a complete enterprise, such as the A.T. Kearney GEO Awards questionnaire [A.T. Kearney, 2000]. Furthermore, the questionnaire is not laid out as a performance measurement instrument. The purpose of the data collection is to standardize data collection for the research of this thesis.

5.4.4 Use of Questionnaire During Research

This section describes how the questionnaire has been used during the research. The questionnaire guided the observations during the case studies. At the end of each case study, the questionnaire was completely filled out. It included extensive comments that complemented the answers to the questions that explain the observations and justify given responses. All filled out questionnaires are available in the database. In addition, the questionnaire was used to structure interviews.

People from various levels of the organizational hierarchy (assistant plant manager, area manager, superintendent, supervisor, manufacturing engineers) filled out the questionnaire. The answers were used to get an initial understanding of the employees' perception of the manufacturing system and were compared with the researcher's observations. Questions that showed a wide spread of responses were often starting points for more discussions. Potential inconsistencies in answers were clarified by follow-up discussions on the phone.

Respondents usually reacted positively to the questionnaire, often stating that the questions forced them to reflect on the manufacturing system design and operation from different perspectives. On average, it took people between 45 – 60 minutes to answer the complete questionnaire. It was rare that respondents answered the open ended questions or provided additional information in the comment field.

The questionnaire also facilitated the process of teaching and understanding the MSDD by referring to questions and then pointing out system dependencies. The completed questionnaires helped there researchers compare their own information and observations with the answers of system participants. Some questions showed a wide spread of answers (e.g., while one person strongly disagreed with a statement another person strongly agreed). In those cases, additional discussions tried to clarify the perceptions and resolve possible inconsistencies.

The filled-out questionnaire is graphically illustrated in an MSDD matrix in Figure 5-3. The boxes are colored coded and represent the average scale of the answered questions of a leaf FR-DP pair. Answering a positively phrased question with "strongly agree" accounts for 5 points (1 point for negatively formulated questions). For example, answering the questions "We are timing each operating step in detail and include the information in the work instructions." – "Variation in work completion time is being solved either by adjusting the work method or through operator training." – "The work completion time often varies between operators. (reverse scale)" with strongly agree, neither nor, and disagree would lead to an average of (5 + 3 + 4)/3 = 4 points. 0-values were not considered in determining the average. That is, if the answers to the questions above were strongly agree, not answered, and disagree, the average was (5 + 4)/2 = 4.5

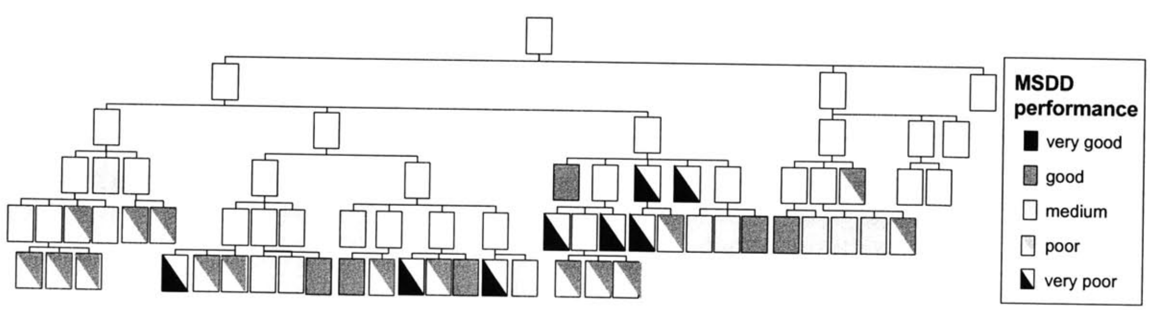


FIGURE 5-3: GRAPHICAL ILLUSTRATION OF FILLED OUT QUESTIONNAIRE.

The graphical illustration of the questionnaire provides a first insight into how the system satisfies the objectives stated in the MSDD. More detailed analysis and categorization is necessary to interpret the findings and derive improvement suggestions as described in 6.3.

The questionnaire format offered an excellent platform to document observations and findings by filling out comment fields for each question. A database facilitated the administration of the questionnaire and documentation of the case studies. It supported the analysis of the MSDD (e.g., understanding of dependencies between leaf FR-DP pairs of different branches) and the development of improvement activities for studied systems. Each question could be related to other FR-DP pairs to indicate similarities or dependencies. For example, questions of FR-DP Q32 were related to questions of FR-DP R13, since both dealt with improvements with respect to quality and time respectively. The purpose of this process was to qualitatively identify possible content dependencies between leaf FR-DP pairs from different branches. Statistical correlation analysis can be applied in future research once more data-points are available.

A comment field for each question includes specific suggestions of how to improve a system relative to that question. An additional field shows literature references e.g., for equipment serviceability (FR-DP P122) or quick changeover (FR-DP T32). Company specific recommendations are also possible. The electronic assembly case study in chapter 6 describes in more detail how improvements were developed from the analysis of the questionnaire.

5.4.5 Review of Data Collection Requirements

The questionnaire satisfies the requirements stated in 5.2. The development process considered both the FR and DP as described above. It started with the phrasing questions for the leaf FR-DP pairs and then reflected on the higher-level pair to ensure that the complete meaning of the MSDD is captured. The concept of phrasing several questions for each FR-DP allows capturing the full meaning of the objectives and means stated in the MSDD. A statistical analysis of the questionnaire showed good reliability of the questions, which ensures comparability of data gathered at different companies.

5.5 Summary

This Chapter described the development of a questionnaire used as the standard data collection tool for the case studies. The questionnaire consists of Likert scale questions associated with the leaf FR-DP pairs. Four requirements for the data collection tool were determined, which are all satisfied by the questionnaire.

Chapter 6 Case Studies

6.1 Introduction

This chapter describes the case studies that are performed as part of the validation process of the MSDD. Four different groups of case studies are described.

(1) The first group compares three bumper production plants. The goal of the case studies is to examine if the MSDD reflects different manufacturing system designs. The section describes in detail how the manufacturing systems of the three plants reflect the FR-DP pairs of the MSDD. The questionnaire is used to guide the data collection and to relate the observations to the MSDD. The analysis of the collected data shows that the MSDD can express and explain the different performance of the three plants. Each plant is described separately before comparing all three plants with each other.

(2) The second case explores how the MSDD can support the design of a new manufacturing system. The case study describes a design project that took place in one of the bumper production plants. The section explains how project objectives have been derived from the MSDD and how the FR-DP pairs and questionnaire can be used for the design of new manufacturing systems.

(3) The third group of case studies compares two different value streams for the assembly of the same product families at the same company. Both value streams show a similar performance relative to the MSDD. The goal of the case study is to examine whether the MSDD can explain differences in manufacturing systems that are not drastically different in their performance. The section develops an analysis approach for the questionnaire that allows clarifying the differences between the two value streams and guides the development of an alternative value stream design.

(4) The last case study analyzes a value stream in a medium sized company that produces automatic process controllers for pressure and temperature. The case study intends to support logical replication. The company is well known for having an efficient manufacturing system design. The evaluation also shows high performance relative to the

MSDD and therefore supports logical replication (see 4.3.2.1). The discussion points out the strengths of the company's manufacturing system design and remaining weaknesses.

Each group of case studies is described separately before the chapter concludes with a summary of the findings.

6.2 Bumper Production Case Studies

The following section compares three manufacturing systems producing plastic fascias for automobiles. The production of the bumpers requires 3 basic operations: injection molding, painting and assembly. These processes are essentially the same for all plants.

The goal of the case studies is to apply the MSDD in plants that produce similar products, but have different manufacturing system designs. The study shows how well the MSDD can explain observed differences. Each system is described and analyzed separately. First a general overview of the system is given, followed by a detailed discussion of every leaf FR-DP pair in the MSDD. The section describes how the manufacturing system of each plant does or does not satisfy the objectives stated in the MSDD. All answers and comments to the questions are documented in the database that is described in chapter 8. The final section of the bumper case studies summarizes the comparison of the three plants.

6.2.1 Plant M Case Study

6.2.1.1 Plant Overview

Plant M produces fuel tanks and plastic bumpers for the automotive industry. The area of interest in this case study is bumper production. The plant ships a daily average of 7,500 bumpers. It produces seven different bumper styles and additional service parts for old car models. The bumpers are painted in 13 different colors. Plant M operates 5 days a week with 3 eight-hour shifts. Additional shifts are scheduled on weekends if necessary. The bumpers are supplied to three customers. The customers operate five days a week with two nine-hour shifts plus some additional weekend shifts. The customer plants are located 30, 200, and 500 miles away from the plant.

6.2.1.1.1 Plant History and Layout

Plant M was founded in 1976 to produce plastic bumpers. Car manufacturers started to replace steel bumpers with plastic bumpers in the late 1970s. The bumpers during that time were not an integral part of the car body design. The bumper size was smaller and the part complexity lower than today. It was not necessary to match the bumper color with the car color. The bumper received an UV protective coat and was color painted for aesthetic reasons only. Quality requirements were much lower than today.

Figure 6-1 illustrates today's layout of plant M. The manufacturing system consists of four main areas: injection molding, paint, assembly, and storage. The bumpers are stored in the AS/RS. Automatic guided vehicles (AGVs) and electrified overhead monorails transport bumpers between the three production areas and the AS/RS.

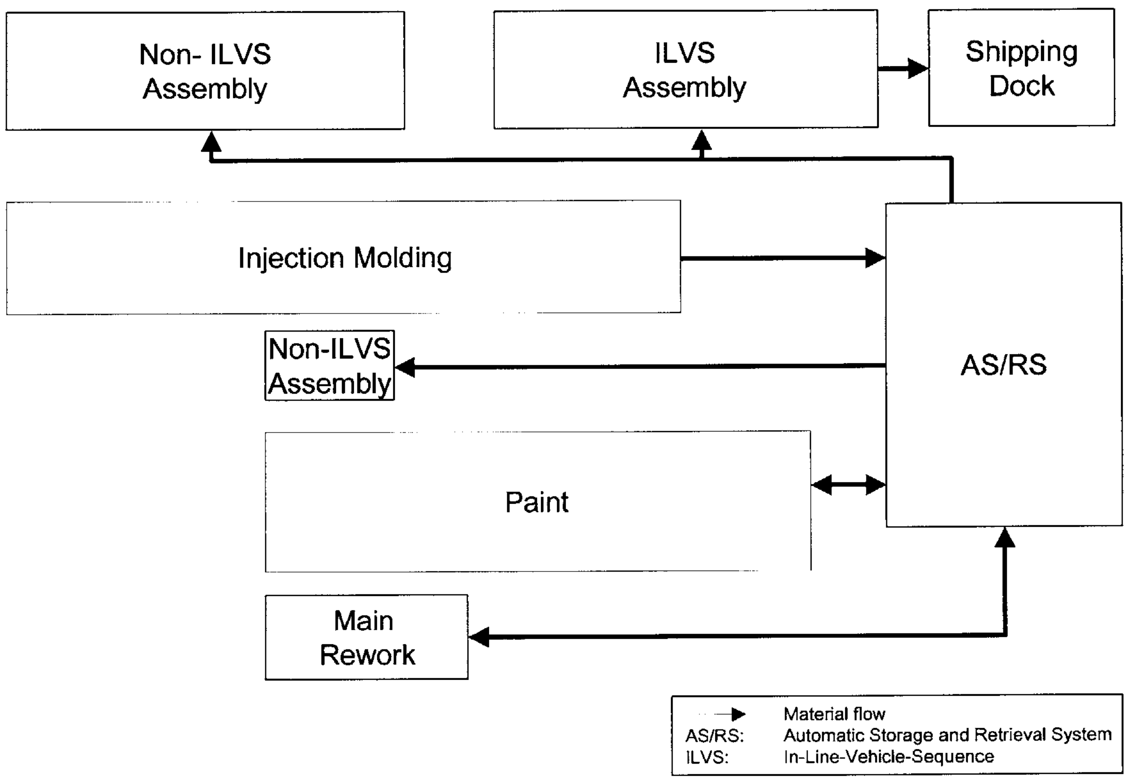


FIGURE 6-1: SCHEMATIC LAYOUT OF PLANT M

The plant has 17 injection molding machines with a clamp force of 4000 tons. The molds of the bumpers in the seventies and eighties required about 2000 – 3000 tons clamping force. The molds were smaller and less complex. Today's molds are larger, more complex and require up to 4000 tons clamping force. The injection molding machines are therefore operated close to their capability limits.

The paint system was installed during the late seventies. The main drivers for the selection of the system were high volume capacity, low direct labor requirements, high reliability and high repeatability. The system is highly automated. Robots apply all paint coats to the parts. It was originally planned to automate load and unload of the bumpers as well, but it was not realized due to part handling problems. The original system was able to produce 14,000 bumpers per day. Other smaller paint systems in the plant were built for prototypes or dual color painting and were manual due to the low volume. These systems are not used anymore. The paint system had to be upgraded several times to accommodate product changes and to match increasing quality requirements. Any upgrade was limited by financial resources and no building extensions were allowed. The present system operates at its limits with high downtimes and fallout rates.

The original assembly was performed on an assembly transfer line. Today's assembly content is much lower and one operator does all assembly at one station. All assembly is manual. The plant installed an In-Line-Vehicle-Sequence (ILVS) assembly area in the summer of 1999, which required significant investment for bumper buffer lanes as described in section 6.2.1.1.3.

The plant has a highly automated material handling system to transport and store the bumpers. The system was installed between 1982 and 1986. Three major upgrades have led to the present state of the material handling system. The system consists of Automatic Guided Vehicles (AGVs), electrified overhead monorails, and an Automated Storage and Retrieval System (AS/RS). The original motivation to invest in the material handling system was to manage the increasing product mix, to reduce the floor space necessary to store inventory, reduce fork lift traffic in the aisles and to reduce labor costs.

6.2.1.1.2 Value Stream

The value stream illustrates material and information flow (Figure 6-2). The symbols are depicted from Rother and Shook [1998]. The material flow is very simple: bumpers flow sequentially through the processes injection molding, paint, and assembly. The parts are sent to the AS/RS after injection molding and paint. The information flow is slightly more complex. A more detailed illustration of the material flow is shown in Figure 6-3.

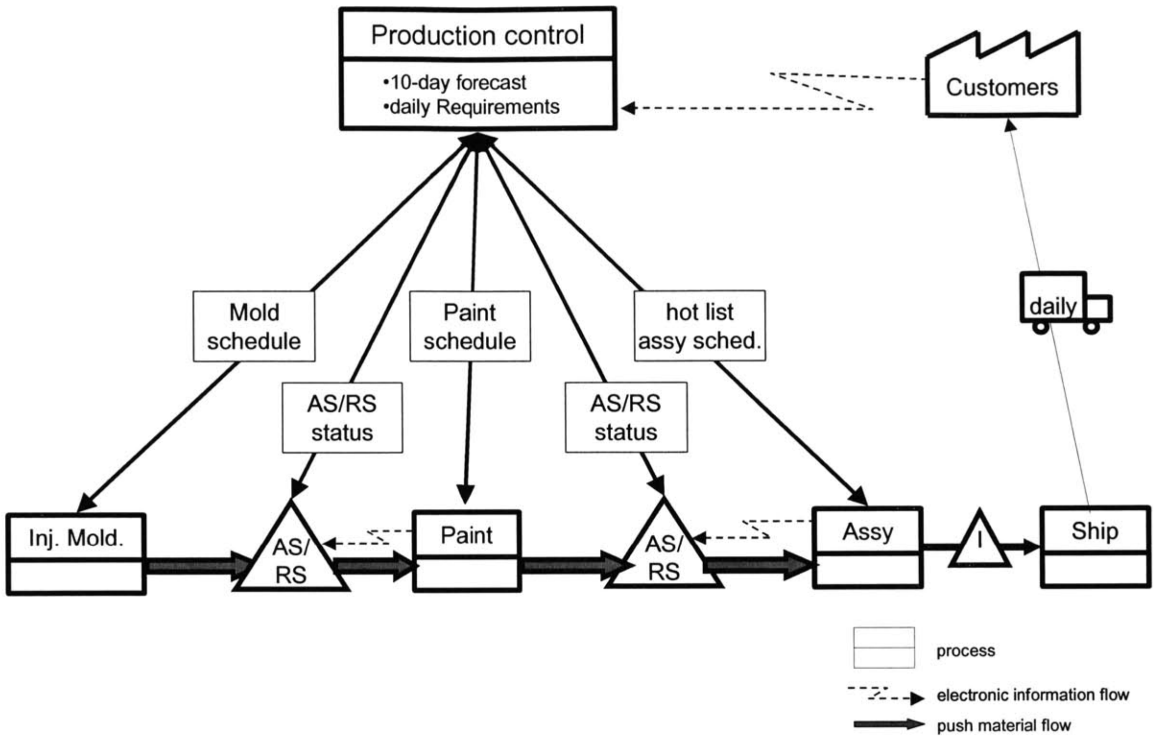


FIGURE 6-2: VALUE STREAM OF PLANT M.

Plant M receives several types of electronic production information from its customers: daily requirements, a ten-day forecast and the ILVS schedule, which reflects the fixed customer schedule for the next five days. Plant M aggregates the forecast into daily requirements by netting the existing inventory in the plant M and at the customer's sites. The result is the production schedule called the "scheduling matrix" or simply "matrix." Schedules for each process are based on the matrix and the matrix is the most important document in the daily operation of the plant. All supervisors and schedulers always carry a copy of the scheduling matrix. However, high process variability that leads to the manufacture of defective parts - particular in the paint process – causes frequent changes in the schedules. Line supervisors and scheduling personnel discuss twice per shift production occurrences to determine necessary schedule adjustments.

Each process is individually scheduled. Injection molding receives a schedule based on tool availability, aggregated daily demand, and output of the paint system. Paint receives a schedule, which takes into account the aggregated daily demand, the configuration of the part jigs in the paint system (see description of the paint process), and availability of molded parts.

Non-ILVS assembly receives a "hot-list" as a schedule. The hot list reflects items that must be built during the day to maintain customers' ability to produce. The desired inventory levels for the customer plants, which are 200 miles and 500 miles away, are two and seven days worth of material, respectively. It is not critical to assemble according to the schedule except for the items on the hot list. The daily objective is not necessarily to produce according to the schedule, but to assemble a given number of parts per day. The ILVS area assembles to the sequence given by the customer. The customer provides a fixed schedule for five days. Plant M is usually 1 – 1 ½ days ahead of the customer. The plant does not issue a separate assembly schedule for the ILVS assembly area.

Figure 6-3 shows the material flow in plant and illustrates the shared resources of the value stream. Seventeen injection molding machines produce bumpers. Some machines are dedicated to one bumper style. The machines are only changed over, if the mold is replaced by another mold of the same style to allow for mold maintenance. Other injection molding machines produce between two and three different styles. The cycle times mentioned in Figure 6-3 indicate a non-balanced situation between the different processes. Reasons for the unbalance are various downtimes, changeover times, and capacity buffers.

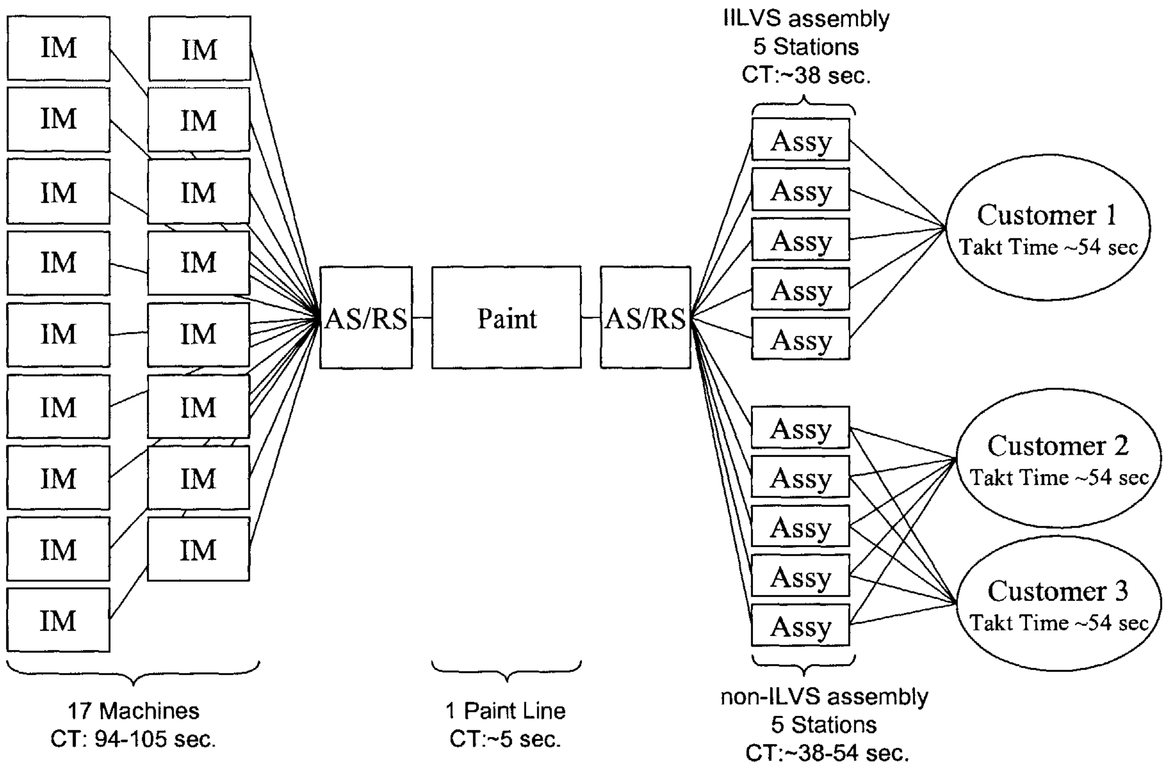


FIGURE 6-3: MATERIAL FLOW IN PLANT M.

6.2.1.1.3 Description of the Processes

Injection Molding

The seventeen injection molding machines produce a daily volume of about 8,500 bumpers. The product variety consists of seven bumper styles for current car models and seven bumper styles for service parts of previous car models. The machines have a cycle time between 94 and 105 seconds. The area operates three eight-hour shifts five days a week. However, not all machines are running at all times. Additional shifts are scheduled for weekends if necessary. The defect rate is between 2-8 percent.

Changeover times are estimated to take between 30 and 45 minutes, but can take up to six hours. The plant has preheating devices for some machines, but it does not always use the devices. Most machines, however, are dedicated to a particular style. The plant has up to four molds for a particular high volume bumper. Tool failure is a major concern. The tools are very complex and are operating at the upper limit of the machine capability as mentioned before.

The schematic layout of the injection molding area is illustrated in Figure 6-4. A robot unloads the bumper from the machine and drops it on a table, which can hold one part only. The operator takes the bumper from the table to his workbench, removes the running gate, deflashes the bumper and loads it onto an AS/RS racks. Each rack consists of six shelves. Each shelf holds one or two bumpers depending on the bumper style. AGV's transport the completed racks to the AS/RS. Seventeen machines are arranged along the aisle. An intermediate storage place holds one mold to be loaded into one of the adjacent machines. The other molds are stored in a dedicated area.

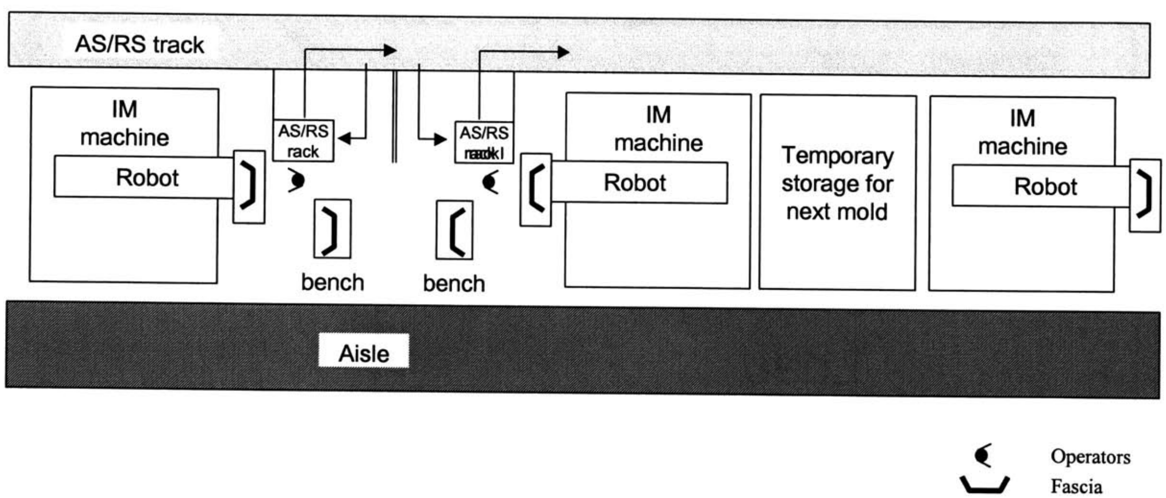


FIGURE 6-4: SCHEMATIC LAYOUT OF INJECTION MOLDING AREA IN PLANT M

Paint

The paint line consists of three major areas: (1) loading, (2) paint, (3) inspection and unloading. The overall daily volume is about 9,500 bumpers. The bumpers are painted in 13 different colors. Service parts only receive a base coat (TPO) but no color paint. The overall product mix is 66 colored bumpers and 14 different service parts. The minimum cycle time of the paint line is between 5 and 7 seconds per bumper, if the conveyor is running. The area operates three eight-hour shifts five days a week with additional shifts on weekends as needed.

The first-time-through yield of the paint system is between 95% and 25%. The average first-time-through yield is 82%, which is similar to other paint systems of comparable size and complexity used in industry. Defective parts can be repainted up to two times. The scrap rate is approximately 5%. The average uptime of the system is around 60%.

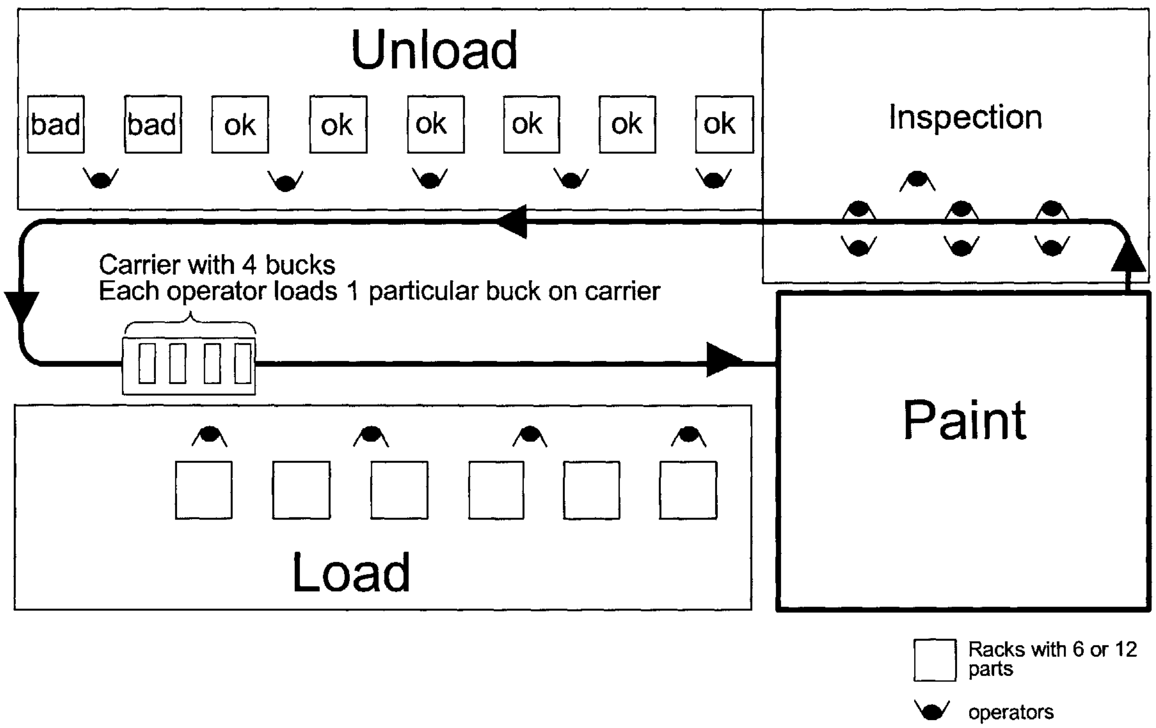


FIGURE 6-5: SCHEMATIC LAYOUT OF THE PAINT M'S PAINT SYSTEM.

The material handling system delivers racks with bumpers to the loading area as shown in Figure 6-5. Four operators load the bumpers onto jigs, where each bumper style has its own jig. Four jigs form one carrier. The carrier is attached to a conveyor chain, which transports the parts through the whole paint system. The conveyor consists of nine chains, which can stop independently from each other and run at different speeds.

Figure 6-6 shows the paint system in more detail. The system is highly automated with almost no direct work content. One operator programs the robots of the adhesion booth according to the incoming bumper style. Another operator programs the color at the entry of the paint booth. The remaining three operators in the paint booth form the setup crew for robots and other equipment. Additional support personnel exist for maintenance, engineering, and paint mix.

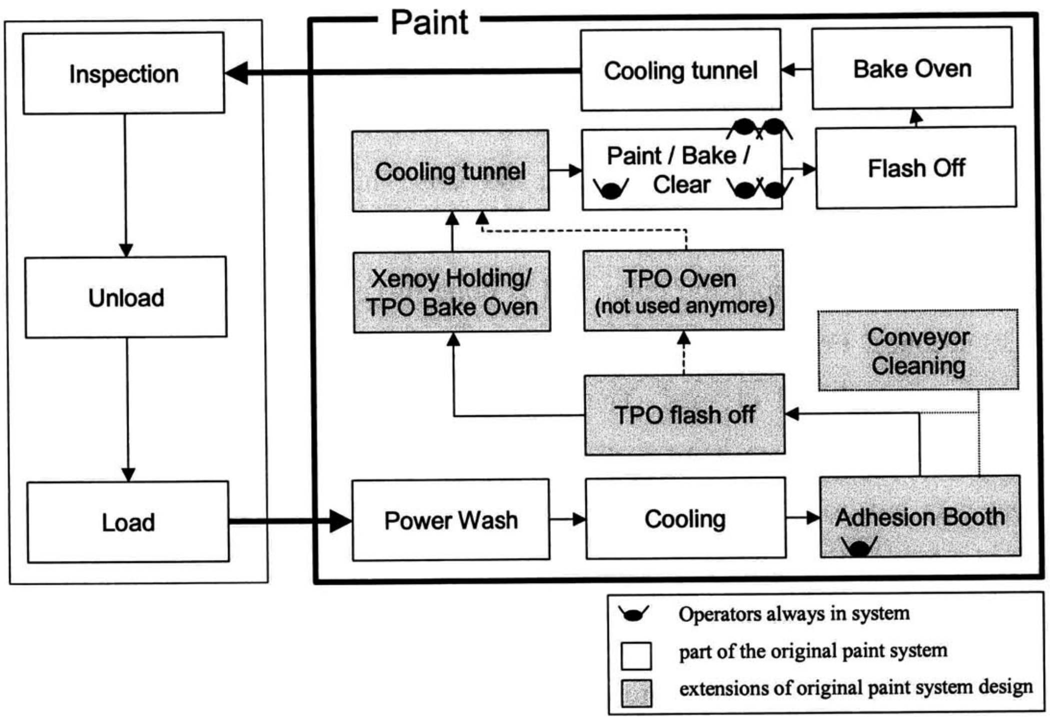


FIGURE 6-6: PROCESSES IN PLANT M'S PAINT SYSTEM.

The shaded boxes represent extensions to the original paint system design. The adhesion booth is fully automated except for one operator, who enters the appropriate programs. The TPO oven is not used anymore and parts flow through the Xenoy holding area instead without any processing. The cooling tunnel cools the parts down to the appropriate temperature to apply the paint.

The parts flow through the power wash, adhesion booth, and paint booth with a conveyor speed of 22 feet per minute. The conveyor speed is 60 feet per minute in all other areas of the paint system. The different conveyor speeds are used to buffer parts in the paint system against breakdowns in different areas. The different chain speeds cause the paint load and unload area to be idle occasionally. For that reason, the paint system seems to be "down" a lot, when observing the shop floor, while in fact it may be operating correctly.

The distribution of the jigs on the conveyor chain determines the possible product mix the paint line can produce. There are usually 40 – 200 jigs of the same style in a row, i.e. the batch size for any given style is between 40 and 200. Changeover of the jigs does not require stopping the conveyor. Jigs are changed over for three reasons: to exchange the jigs for another style, for jig maintenance, or for carrier cleaning. Due to the high defect rate of the paint system, the jig configuration is sometimes changed on short notice to accommodate high fall-out.

The parts are painted in batch sizes of 12 to 200 parts. There are two types of changeover: between styles and between colors. The style changeover requires a program adjustment for the robots, which apply the color and is done instantaneously. Color change takes about 30 seconds. For every color change the paint guns and color hoses of the robots have to be flushed and cleaned. The first parts of a new color batch are often of unacceptable quality, since paint particles remain in the paint booth for some time. In addition, it is not possible to paint the parts in every possible sequence, e.g., it is not possible to paint white after red. The problems in changeover in the paint booth are a major reason for the attempt to maximize the color batch sizes.

The inspectors check for quality problems and color conformity. There is one inspector for each side of the bumper. The operator determines the type of defect and concludes, if the bumper can be buffed or must be repaired. Any quality problem is reported to an operator, who keeps statistics about the defects. The next two operators down the line attach bar code stickers to the inside of the bumpers. The sticker contains information about the date, shift, part number, and paint batch. Bumpers that need to be repaired and have already been painted three times, are scrapped. The last two operators in the inspection area are taping parts of the bumpers to avoid damage during subsequent transportation.

Five operators unload the bumpers from the jigs and load them into AS/RS racks. There are 8 drop stations for AS/RS racks in the unload area. The first six racks are for good parts, the last two racks are for parts that either need repair or buffing. Each rack can hold 6 or 12 parts depending on the bumper style. Racks must be filled with bumpers of the same style and color. Racks are often partially filled due to either fall out, batch sizes, which are not divisible by six, or because unload operators do not complete one rack before unloading parts into the next rack.

The last two inspection operators program the racks with the color and style of the bumpers. Whenever a new batch comes down the line, the operators wait until the last good part of the previous batch has been unloaded from the line and the racks are released into the AS/RS. Then the operator types the new code for the next batch and all racks leaving the unload area are associated with the new code. Racks are frequently mislabeled, i.e. the rack holds parts other than shown in the AS/RS. Mislabeling can only be noticed at assembly, which is the next operation.

The operator unloading defective parts can mix bumper colors in one rack, but not styles. The operator separates parts that require repair and parts that can be buffed. Repair and buffing are performed in separate areas (see Figure 6-1). Repair parts are reworked and sent back to paint or are scrapped. Repair bumpers can only be painted with three colors. Scheduling closely follows the inventory of repair parts and releases them to paint load as soon as one of the three colors comes up. Otherwise, repair parts would occupy too much capacity of the AS/RS.

It may also happen that a whole batch of bumpers is quarantined when color seems to be of insufficient quality. A supervisor is called to make the final decision about whether the parts are good or bad. It can take several hours before the final decision is made. The parts have to be sent into the AS/RS to clear the paint conveyor. The supervisor has to call down a sample of parts to make the final decision. The AS/RS racks are then programmed as carrying either good parts or bad parts.

Assembly

The bumpers require assemblies such as attaching fog lights, grills, brackets, turn signal, and reflectors. The assembly is manual. Almost all assembly stations are laid out so that one operator assembles the whole bumper. This was not the case in the past, when the several operators assembled bumpers on a conveyor line. Plant M has distinct assembly areas for ILVS and non-ILVS as shown in Figure 6-1.

The **ILVS area** shown in Figure 6-7 can be divided into three sections: (1) unloading bumpers from AS/RS racks and loading them into the WIP lanes, (2) the WIP lanes, (3) the assembly and packaging sections. The ILVS area assembles the front, rear sedan and rear wagon bumpers of one car model. There are 10 different colors. The average volume for front and rear bumpers is 1,300 and 1,400 per day respectively. The assembly time is approximately 95 seconds for front bumpers and 40 seconds for rear bumpers. The ILVS area operates two nine hour shifts per day. The defect rate at assembly is between 2 and 3%. Most of the defects are due to defective incoming parts from injection molding and paint.

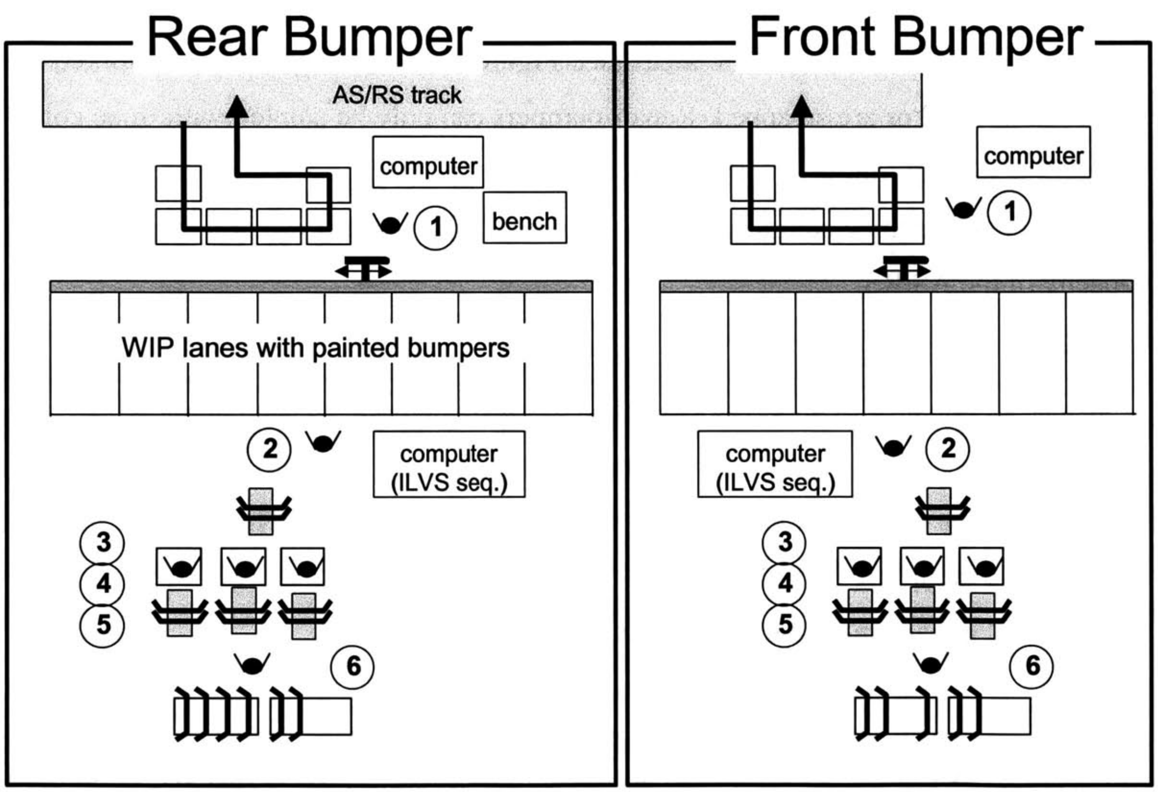


FIGURE 6-7: THE ILVS ASSEMBLY AREA IN PLANT M.

The first operator unloads parts coming from the AS/RS. The AS/RS delivery schedule depends on the ILVS schedule of the final assembly plant and the inventory status of the WIP lanes. Up to 5 AS/RS racks may be queued in front of the unloading station.

Operator 1 unloads the racks in a FIFO manner and loads the bumpers onto a sliding rack and puts them into the appropriate WIP lane. He also attaches a foot pad to rear wagon bumpers. The operator has to walk between 10 and 50 feet to load the bumpers into the gravity chutes of the WIP lanes. The operator sometimes stacks bumpers in batches of two or three to reduce walking.

Operator 1 uses the computer to record defects and other occurrences. The AS/RS racks can be mislabeled i.e. the rack holds different parts than shown in the computer system. The operator sends the rack to the AS/RS inspection area. Mislabeling is caused by paint unload. It is also possible that the number of parts on the rack deviates from the number of parts mentioned in the computer. If a bumper on the rack is defective, the operator puts the bumper aside and enters the defect in the AS/RS control system. The operator can also change the sequence, in which racks are ordered from the AS/RS if he recognizes that the WIP lane of a particular color is getting low.

The WIP lanes hold up to 118 parts for each color and style in gravity chutes. Each lane consists of three levels. One level can hold 18 parts. Rear bumpers for sedan and station wagons have 11 lanes with an overall capacity of almost 600 bumpers. Front bumpers have 8 lanes with an overall capacity of about 430 bumpers.

The ILVS assembly has three assembly stations each for front and rear bumpers. Operator 2 picks bumpers from the WIP lanes according to the ILVS schedule. He prints the sequence for the next shipping truck and picks the bumpers accordingly. He attaches a bar-code sticker to the bumper and puts the bumper onto a conveyor belt, which can hold up to four bumpers. Operators 3-5 take the next available bumper from the conveyor and assemble the bumper. The last operator, 6, checks the sequence of the bumpers and loads the bumper on the shipping rack.

The **non-ILVS** assembly area consists of five assembly cells. Three of the cells are dedicated to a particular bumper style. Two cells can assemble two or more styles. Each cell has two assembly stations. The non-ILVS area assembles front, rear sedan, and rear wagon bumpers for car model A and rear sedan bumpers for car model B. There are 9 different colors for each bumper, which are the same for both car models. The average daily volume is 1700 front, 1600 rear sedan, and 200 rear wagon bumpers for car model

A and 300 rear sedan bumpers for car model B. The assembly cycle time is 38 - 54 seconds per bumper. The non-ILVS area operates three eight hour shifts per day on five days per week. The number of operators per cell varies between two and six. The defect rate is about 2-3% with most of the defects due to incoming material.

Figure 6-8 illustrates a typical non-ILVS assembly station. The AS/RS sends material to the assembly cell. Two operators assemble the bumpers. A third operator inspects the part and drops the part onto a conveyor, which moves the parts about 6 feet in length and 2 feet in height. Two operators wrap the bumpers before the last operator loads the parts into shipping racks.

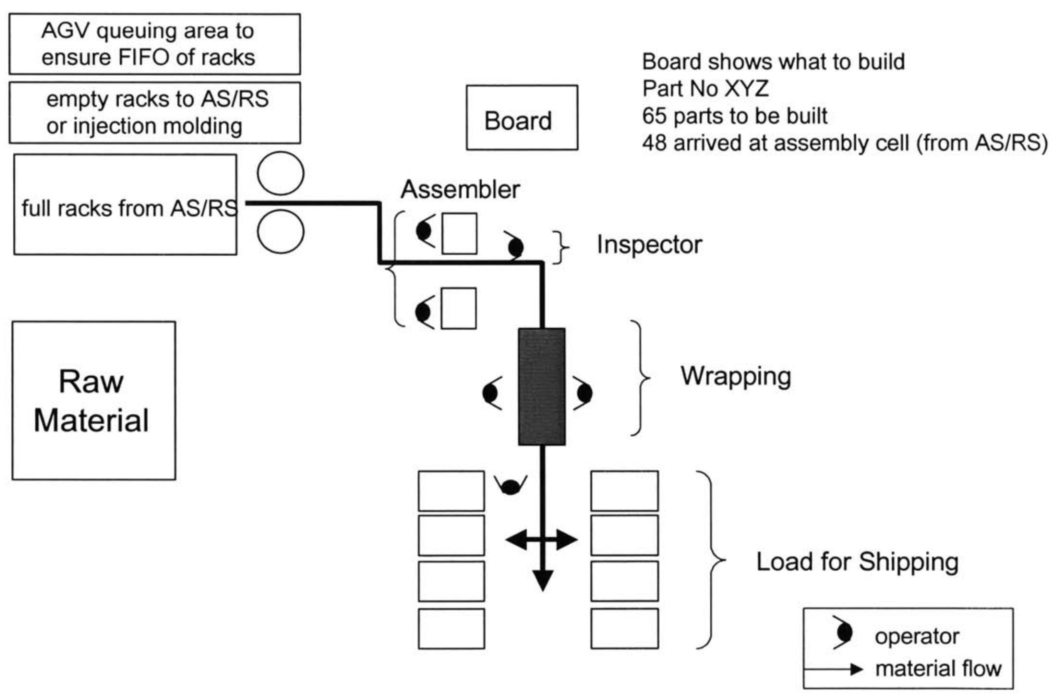


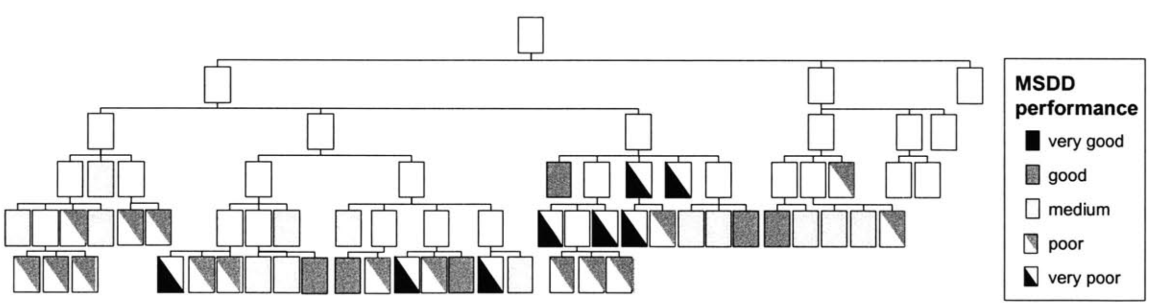
FIGURE 6-8: TYPICAL STATION FOR NON-ILVS ASSEMBLY.

The board in the cell shows the part number that must be assembled next. The cell experiences the same problems as the non-ILVS area: mislabeled racks, wrong number of parts per rack, defective parts in the rack. The inspector records those occurrences with the computer.

The defect rate at assembly is approximately 2%. However, plant M claims that most of the defects reported by the customer plant are due to mishandling of the parts at the customer plant. Unfortunately for plant M, this is hard to prove. As a result, plant M wraps the bumpers with two layers of cloth. In addition, tape is applied to the edges of the bumpers to avoid surface damage. There is a feeling in plant M that much of the wrapping and taping evolved from history and should not be necessary. It is also speculated that the customer blames plant M for defects that are caused by material handling at the customer site.

6.2.1.2 Evaluation and Analysis

The overall evaluation of plant M is shown in Figure 6-9. The performance relative to the MSDD is poor. The evaluation summarizes observations made during plant visits, discussions with personnel, and answers of respondents of the questionnaire. Seven employees filled out the questionnaire: the assistant plant manger, area manager of the bumper production, the superintendents of injection molding, paint, and assembly, the industrial engineer, and a manufacturing engineer.



	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M overall	20	49	39	21	2	1

FIGURE 6-9: OVERALL EVALUATION OF PLANT M RELATIVE TO THE MSDD AND SCORE DISTRIBUTION OF QUESTIONS.

The following paragraphs describe the analysis in detail. Each decomposition branch of the MSDD is discussed separately. Within a branch, the write-up follows the MSDD decomposition from left to right and refers in brackets to the FR-DP pair being discussed.

6.2.1.2.1 Quality (FR-DP Qx)

The quality branch of the MSDD focuses on the ability of individual processes to manufacture products according to product specifications. The overall performance is medium to poor. Table 6-1 summarizes the quality branch for plant M and shows the score distribution of the questionnaire.

Plant M – being a supplier for the automotive industry – must deliver high quality to its customers. The internal defect rate, however, is fairly high. This is partially due to the nature of the processes: The first time through percentage of 82% at the paint system averages the industry standard. Nevertheless, there are some problems inherent in the system design and operation, which contribute to the internal defect rate: no formal operator training, low enforcement of work methods, complex injection molding tools, and problems in integrating new technology in the paint system.

TABLE 6-1: SUMMARY OF QUALITY BRANCH

	FR	DP	Plant M
Q11	Eliminate machine assignable causes	Failure mode and effects analysis	Plant M has a database to record all machine problems, but obtaining data is not standardized. Injection molding and paint operate at process capability limits. High variation and fall-out rate at paint.
Q12	Eliminate operator assignable causes	Stable output from operators	Most operators are only trained on the job. Work methods are not clearly defined and not adhered to. High variation in operator output.
Q13	Eliminate method assignable causes.	Process plan design	Process descriptions exist for most operations, but are not frequently updated. Assembly operators tend to create their own sequences. No standard improvement procedures.
Q14	Eliminate material assignable causes	Supplier quality program	Most incoming material is defect free. Strict requirement for suppliers. Some cooperation with suppliers.
Q2	Center process mean on the target	Process parameter adjustment	Processes are generally operated within tolerances, not necessarily on target. Continuous process monitoring at some processes.
Q3	Reduce variation in process output	Reduction of process noise	Paint system sensitive to dust etc. due to paint extensions over the years. Continuous efforts to make processes more robust, but limited time due to fire-fighting.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M - Quality	1	15	10	2	0	0

Machine assignable causes (FR-DP Q11)

Plant M has to deal with some problems regarding the stability, reliability, and quality of the processes. The molds in injection molding are very complex and force the plant to operate molding machines at the upper limit of their capabilities. The paint system was originally designed for a different paint process. The upgrades of the system over the years have made the system difficult to control. The physical layout of the paint system causes dirt contamination, which the plant has been improving for several years now.

While plant M tries to eliminate assignable causes, it often does not fix a problem permanently (see discussions in section 6.2.1.2.3 "Predictable Output"). Plant M also has frequent meetings to eliminate quality problems.

Injection molding's defect rate is approximately 2.5% according to the database. 2% of the defects are due to machine assignable causes such as short shots, oil leaking, and excess flash. The molds are complex and not always perfectly maintained. The remaining defects are due to operator errors such as chatters and poor trim. Paint and assembly report additional 1.5% and 0.3% defects, respectively, which are due to injection molding. Therefore, the overall defect rate of injection molding is about 4%.

Paint experiences a fall out rate between 5% and 75%, with an average first time through percentage of around 82%. Approximately half of the defects are due to machine assignable causes such as broken or dirty paint guns. The rest is caused either by incoming material (paint and molded parts) and wrong process parameter adjustments. The most frequent problem is foreign substance such as dirt coming in from the environment.

Operator assignable causes (FR-DP Q12)

Most operators are only trained on-the-job (FR-DP Q121). Experienced operators teach new operators the work tasks. According to the answers of the questionnaire, training procedures do not exist for every operation. Operators only have to go through a formal safety class. Training for setup and maintenance employees becomes more formal and thorough.

Work instructions exist for most operations and describe the work tasks, necessary material, critical inspection points, work sequence, but contain no timing information (see discussions in section 6.2.1.2.2 "Identifying and Resolving Problem"). One can observe a lot of variability in performing the work tasks between different cycles and between operators. Work standards are not enforced (FR-DP Q122). For example, some operators at paint unload stack two bumpers before carrying them to the AS/RS rack. Others carry each bumper individually – as it is described in the work instructions. Some operators at ILVS assembly pick two bumpers from the color lanes, stack them and carry them to the assembly conveyor. Others carry each bumper individually. The sequence in which operators assemble parts to the bumpers, differs between operators. Some of the differences in task performance can be explained by the physical layout of the workstations. At paint load and unload, for example, it is tempting to pick more than one bumper at a time to reduce walking.

Downstream processes often detect defective parts from upstream operations (FR-DP Q123). According the database, approximately 8% of the defects at paint are due to defective bumpers sent from injection molding. Almost 30% of the defects recorded at assembly are caused by injection molding or paint. This suggests that either the operators at the upstream processes have no time to inspect the parts thoroughly or do not perform the work tasks properly.

Method assignable causes (FR-DP Q13)

Operation sequences are defined for most operations. Descriptions are not always updated. Process changes and improvements are often not documented and not reflected in the descriptions. For example, assembly descriptions for one bumper type did not reflect that additional tape had to be put on the bumper for surface protection. However, operators do attach the tape, after it has been orally explained.

Material assignable causes (FR-DP Q14)

Plant M has strict requirements for suppliers to ensure high quality of incoming material. Most quality checks of incoming material have been eliminated. However, one area manager pointed out that the processes themselves are the quality check. There is some cooperation with suppliers, but not in a regular standard way.

Process mean (FR-DP Q2)

Processes are generally operated within the specified tolerances. Plant M does not have a process in place that continuously monitors the manufacturing processes to recognize when the process is approaching the upper or lower specification limits. Process parameter adjustments are usually done, when a defect or a disruption occurs.

Process output variation (FR-DP Q3)

The paint process is very sensitive to environmental disturbances such as dirt or humidity. Some extensions of the paint system (e.g., the TPO oven) are causing dust problems due to the construction of the booths. The plant is continuously improving the system to avoid such disturbances. It does not seem that plant M has standard procedures in place to convert common causes for defects into assignable causes according to discussions and the answers in the questionnaire.

6.2.1.2.2 Identifying and Resolving Problems (FR-DP Rx)

The scope of the "identifying and resolving problems" branch is how production disruptions are recognized, communicated and resolved. Plant M's overall performance in this branch is medium to poor. Variation in manual work cannot be determined, since time standards do often not exist, or are not enforced. Communication paths are defined but not always followed. Time pressure and process instabilities lead to "fire fighting" and prevent elimination of root causes. This also influences the predictability of operators' output (see discussion in Section 6.2.1.2.3).

TABLE 6-2: SUMMARY OF THE IDENTIFYING AND RESOLVING PROBLEM BRANCH.

	FR	DP	Comment
R11	Rapidly recognize production disruptions	Subsystem configuration to enable operator's detection of disruptions	System does not expose problems. Time standards are not defined. There is low discipline to follow defined procedures. Disruptions are often hidden. Equipment availability has high variation.
R12	Communicate problems to the right people	Process for feedback of operation's state	Communication paths are predefined in most cases, but are sometimes not very direct.
R13	Solve problems immediately	Standard method to identify and eliminate root cause	Standard problem solving procedures do not exist. Repair is focused to keep production moving and does not eliminate root cause of disruption.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M - Ident/Solve Problem	3	6	6	4	0	0

Recognition of production disruptions (FR-DP R11)

The system does not expose disruptions very well due to the physical system design and the lack of standardized operations (FR-DP R111). The physical layout does not support the recognition and communication of disruptions between departments. Injection molding, paint, and assembly are physically separated by the AS/RS. Fluctuations in the inventory levels are hidden in the AS/RS. Injection molding operators work in isolated areas surrounded by the machines and are almost invisible from the aisle (Figure 6-4). There are no visual tools in injection molding indicating a problem.

Most machines are connected to a central monitoring system, which allows supervisors to look up the status of any machine or process in real time – if the supervisor is at a computer workstation. Visualization of equipment status on the shop floor, however, is rare (FR-DP R111).

Operationally, disruptions may not be noticed for several cycles (FR-DP R112). No area has a display showing the number of parts produced and the number of parts that should have been produced. Therefore, operators cannot determine if they are ahead or behind schedule. While major disturbances – such as a tool break in injection molding – are noticed quickly, smaller disruptions are unlikely to be noticed. Industrial engineering standards only provide information about how many parts need to be produced per hour. Single operating tasks are not timed. As a consequence, it is not possible to compare the actual performance of work to the desired work method. This fundamental problem eliminates the ability to recognize problems close in time and space to their occurrence. In addition, there is a general lack of discipline in following any kind of standards (FR-DP R113).

Communication of production disruptions (FR-DP R12)

Communication devices in the plant allow for rapid correspondence. Every line manager and most supervisors wear radio communication devices. Operators have to contact their supervisor, whenever they recognize a problem. Supervisors then write a work request or call the maintenance crew to address the problem.

Line managers pointed out that machine breakdowns are not communicated quickly enough. For example, when a machine goes down in injection molding, the operator has to walk to the next phone to page the supervisor. It may take several minutes until an action is initialized to solve the problem. The plant relies more on technology than on using visual control techniques such as Andon lights.

Solving of production disruptions (FR-DP R13)

Repair and maintenance often solves problems only temporarily to ensure that production can continue. Reoccurrence of the problem is likely, since root causes are not eliminated. The focus is on getting a machine up as fast as possible rather than fixing the problem in a way that reoccurrence is not likely (see also discussion under preventive maintenance (FR-DP P12). There are no standard procedures defined for problem solving. Existing problems are discussed in a group, but there is no formal process to capture lessons learned.

6.2.1.2.3 Predictable Output (FR-DP Px)

The "predictable production output" branch distinguishes the resources information, equipment, people, and material and states general objectives to achieve predictability. Plant M faces some major challenges with respect to predictable output as a result of both system design and operation. System design aspects are, for example, the mold design (which is beyond the immediate control of the plant), work instructions, and missing preventive maintenance procedures. One of the most significant points in the operation of the system is the lack of enforcing work standards. Unpredictable resources are also reflected in unpredictable inventory levels. The plant meets overall customer demand, but it requires high efforts of coordination and fire fighting.

TABLE 6-3: KEY OBSERVATIONS OF PREDICTABLE OUTPUT BRANCH FOR PLANT M.

	FR	DP	
P11	Ensure availability of relevant production information	Capable and reliable information system	Equipment status can be monitored real time through a computer network, but requires supervisors to be at a computer station. An information database files all production occurrences, but recording procedure is unreliable. Scheduling information is issued centrally and without timing information. Operators cannot determine if they are ahead or behind schedule.
P12	Ensure predictable equipment output	Maintenance of equipment reliability	Complex equipment in injection molding, molds, and paint. Parts became larger and more complex over the years. Poor maintenance, equipment and tools are not in a high state of readiness. Three shift operation prevents establishing of dedicated time for repair and maintenance. Mostly fire-fighting.
P13	Ensure predictable worker output	Motivated work-force performing standard work	Standard procedures exist for mutual relief, but absenteeism often affects ability to produce to schedule. Work instructions do not contain timing information for each task, low operator discipline, high variation in work completion time.
P14	Ensure material availability	Standard material replenishment system	Goal is to have 3-7 days worth of finished parts between the plant and the customer for non-ILVS assemblies, and 1-2 days for ILVS assemblies. Internal inventory levels are not defined and fluctuate significantly due to process instability and schedule adjustments.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M - Pred. Output	4	10	7	6	1	0

Predictable production information (FR-DP P11)

The scope of predictable information is to provide and transfer information necessary for the operation of the system, which includes schedules and operations instructions.

Plant M has a central scheduling department (see discussion in section 6.2.1.1.2). Every area manager and supervisor has a copy of the schedule. The production output is continuously monitored and communicated to allow necessary changes of the schedule. The information flow between the departments mostly involves central scheduling. The employees of central scheduling are often on the shop floor to discuss current issues with the production managers. Most scheduling information is transferred either by phone, personal discussions, or walkie-talkie.

As said before, it is not possible to monitor if production is keeping up with the schedule. For example, the paint schedule only shows the sequence of color batches but does not have times associated with it. Schedules in non-ILVS assembly show the sequence and quantity of parts, but operators cannot determine if they are ahead or behind schedule.

Information regarding the work tasks is available at most stations, even though work instructions are sometimes not updated. Information about the process (e.g., about the paint booth) is recorded and orally communicated to the supervisor if the process is not working properly. The plant also has the technology to view the status of most machines on a computer real time.

The plant collects data about all occurrences and enters them into a central database (see 6.2.1.2). However, the process of recording the data is not well established across the plant, so that some managers do not trust the data and do not use them for analyses.

Predictable equipment output (FR-DP P12)

The MSDD views predictable equipment output as a result of equipment design and maintenance. The equipment in plant M experiences high downtimes. According to the database, the unscheduled downtimes in injection molding and paint are on average around 20% of the available production time. Plant M has no dedicated times for preventive maintenance. Maintenance is mostly done in response to disturbances.

The equipment design (FR-DP P121) must be seen in the context of the plant's history (see 6.2.1.1.1). While serviceability of equipment and tools are important considerations according to plant employees, the influence of the plant on the selection and design of the equipment was often limited in the past. The injection molding machines have been selected for a less complex part than is now produced. Some molds are particularly sensitive to breakdowns. The paint system evolved over the years and new processes were added to the existing system.

It is desired that machine vendors are located in close proximity and can be called in with short notice to repair major breakdowns. Most repair and maintenance, however, is done in-house. Molds are often repaired outside, as they require special tools. The paint system is sensitive to replacement of parts. For example a nozzle of a paint robot was congested and needed to be replaced. The repair required stopping the line for several hours. Therefore the repair was postponed for two days to the weekend. As a result, for two days, some colors experienced a higher defect rate until the final repair.

Maintenance (FR-DP P122) in injection molding is done in three different ways: regularly based on number of run cycles, repair requests, and process issues observed by machine operators. Any machine breakdown leads to a repair request. The requests are ranked by priority to determine the repair sequence, which is then communicated to the line and repair supervisors. Operators call their supervisors when they recognize process problems. The supervisors then initiate maintenance. The procedure is similar in paint and assembly.

Time for preventive maintenance in paint is limited due to numerous equipment breakdowns and three shift operations. Weekends are also often used for production reducing the available time for preventive maintenance even further. Standard equipment checks are mostly done during repairs. In summary, tools and equipment are not in a high state of readiness.

Predictable operator output (FR-DP P13)

Several aspects of predictable operator output have already been discussed under the quality branch (training, standard work methods) and the identifying and resolving problems branch (system configuration to allow quick recognition of disruptions). The predictable operator output branch further details time-related aspects of stable operator output.

Plant M has no tools in place to manage the operators' work on a per cycle basis (FR-DP P131). As a result, task completion time varies between operators and between cycles. Work instructions do not contain timing information for work tasks (e.g., "attach bracket to bumper – 5 secs.") It is often not known to the operators how long a particular task is supposed to take. Subsequently, deviations from the standard cannot be noticed and cannot be enforced (FR-DP P131). Weekly performance in assembly differs from the standard by 60% (too slow) to 150% (too fast) according to the database. The database does not provide root cause information for the deviations, which could also stem material shortages or overstaffing of an assembly cell. Some cells operate with more operators than determined by industrial engineering standards. In some cases, the overstaffing became the unofficial standard. However, the industrial engineering standard has not been changed.

Operators often do tasks in a different sequence than mentioned in the work standard (see also discussion under the quality branch), which may lead to quality variability of the operator's output. The variability in operator's output both in time and quality may also correlate with the lack of standard training (Q121).

Plant M has standard procedures in place to relieve operators for allowances and breaks (FR-DP P133). However, plant M experiences lost production due to missing operators, who may be late from a break or are not coming at all (FR-DP P132). No tools are in place to alert operators in advance of the break end (e.g., a sound alarm).

It may also be that operators do not feel the importance of perfect attendance, as long as it is possible to catch up with production during the shift. The goal of producing a given number of parts per shift drives the behavior of the plant's operator. It is not important to follow repeatable work on a per-cycle basis as long as the overall production goal can be met.

In this context it is interesting to note that the performance measurement system of plant M is largely based on the work time per part. The number of shipped parts is multiplied by the currently authorized time per part. The result is compared with the actual worked time to determine the overall plant performance. Considering the significance of the cycle time per part it is surprising that plant M cannot control task performance on a per cycle basis. Instead it relies on aggregated numbers for the performance evaluation of the operators.

Material availability (FR-DP P14)

Inventory levels for work in process and finished bumpers vary significantly both in mix and quantity (FR-DP P141). In order to support the ILVS customers, the plant has about 1 day's worth of molded bumpers ahead of paint, 1 ½ day's worth of painted bumpers ahead of assembly and up to 1 ½ day's of assembled bumpers ready for shipment. The inventory levels for non-ILVS customers are lower. The plant has less than a day of molded parts ahead of paint and less than a shift of painted bumpers ahead of assembly. Assembled parts are shipped every day.

There is no standard quantity of inventory defined for any part type (FR-DP P141). Processes are sometimes starved due to unavailability of the right parts. High fall out rates in paint can cause major rescheduling in assembly. Missing molded parts can also cause paint to be starved.

The delivery frequency of material is not necessarily initialized by downstream consumption, but on preset time intervals (FR-DP P142). Purchased parts are usually delivered once or twice per shift. The automatic material handling system delivers the bumpers. An operator uses the scheduling matrix to program the release of racks from the AS/RS. The transit time is between 20 and 40 minutes.

6.2.1.2.4 Delay Reduction (FR-DP Tx)

This section describes the system design aspects, which directly influence the operating pattern of the plant. The MSDD distinguishes five delays: transportation lot size delay, process delay, run size delay, transportation delay, and systematic operational delays. Table 6-4 summarizes key observations of the delay branch for plant M. The overall performance is poor. Processes are grouped into functional departments and physically separated from each other. Process cycle times are not balanced. All operations tend to have large run sizes. The material handling system can cause congestions and starve operations.

TABLE 6-4: SUMMARY OF DELAY REDUCTION PLANT FOR PLANT M.

	FR	DP	Plant M
T1	Reduce lot delay	Reduction of transfer batch size (single-piece flow)	Plant M transports bumpers in AS/RS racks holding between 6 and 12 parts, which makes lot delay insignificant. Purchased parts are often transported in large bins which hold up to half a shift worth of material (see also T5 - systematic delay).
T2	Reduce process delay	Production balanced according to takt time	Plant M production is not balanced between injection molding, paint, and assembly. Balanced production is a result of capacity planning and designing how different processes in a system can achieve a continuous material flow. Achieving a continuous flow requires to consider the whole value stream when determining the cycle times and number of machines necessary for each operation. Plant M focused on single operations when designing the system. One paint line serves multiple assembly cell. Each assembly area has a different cycle time based on the number of workers in the cell and the work content required for each bumper.
T3	Reduce run size delay	Production of the desired mix and quantity during each demand interval	Plant M tends to have large run sizes throughout the value stream. Minimum run size in paint is 12 units. Paint requires c/o between colors and styles. Run sizes in non-ILVS assembly depend on part availability. Frequent over- or underproduction compared with schedule.
T4	Reduce transportation delay	Material flow oriented layout design	All processes are grouped into functional departments: injection molding, paint, assembly, and AS/RS inventory. Plant M uses an automatic material handling system to move and store parts. Transportation takes up to 25 minutes between processes.
T5	Reduce systematic operational delays	Subsystem design to avoid production interruptions	The design of all operations must facilitate the automatic material handling system. Delivery and pick up of material does not interfere with production resources. However, the material handling system can cause congestion of the system and starving of operations. Material delivery in assembly can interrupt operators as fork lifts are required to bring in new material.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M - Delay reduction	9	13	9	4	1	1

Transportation lot size delay (FR-DP T1)

Lot size delays are insignificant. The internal transportation lot size of bumpers is determined by the material handling system. Each AS/RS rack can hold between 6 and 12 parts depending on the bumper style. Injection molding and paint receive raw material through pipes. Assembly is the only process requiring piece parts such as brackets, front grills, and other small parts. The parts are brought to the assembly areas on pallets mostly by forklifts. Pallets hold up to a shift of material. The assembly operators pick up parts from the pallet and load them into storage bins adjacent to the assembly station.

Process and run size delay (FR-DP T2)

The system design and operation does not reflect the customer demand rate. The system design seems to be focused on individual operations rather than on an overall system perspective (see also Figure 6-3). Each process has a different cycle time and operating pattern. As a result, there is no clear customer-supplier relationship between the processes (FR-DP T21).

Cycle times at injection molding are strongly influenced by the design of the bumper, material and equipment (FR-DP T221). The customers design the bumpers and there is little interaction with the bumper production plant during the design process.

The cycle time of the paint system is rooted in the original design of the bumper production as described in section 6.2.1.1.1. The paint system produces the overall daily demand. Bumpers come off the paint line every 5 seconds (when the conveyor is running). Since the bumpers cannot be assembled at that rate, they must be stored and distributed to several assembly areas as shown in Figure 6-3. The cycle times of the paint system and assembly are therefore unbalanced leading to process delay (FR-DP T2).

The ILVS assembly lines shown in Figure 6-7 provide a good example of how the design of the system leads to unbalanced production both with respect to the total value stream and within the assembly area: the ILVS assembly area operates two nine-hour shifts per day, while the rest of the plant operates three shifts per day, which automatically leads to inventory between paint and assembly (FR-DP T21).

The allocation of operators and the work content per operator are not linked with the production rate of the area (FR-DP T222). The area assembles rear bumpers for sedans and station wagons, which have a total assembly content of 40 sec and 50 sec respectively. Considering the available time and customer demand, the area would have to assemble one bumper approximately every 55 seconds. Thus, it should be possible to satisfy customer demand with one assembly operator. However, the line has three assembly stations. Thus, output of the line exceeds demand, when all stations produce (FR-DP T21).

The assembly line is easily able to meet customer demand without paying close attention to work standards. Cycle times per bumper vary greatly between operators and between cycles during observations (see also FR-DP P131). It is also possible to work ahead and take unplanned breaks.

Run size delay (FR-DP T3)

The MSDD emphasizes two points to reduce run size delay: (1) providing the knowledge of the required product mix and quantity (FR-DP T31), (2) producing in sufficiently small run sizes (FR-DP T32).

Plant M creates central schedules for injection molding, paint, and assembly as described above. The line managers and the scheduling personnel have frequent meetings during the shift to discuss the status of production and to adjust the production schedule (FR-DP T31). Plant M's overall daily production is close to the overall customer demand. However, the production mix does not reflect the customer demand (FR-DP T3).

Plant M prefers to schedule large run sizes (FR-DP T32). Run sizes depend on customer demand, process variability, and equipment status. The production schedule for injection molding determines for each bumper style how many parts are needed during the day. However, if a daily demand for a bumper style is 2000 it is also acceptable to produce more (e.g., 2200 parts) as long as the AS/RS has capacity to hold additional inventory. Sometimes the production volume is reduced because the AS/RS is full. Injection molding tries to limit the number of changeovers. Changeover times can vary between 30 minutes and 8 hours and are difficult to predict.

Paint tries to avoid changeovers as much as possible. A color changeover takes up to 30 seconds or four cycles in the paint booth. The first parts of a new color batch are likely to be defective. Therefore, paint tries to run large batches. However, paint must also react to fallout and it may be necessary to split one large batch into two smaller.

The schedules for non-ILVS assembly areas are most flexible. The schedule contains a "hot-list" with items, which must be assembled at a given day to avoid a shutdown of the customer. Otherwise, the non-ILVS areas work mainly based on part availability. A shortage of parts from the hot list can cause rescheduling of paint (FR-DP T31).

Three of the five non-ILVS assembly cells are dedicated to a bumper style and have no changeover time (FR-DP T32). The other two cells require some time to deliver the new purchased parts into the cell. Therefore, the non-dedicated cells tend to batch the styles during the day. There is no changeover time between colors.

Transportation delay (FR-DP T4)

Transportation delay is defined as the total time parts spend in transport including time waiting for transport. The automatic material handling system transports all bumpers between the operations. The transportation time is between 15 and 45 minutes depending on the distance the parts have to travel.

Transportation time from injection molding to the AS/RS is on average 15 minutes. The AS/RS sends parts to the paint load area according to the paint schedule. The overall transportation time for parts from the AS/RS to paint load is about 25 minutes, which includes the transit time and waiting time of racks in front of paint load. Painted parts are loaded into racks and are sent to the AS/RS, which takes about 20 minutes. Sending parts from AS/RS to assembly also consumes on average 25 minutes including the transit and queuing in front of assembly. In summary, every part spends about 85 minutes in transit, which can be translated into 500 parts in transit at any given time considering the production rate of one bumper every 10 seconds.

Parts requiring repair or buffing after paint need additional transportation to and from the rework areas, which accumulates another 45 minutes of transportation time.

Systematic operational delays (FR-DP T5)

Systematic operational delays take place when production and support resources interfere with one another due to layout or operational problems. Plant M experiences some of those delays.

The automatic material handling system is well integrated into the work loops of the operators in all areas of the system (FR-DP T51). However, the material handling system has a very strong influence on the pace of the plant's bumper production. If no empty racks area available, the AS/RS shuts down production at injection molding and paint. The AS/RS is often operating at capacity limits and empty AS/RS racks are of common concern. Shutting down the production does not happen frequently, though. ILVS assembly depends on timely delivery of parts. It may happen that the automatic material handling system queues racks in front of ILVS assembly, which can lead to production disruption of ILVS assembly.

Small assembly parts often require forklifts to deliver the material on pallets or in large bins. Some assembly cells require the operators to step aside when new material is delivered (FR-DP T51).

Injection molding has isolated work loops by having one operator per machine (FR-DP T52). The work loops in paint are difficult to maintain when the paint system is running at full speed. The work loops frequently overlap, which can cause interference when carrying the bulky bumpers (FR-DP T52). The operations at paint inspection are very narrowed to avoid interference leading to unbalanced work loops.

Assembly experiences some coordination problems between the operators as well (FR-DP T52). ILVS has three operators working on three assembly stations. They pick up the bumper from one shared conveyor, which can lead to interferences in the work loop of each operator. The time losses may not seem significant but disrupt constant work patterns. Non-ILVS assembly experiences fewer interruptions since operators do not share resources.

6.2.1.2.5 Direct Labor (FR-DP Dx)

The focus of the operational cost branch is the effective utilization of direct labor by eliminating non-value added sources of costs. The system design of plant M is strongly influenced by the desire to eliminate direct labor (see section 6.2.1.1.1). However, the remaining direct labor is often not used very effectively. Table 6-5 summarizes the main points relative to the MSDD.

TABLE 6-5: SUMMARIES OF DIRECT LABOR FOR PLANT M.

	FR	DP	Plant M Comment
D1	Eliminate operators' waiting on machines	Human-Machine separation	Operators in injection molding are fully paced by the machine. The manual cycle time of the operators is sometime up to 10-20 sec faster than the machine cycle time, leading to significant idle time. Manual operations in paint are designed for the fastest line speed (1 part every 5 sec). However, the line is often down leading to significant idle times of the operators. No waiting on machines in assembly, since assembly is manual. Cross training is limited. Operators in paint, for example, can switch between load and unload, but not to inspection. Assembly operators are capable of performing all assembly tasks.
D2	Eliminate wasted motion of operators	Design of workstations / work-loops to facilitate operator tasks	Most workstations have to accommodate drop off and pick up locations for the material handling system, which usually increases walking. Loading and unloading of parts at the paint line requires a lot of walking, since the conveyor line moves fast and the parts are large. Assembly stations also require walking, which is partially due to the size of the parts.
D3	Eliminate operators' waiting on other operators	Balanced work-loops	Overall, work loops are not well balanced in plant M. The work content of operators in paint inspection, load and unload differs greatly. The work content of assembly operators is also very different. Balancing work loops does not seem to be a design goal.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M - Direct Labor	3	6	6	5	0	0

Operator waiting time (FR-DP D1)

The injection molding machines can run autonomously while the operator trims the part and loads it onto the AS/RS rack. The work content differs between the bumper styles. Some operators are idle almost half of the machine cycle, while others can barely keep up with the machine cycle time. There is no intermediate buffer between the machine and the operator. Therefore the operator is fully paced by the machine (FR-DP D11).

The paint system has several conveyor chains, which move at different speeds. The chain at load and unload moves faster than the chain in the paint booth (see process description in 6.2.1.1.3). The different chain speeds intend to optimize the output of the paint booth, which is the bottleneck operation. Since the chain in the load and unload area is the fastest chain of the paint system, it automatically means that load and unload operators frequently have to wait for the machine (FR-DP D11).

Operators are generally able to perform various operations within their subsystem (FR-DP D12). Operators in injection molding can work on any machine. Paint operators only rotate between load and unload stations. There is no rotation with inspection or jobs inside the paint system. Assembly operators are able to perform any task within the assembly system.

Wasted motion (FR-DP D2)

The MSDD distinguished three types of wasted motion: unnecessary walking between stations (FR-DP D21), needless walking during work preparation due to missing tools etc. (FR-DP D22), and wasted motion during the work itself (FR-DP D23).

Most workstations have to accommodate drop of and pick up locations for the material handling system. For safety reasons, it is necessary to position the drop off away from the workbenches of the operators increasing walking distances (FR-DP D21). Loading and unloading of parts at the paint line requires a lot of walking, since the conveyor moves fast and the parts are large. On average, load and unload operators walk about 30 feet to load / unload one bumper. The distance is a result of the fast moving chain, the size of the bumpers and the drop off position of the AS/RS racks.

Walking distances in assembly are not very long. Operators pick up parts from the rack and load them to an adjacent workbench. Only operators at the ILVS lines have to walk long distances to load / unload parts from the WIP lanes (FR-DP D21).

Tools and equipment necessary to perform a work task are usually available when the operator needs them (FR-DP D22). However, the plant does not strongly enforce keeping workstations in clean and orderly condition according to discussions and answers in the questionnaire.

Wasted motion in the work task itself only occurs in assembly (FR-DP D23). Assembling the parts to the bumpers can be difficult. The bumpers are large and the side flanks can bend easily. This requires the operator to hold the side flanks with one hand, while the other hand inserts screws or attaches parts. In addition, part feeding is not always very convenient for the operators. As a result, operators put screws and other small assembly parts on the workbench to avoid reaching for the bins.

Balanced work loops (FR-DP D3)

The fast cycle time of the paint system makes work loop balancing at paint load and unload virtually impossible. A good example is the inspection area (see Figure 6-5). One operator attaches a bar code sticker to the bumper, which takes only about one and a half seconds. The operator is idle for the rest of the cycle. Two other operators attach tape to some bumper styles, which takes almost five seconds. However, the operators are idle for any other bumper style.

Assembly places the highest emphasis to the efficient use of direct labor. The equipment can easily be reconfigured to accommodate better ergonomics. However, operator work loops are not designed in detail. It frequently occurs that operators within an assembly cell are idle, while others are working. As discussed before, work instructions do not contain any timing aspects, tasks are performed differently between cycles and between operators, and standards are not enforced (see also discussion under process delay for ILVS assembly area). As a result, most work loops within one team of assembly operators are not balanced, operators interfere with each other, and the worker utilization does not seem to be optimal.

All previous discussions regarding operator standards (quality section FR-DP Q122, time sections FR-DP R111, FR-DP P13, FR-DP T222, FR-DP T5) pointed out the lack of existing or enforced standardized work. The result becomes obvious in the direct labor branch of the MSDD.

6.2.2 Plant T Case Study

6.2.2.1 Plant Overview

The bumper production of this case study belongs to a factory that produces various parts for cars and includes final car assembly. The following write up refers to the bumper production as plant T. Production volume is around 4,200 bumpers per day. The plant produces six different bumper styles in seven different colors plus additional service parts for old car models. All operations in plant T operates 5 days a week with two 8-hour shifts. Four to five Saturdays per year are scheduled for production. The bumpers are delivered to the final car assembly line in an adjacent building.

6.2.2.1.1 Plant History and Layout

The factory was founded in 1986. The overall layout of the bumper production is illustrated in Figure 6-10. The bumper production consists of one molding area with 3 Reaction Injection Molding (RIM) machines and 4 injection molding machines. Molded parts are stored on the floor between injection molding and paint. Paint has two paint lines, each dedicated to one final vehicle line. Assembly is integrated with paint unload. The bumper production system is a copy of the parent's system abroad. No new technology was installed.

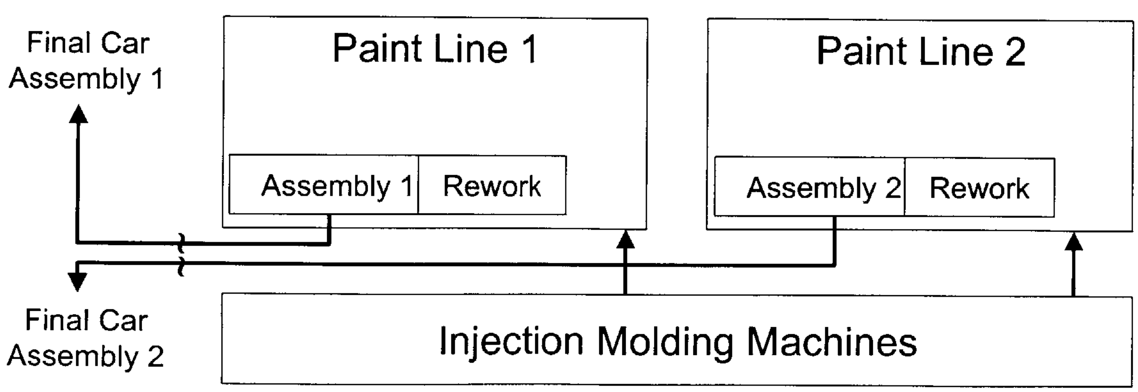


FIGURE 6-10: SCHEMATIC LAYOUT OF PLANT T.

The factory started production with one final car assembly line. The production rate of the bumper production system was aligned to the rate of the vehicle assembly line and had only one paint line. The second paint line became necessary when the assembly plant added another vehicle assembly line. Both vehicle assembly lines operate at a cycle time of around 55 seconds.

Parts are stored in racks on the shop floor. Operators in injection molding manually pull the racks to and from the WIP lanes between injection molding and paint. Another operator uses a tug to bring racks to and from the paint line. A tug also delivers bumpers to final vehicle assembly.

6.2.2.1.2 Value Stream

The information flow for the bumper production is integrated into the control of the entire vehicle factory as shown in Figure 6-11. Production control coordinates the vehicle paint shop, vehicle assembly line and the bumper production. The vehicle paint feeds back which car bodies have been painted. Production control then determines the exact car sequence for each vehicle assembly line and transmits that sequence to each of the bumper paint lines. The sequence consists of 20 sets of front and rear bumpers. Those bumpers are assembled at the vehicle assembly line around 2 hours after releasing the order to the bumper area.

The order for bumpers is printed out at the paint booth to determine the color sequence and at the bumper assembly to load the bumpers in the right sequence onto the racks, which are tugged to the vehicle assembly line. Paint and injection molding are linked through a kanban system.

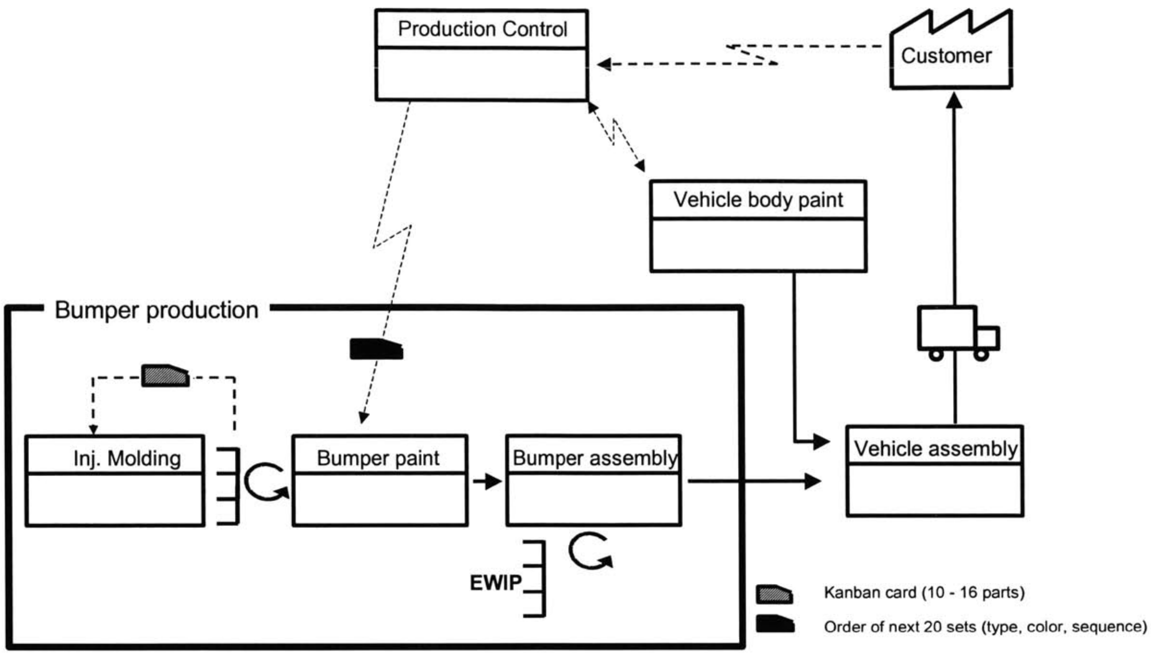


FIGURE 6-11: VALUE STREAM OF PLANT T.

The material flow in plant T is shown in Figure 6-12. The area produces bumpers for three car types A, B, and C. Paint line 1 paints bumpers for type A and C and delivers them to vehicle assembly line 1, paint line 2 paints bumpers for type A and B and delivers them to paint line 2. Each paint line produces one bumper every 46 seconds. A detailed description of the paint line is given in 6.2.2.1.3.

Three RIM injection molding machines produce the rear bumpers for style A. Three of the four injection molding machines are dedicated to a bumper style and are only changed over to produce service parts. The fourth machine produces front and rear bumpers for type C. The bumper assembly takes place immediately after paint unload without intermediate storages. Assembly content for each bumper varies between 0 and 90 seconds depending on the bumper style.

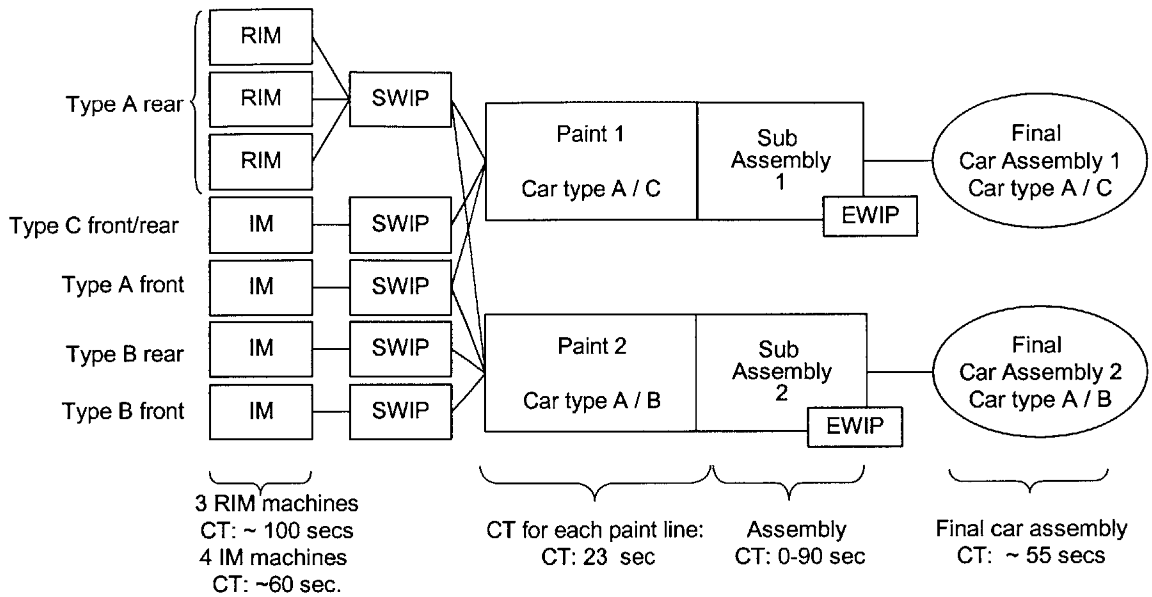


FIGURE 6-12: MATERIAL FLOW IN PLANT T.

6.2.2.1.3 Description of the Processes

Injection Molding

The injection molding machines produce a daily volume of about 4,700 bumpers including service parts. The product variety consists of seven bumper styles for current car models. The injection molding machines have a cycle time between 53 and 64 sec.; cycle time of the RIM machines is around 100 seconds. The defect rate is around 2%. Mold changes take between 15 and 30 minutes.

The schematic layout of the injection molding area is illustrated in Figure 6-13. A robot unloads the bumper from the machine, removes the gate and drops it onto a conveyor. The conveyor can hold up to 20 parts. The operator picks the bumper from the conveyor, deflashes the bumper, checks the quality and loads it onto racks. Each rack can hold between 10 and 18 parts depending on the style. The operator attaches a kanban to the filled up racks and pushes the rack into the Standard Work In Process (SWIP) lane. Every shift produces every bumper style. The standard manual cycle time is 60 seconds for all bumper styles.

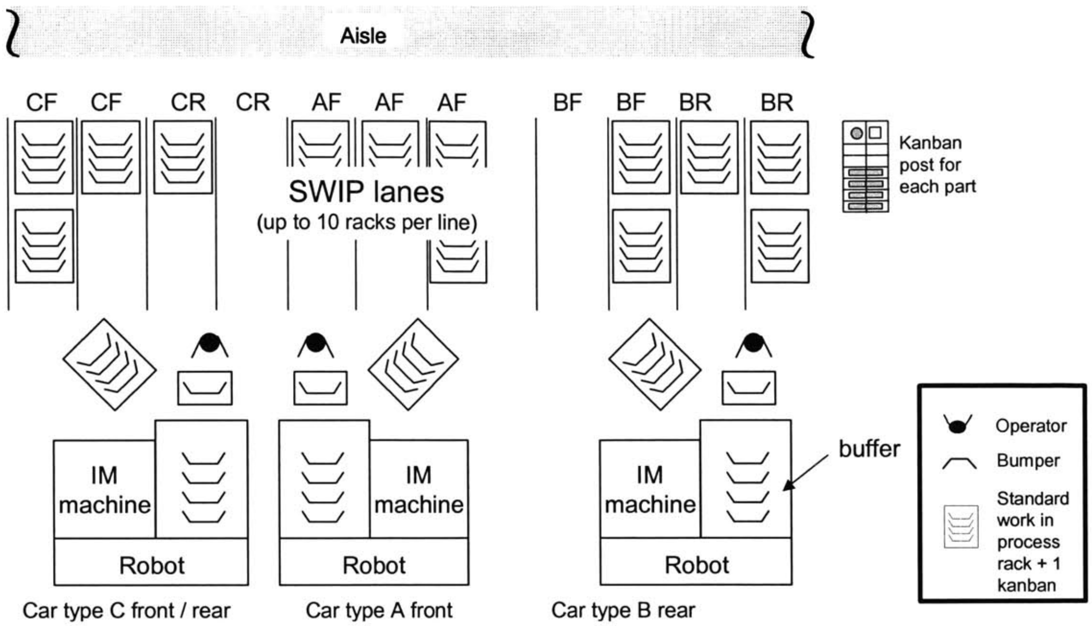


FIGURE 6-13: SCHEMATIC LAYOUT OF INJECTION MOLDING AREA AT PLANT T.

Paint

The paint consists of the same basic operations as the system in plant M, but the system is structured very differently. The overall daily volume is around 4,500 bumpers per day. The bumpers are painted in 9 different colors for a total of 38 different parts. Each paint line produces one bumper every 23 seconds. The first-time-through yield of the paint system is 95%. The defective parts are repaired or buffed. Scrap rate is 1%. The average downtime of the system is around 3-4%. Throughput time is about 4 hours from load to unload and about 90 minutes from paint booth to unload.

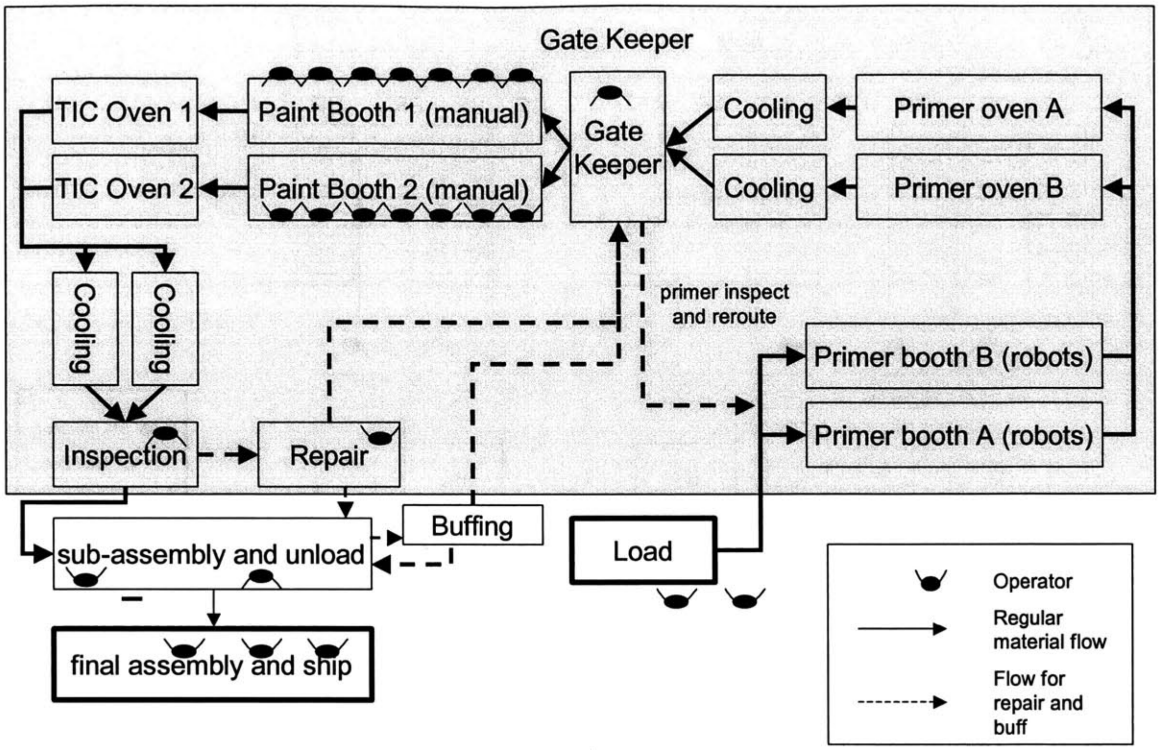


FIGURE 6-14: SCHEMATIC LAYOUT OF PLANT T'S PAINT SYSTEM.

One operator loads bumpers onto jigs similar as in plant M. The conveyor consists of several chains, which can stop independently from each other and run at different speeds. In addition, it is possible to reroute parts within the system, for example from repair to the paint booth and from intermediate inspection at the gatekeeper back to the primer booths. The whole system has two primer and paint booth lines each with a cycle time of 46 seconds as illustrated in Figure 6-14. First time through of the primer booths is around 93%. Defective parts are sent through the primer again. One bumper style requires two layers of primer for one particular color.

The gatekeeper receives the order sequence for 20 sets of bumpers from production control. He determines the color of the parts going into the paint booths according to the order sequence. Bumpers are not necessarily painted in the exact same sequence as specified in the order. The gatekeeper tries to batch parts of the same color within one order. Both paint booths of paint line 1 are fully manual, while one of the two paint booths of paint line 2 is automated. The primer booths are all automated.

The bumpers are inspected before they exit the paint system. Defective parts are sent to a repair station where an operator determines if a part can be buffed, needs to be repainted or must be scrapped. Parts that have been painted three times, are scrapped. All repair parts are painted in the same color again. If a part is scrapped due to a defect at injection molding, it is sent back to injection molding for examination. Parts requiring repaint are sent back to the gatekeeper. Releasing a repair part into the paint booth does not reduce the number of parts required by the production control order. Only scrapped parts need to be added to the order list.

In most cases, the color batch size in paint is one. There is no changeover in the paint booth between styles. Color changeover takes about 6 seconds. In the manual paint booths, operators unplug a paint hose from the paint gun, plug in another color hose, and spray some paint to the floor to ensure that no paint of the previous color is left in the gun. Red, black, and white have dedicated guns. The changeover does not lead to any loss of production time as the regular work loop leaves enough time to accommodate the changeover. The paint booths have a very strong air flow from top to bottom. The air inside the booth is so clean that operators do not have to wear masks.

Each paint line has around 550 jigs in the system. The jig distribution depends on the daily requirements. There is usually only one jig of the same style in a row. Changeover of the jigs does not require stopping the conveyor. Jigs are mostly changed for maintenance.

Assembly

The assembly is integrated in the paint unload area. Each paint line has a different layout to account for different assembly content of the bumper styles. Figure 6-15 illustrates the area of paint line 2. The assembly content per part is between 0 and 90 seconds. The assembly process is divided among all group members of the unload and assembly area. Each operator has defined a standard work combination routine, which includes all necessary work steps and allocated time for each work step.

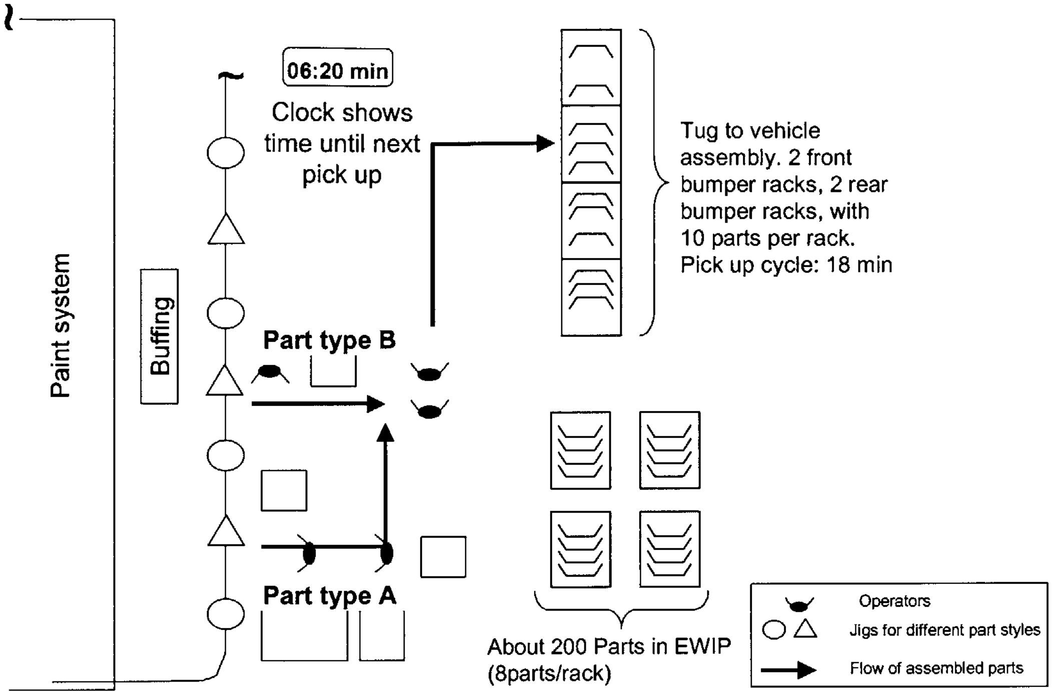


FIGURE 6-15: SCHEMATIC LAYOUT OF PAINT UNLOAD AND ASSEMBLY AREA.

The unload operators are also responsible for buffing. Whenever a part requires buffing, the operators store it in the buffing section, which is on the other side of the conveyor. When the storage place is filled up with parts, the operator buffs the parts. This activity is not integrated in the standard work procedure and is done when the paint line is down or during breaks.

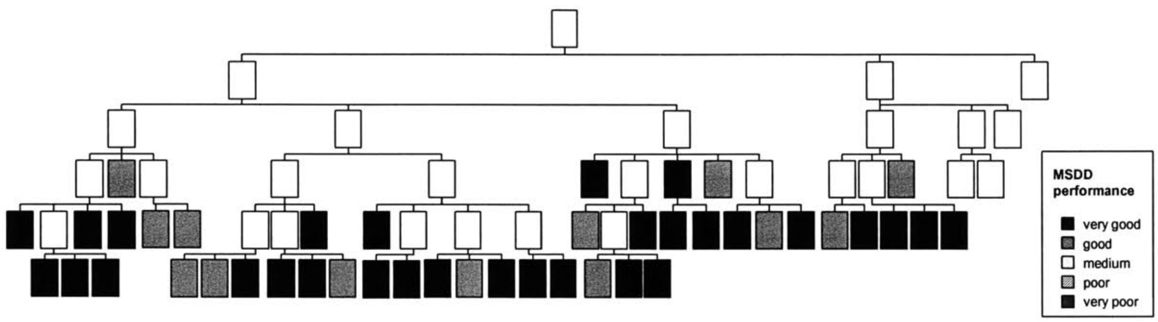
Assembled bumpers are either loaded directly onto the racks, which are tugged to vehicle assembly line or to an intermediate storages place called Emergency Work In Process (EWIP). Two operators load the assembled bumpers onto racks according to the sequence of the order list. Every 18 minutes, an operator picks up a set of 20 bumpers (front and rear) and takes them to final vehicle assembly. The bumpers are not wrapped or have any tape attached to them as in plant M.

As mentioned earlier, the parts are not necessarily coming down the line according in the exact sequence of the order list due to color batching, repair parts and fallout. However, operators in the assembly area try to load parts from the paint line directly into the tug racks. If the racks are not completed as the next pick up approaches, operators fill up empty spots with parts from EWIP. The EWIP is refilled when parts are coming down the paint line that cannot be loaded onto the tug racks.

6.2.2.1.4 Performance Measurement System

6.2.2.2 Evaluation and Analysis

The overall evaluation of plant T is shown in Figure 6-16. The performance relative to the MSDD is very good. The evaluation summarizes observations made during plant visits, discussions with personnel. One manager of the quality department filled out the questionnaire relative to the bumper production area. In addition, four more employees of the quality department filled it out for quality assurance areas such as final vehicle test.



	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant T Overall	0	2	10	29	90	1

FIGURE 6-16: OVERALL EVALUATION OF PLANT T RELATIVE TO THE MSDD AND SCORE DISTRIBUTION OF QUESTIONS.

The following paragraphs discuss the analysis in detail. Each decomposition branch of the MSDD is discussed separately.

6.2.2.2.1 Quality (FR-DP Qx)

Plant T achieves the highest score in almost every question related to quality as summarized in Table 6-6. The company has very low defect rates, consistent output and a thorough quality program with standard improvement procedures.

TABLE 6-6: QUALITY SUMMARY FOR PLANT T.

	FR	DP	Plant T
Q11	Eliminate machine assignable causes	Failure mode and effects analysis	Thorough program for elimination of equipment assignable causes. Each process has a board displaying ongoing projects. Close cooperation with central quality department.
Q12	Eliminate operator assignable causes	Stable output from operators	Extensive training of all operators. Enforcement to follow standardized work, which are clearly described for every operation.
Q13	Eliminate method assignable causes.	Process plan design	Process descriptions exist for every operation. Continuous improvement activities throughout the plant.
Q14	Eliminate material assignable causes	Supplier quality program	Some problems with incoming material. Close cooperation with suppliers to ensure quality material.
Q2	Center process mean on the target	Process parameter adjustment	Processes are generally operated within tolerances, not necessarily on target. Deviations from target, if proven that output achieves better quality. Continuous process monitoring.
Q3	Reduce variation in process output	Reduction of process noise	Continuous improvement processes to eliminate noise and make processes more robust.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant T - Quality	0	1	0	6	21	0

Machine assignable causes (FR-DP Q11)

Plant T has very stable and reliable manufacturing processes. Defect rates in injection molding are similar to plant M (~2%), but the paint system operates much more reliably. Defects are rigorously examined to eliminate root causes. For example, paint sends defective parts back to injection molding, if the defect is due to an injection molding problem. Operators in injection molding examine the part and take necessary action to avoid reoccurrence.

Operator assignable causes (FR-DP Q12)

Operator training and consistent task performance is very important in plant T (FR-DP Q121). Every operator receives standardized training. Operators in injection molding, for example, go through a five day formal training. The first two days, new operators observe how to perform the tasks, study the work instructions and become familiar with the production environment. The last two days, they perform the tasks under supervision. The work instructions contain information about the work sequence, detailed description of the individual tasks, and timing charts. Manual cycle time at injection molding is 60 seconds for each bumper. Adherence to defined work methods is enforced throughout the plant to ensure consistent operator output. Standardized work methods are developed and continuously updated in cooperation with the team leaders. Every operator can access the standardized work combination at his workstation or in the break area (FR-DP Q122).

Method assignable causes (FR-DP Q13)

Operation sequences are defined and continuously improved for all operations. Operators are encouraged to improve work methods, but must document the changes – for example altering the sequence in which parts are assembled to the bumpers. Furthermore, the team leader has to sign off the changed work method, which then becomes the new standard. Improvements are often based on team kaizen.

Material assignable causes (FR-DP Q14)

Plant T strives for long lasting relationships with their suppliers to improve quality, delivery and costs. The plant inspects incoming material, since incoming material is not always defect free.

Process mean (FR-DP Q2)

Processes are generally operated within tolerances, not necessarily on target. Processes are continuously monitored both automatically and manually. Maintenance operators have predefined routes in which they check the processes.

Process output variation (FR-DP Q3)

The paint system is sensitive to dust and other environmental disturbances. Air filters are regularly exchanged. In general, the company applies a rigorous program to make processes insensitive to environmental influences.

6.2.2.2.2 Problem Resolution

The physical layout of plant T and its operation support the quick recognition of disruptions as summarized in Table 6-7. Work standards include time information for each task and are strictly enforced. Clear material flow paths support fast feedback between subsequent processes. The plant has clear procedures for problem solving.

TABLE 6-7: SUMMARY OF IDENTIFYING AND RESOLVING PROBLEM BRANCH AT PLANT T.

	FR	DP	Plant T
R11	Rapidly recognize production disruptions.	Subsystem configuration to enable operator's detection of disruptions.	Clear flow paths throughput the system. Inventory is visible on the floor and fluctuations are easy to recognize. Each operator cycle has a man-machine chart showing the relationship between the task and timing. Standards are enforced and improved. Equipment availability is high.
R12	Communicate problems to the right people	Process for feedback of operation's state	Communication paths are predefined and enforced. Operators contact supervisor, how then initiates further action.
R13	Solve problems immediately	Standard method to identify and eliminate root cause	Standard problem solving procedures do exist. Each area has its own board showing ongoing improvement activities. Solving problems is focused on eliminating root cause.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant T - Ident/Solve problems	0	0	0	8	11	0

Recognition of production disruptions (FR-DP R11)

The physical layout of Plant T supports visibility between departments. The injection molding area and the paint system are only separated by an aisle. Inventory between injection molding and paint is visible on the shop floor. Whenever material is picked up from injection molding and delivered to paint, the material handling operator can see potential material shortages (FR-DP R111).

It is possible to get an overview of the whole injection molding area by standing in the aisle (see Figure 6-13). Operators are not hidden as in Plant M. Each injection molding machine has a status light next to the operator, which can also be seen from any point in the injection molding area. Whenever the machine is down or the operator has a problem, the light turns on calling for the supervisor (FR-DP R111, R112).

Plant T has clearly defined work instructions with detailed timing information. Each operator has a man-machine chart showing the sequence of activities and the timing of each step. Operators are trained to perform the tasks according to the standardized work methods. Deviations from the standard are relatively easy to recognize both for the supervisor and the operator himself. If operators cannot perform their work according to the standard it may indicate a problem (e.g., with incoming material or tools), lack of operator training, or the need to adjust the standard. The system is laid out and operated to expose problems and solve them quickly. Each injection molding machine has a counter that indicates parts made versus parts plan (FR-DP R111).

The work loops of the assembly and loading operators do not seem to be very clearly specified. One assembly operator has to unload parts, perform minor assemblies and is also responsible for buffing parts (see operator of part type B in Figure 6-15). Since the number of parts to be buffed is unpredictable, his work loop is not tightly defined and the operator is idle for part of his cycle. The operators, who load the tug racks, do not have tightly defined work loops, since the cycle varies depending on the number of parts they have to pick / deliver from EWIP. However, it is quickly recognized if the operators fall behind for more than one or two cycles, since every 18 minutes four racks with 20 front and rear bumpers are picked up for delivery to final car assembly. A clock shows the remaining time until the next pick-up. When the next pick-up approaches and the racks are not completed, it indicates a problem and the supervisor helps to finish the racks.

The regular pick-up cycle also helps to identify problems at the downstream customer, if the parts are not picked up after 18 minutes. That is, upstream processes can recognize occurring problems at the downstream process and can initiate necessary reaction such as stopping the line (FR-DP R111).

Communication of production disruptions (FR-DP R12)

When operators recognize a problem or disruption, they contact their team leader, who then either solves the problem or call the for repair support. Operators are allowed to fix problems by themselves, but must report the problems. All supervisors have radio communication devices and/or walkie-talkies (FR-DP R122).

Machine breakdowns start a signal light or sound an alarm as described above for the injection molding machines. The paint process also facilitates fast feedback of occurring problems. If an inspector detects a defective part, the part is sent directly to repair and from there back into the paint booth. The part does not leave the paint system as shown in

Figure 6-14. The paint system in plant M has much longer communication paths leading to longer feedback times.

Solving of production disruptions (FR-DP R13)

Operators in the plant are organized in teams. Team members discuss any disruptions in regular team meetings. Problem solving includes documenting the problem, determining the root cause, assigning responsibilities and eventually solving the problem. Every operator has to be able to understand and use the problem-solving sheet. In addition to problem solving, the plant has also a well-organized continuous improvement process.

The emphasis is on resolving problems and preventing reoccurrence. If a problem can only be temporarily fixed to maintain production, it is tried to permanently correct the problem after the shift. The company operates two shifts per day with 2-3 hours between shifts, which allows for preventive maintenance, repair, and long-term correction of problems.

An important aspect of the problem solving process is to make the problem visible, i.e., only reporting a defect is not as desirable as to send the defective part to the process that caused the defect. For example, if a defect at paint is caused by injection molding (e.g., poor trimming), the part is sent back to injection molding even though the part must be scrapped. Injection molding examines the part, tries to determine the root cause of the defect, and uses the insight for future improvements.

6.2.2.2.3 Predictable Output

Plant T has very reliable production resources. Preventive maintenance and thorough problem resolution result in a high state of readiness of equipment and tools. Operator discipline is high, work instructions are detailed, enforced and continuously improved. Inventory levels are very low and standardized. A kanban system links paint and injection molding. Defined material delivery routes are repeated every 4-5 minutes between injection molding and paint, and every 18 minutes between final car assembly and bumper assembly.

TABLE 6-8: KEY OBSERVATIONS OF PREDICTABLE OUTPUT BRANCH FOR PLANT T.

	FR	DP	Plant T
P11	Ensure availability of relevant production information	Capable and reliable information system	Very clear and simple information flow. Production schedule determines the overall daily demand, which is released to all operations. The exact order sequence is sent from production control to the bumper paint system every 60 parts. Paint and injection molding are linked through a kanban system. Production status is displayed real time at all operations. Ongoing improvement activities are accessible at dedicated areas on the shop floor.
P12	Ensure predictable equipment output	Maintenance of equipment reliability	Strictly followed preventive maintenance program. 2 shift operation allows time for maintenance between shifts. Company has defined standards with respect to equipment design (e.g. panel location, stop buttons). High readiness of tools and equipment.
P13	Ensure predictable worker output	Motivated work-force performing standard work	Detailed work instructions include required time for each task. Standards are enforced, followed and continuously improved. Absenteeism can affect production, but is softened through operator rotation within the whole plant.
P14	Ensure material availability	Standard material replenishment system	Kanban system with defined SWIP levels (less than 1 shift worth of material) between injection molding and paint. Paint and assembly produce ILVS and hold app. 90 minutes worth of finished bumpers. Paint pulls every 4-5 minutes parts from injection molding, final car assembly picks up parts every 18 minutes from bumper assembly.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant T - Predictable output	0	0	2	4	22	0

Predictable production information (FR-DP P11)

Scheduling of the bumper production is a mix of central schedule and pull system. The central schedule determines the daily production volume and is adjusted approximately once per month. No special daily schedules are issued. Each paint line receives releases for the next 40 bumpers that must be delivered to the final vehicle assembly line 150 minutes later. Paint produces according to the schedule and pulls material from the inventory after injection molding. Injection molding accumulates consumed kanban cards during the shift. The next shift in injection molding works off the accumulated kanban cards to refill the inventory.

Every operator has access to the work instructions either at the workstation or in the department meeting area. The meeting area also shows information regarding ongoing improvements, quality concerns and upcoming projects.

Predictable equipment output (FR-DP P12)

As described in the plant history section 6.2.2.1.1, the bumper production is a copy of an existing line of the parent company in Japan. Some labels on machines are in Japanese and cannot be read by the local maintenance personnel. The company, however, stresses standard machine components such as locations of panels, stop buttons (FR-DP P121).

Equipment and tools are in a high state of readiness in plant T. Downtimes in injection molding and paint are on the order of 5% and 4%, respectively. Tool breakdowns in injection molding can cause major problems as mold repair can take several hours or days. Plant T has a rigorous preventive maintenance program (FR-DP P142) and uses the time between the two daily shifts to repair and maintain tools and equipment. Repair and maintenance is done in-house except for mold repairs. Plant T has a relatively high number of indirect workers for maintenance.

Predictable operator output (FR-DP P13)

Plant T enforces that operators follow the standardized work methods. Variation in work completion time is very low (FR-DP P131). The plant signals the end of breaks by playing music to ensure that operators are at their workstations on time (FR-DP P132).

Supervisors help out in production to relieve operators (FR-DP P133) or to increase production output (e.g., in case of production disturbances). The percentage of time team leaders spend on-line is a system performance measurement. High online percentage indicates frequent problems or absenteeism and leads to improvements activities.

In case of unplanned absenteeism (e.g., on Monday mornings), the plant assigns team leaders to take over operator jobs (FR-DP P133). It is also possible to utilize workers from other departments of the plant. Those departments then assign team leaders to work on line to free up a team member. Operators are usually cross trained and capable in performing several different jobs. As a result, the existing level of unplanned absenteeism does not severely affect the plant's ability to meet production schedule (FR-DP P132).

Material availability (FR-DP P14)

Inventory levels are defined for each bumper style and color. Injection molding has less than one shift of material in front of paint. The plant holds approximately two hours worth of assembled bumpers after assembly. The inventory serves as emergency stock, if paint is not able to produce according to the sequence sent from body paint (see Figure 6-11). In general, bumpers released to the paint booth are assembled to the final car less than three hours later.

Material delivery is integrated in a regular operator route (FR-DP P142). Each paint line has one operator responsible for pulling molded parts from injection molding to paint load every 3-5 minutes. The operator pulls one rack holding 10 – 18 parts at a time. There are at most two racks in front of paint load per part type. Final car assembly pulls 20 sets of front and rear bumpers from each paint line every 18 minutes. A clock in the bumper assembly area counts down from 18 minutes to indicate the next upcoming pick-up (FR-DP P142).

6.2.2.2.4 Delay Reduction (FR-DP Tx)

Plant T achieves a very smooth material flow in the value stream with little operational delays as summarized in Table 6-9. Injection molding machines are grouped into an area adjacent to paint. Paint cycle time is balanced with final customer. Run size in injection molding is one shift of material, run size in paint is mostly one. WIP is stored in racks on the shop floor and moved either manually or with a tug.

TABLE 6-9: DELAY REDUCTION SUMMARY FOR PANT T.

	FR	DP	Plant T
T1	Reduce lot delay	Reduction of transfer batch size (single-piece flow)	Transportation lot size between injection molding and paint is 10 - 18 parts, between paint and car assembly is 40 parts. All bumpers are held in racks, which are pulled by tugs.
T2	Reduce process delay	Production balanced according to takt time	Paint lines are balanced to final car assembly lines. Cycle time of paint lines is 46 seconds for one set of front and rear bumpers. Final car assembly line has a takt time of 55 seconds. If the paint line runs very stable and is ahead of the final car assembly line, it shuts down. Cycle times in injection molding are close to consumption rate.
T3	Reduce run size delay	Production of the desired mix and quantity during each demand interval	Run size in injection molding is one shift of demand. Run size in paint is one. The jig sequence on the paint conveyor is model A front, model A rear, model B front, model B rear. The mix is also important to level out different assembly times at the paint unload stations. Changeover time in paint between colors is 5 seconds and can be accommodated within the regular paint cycle time.
T4	Reduce transportation delay	Material flow oriented layout design	Injection molding is adjacent to the paint lines. Each paint line has one operator, who tugs racks with molded parts to paint load, which takes about 2-3 minutes. No transportation between paint and assembly.
T5	Reduce systematic operational delays	Subsystem design to avoid production interruptions	Good separation of support and production resources. Some interference at assembly stations.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant T - Delay reduction	0	1	7	5	23	1

Transportation lot size delay (FR-DP T1)

Lot size delays are insignificant. Bumpers are stored in racks, which can hold between 10 and 18 parts. Transportation lot size to final vehicle assembly is 20 sets of front and rear bumpers. Injection molding and paint receive raw material through pipes. Parts for assembly are moved in bins and pallets with up to half a shift of material.

Process and run size delay (FR-DP T2)

Plant T achieves a relatively smooth flow of material through the system with clear customer-supplier relationships (FR-DP T21). Each of the two paint lines is dedicated to one vehicle assembly line. Both vehicle assembly lines produce type A cars. Subsequently, both bumper paint lines produce type A bumpers, even though it would be possible to dedicate one paint line exclusively to type A. Plant T, however, prefers to produce with each paint line the exact demand of the downstream customer and achieves a clear customer – supplier relationship.

The cycle time of the paint line is 46 seconds for one set of front and rear bumpers, which is 9 seconds faster than the cycle time of the vehicle assembly line (FR-DP T221). The additional capacity accounts for fall-out at paint. The paint line stops operation when the customer line is down or on break or if the paint line operates without any defects and is therefore faster than customer demand.

Cycle times in injection molding are longer than cycle times at paint. The company works together with product design to shorten the cycle time (FR-DP T221). Injection molding is able to catch up with production by working through breaks and by overtime between shifts. The company aims at reducing the machine and manual cycle times to match the cycle time of the paint line (FR-DP T221).

Manual operations in the paint system are paced by the conveyor speed and the tasks are divided in such a way that the conveyor cycle time can be met (FR-DP T222). The cycle times vary between 23 seconds (paint load and unload) and 46 seconds (paint booth). The manual cycle time of the operators is slightly shorter than the automatic cycle time to ensure that the paint system does not have to wait for operators. This may lead to some idle time of operators from time to time (see discussion under balanced work loops FR-DP D3).

The paint area also levels out different cycle time (FR-DP T223). The bumper assembly time varies from 0 to 90 seconds. Operators could not keep up with the conveyor speed if several bumpers requiring 90 seconds assembly time would come down the line in a row. The jig distribution as in 6.2.2.1.3 rarely has two bumpers of the same type in a row. One reason for this type of configuration is to level out the different assembly cycle times.

Run size delay (FR-DP T3)

The scheduling and order release mechanism of plant T has been described above. The gatekeeper at the paint booth and the operators at unload receive the order sequence from production control (FR-DP T31). The bumper area essentially produces bumpers in the same sequence as the vehicle assembly line consumes them. Run size in paint is one (FR-DP T32). The run size in injection molding is one shift of material, except for service parts that are produced in larger batches. Injection molding essentially refills the parts, which the previous shift has consumed.

Schedule adherence is almost 100%. It is very rare that the bumper area misses a shipment to the vehicle assembly line according to their records. If it does occur, the next available bumper is sent to the assembly line as soon as possible. In the worst-case scenario, the bumper is attached to the car after the assembly line.

Transportation delay (FR-DP T4)

Transportation only occurs between injection molding and paint. Operators in injection molding load the molded bumpers onto racks and manually push the racks into WIP lanes. Each paint line has one operator, who tugs racks to the paint load area. The operator repeats his round every five minutes. Transportation distance between SWIP lanes and the paint load is between 30 and 450 feet. No transportation is required between paint and assembly.

Systematic operational delays (FR-DP T5)

Support and production resources are well separated in plant T (FR-DP T51). Material supply is all manual and does not lead to lost production time. For example, the paint load operator has one rack of molded parts for every bumper style in front of him. When a rack is empty, the material delivery person pulls the empty rack into the aisle and replenishes it with a full rack, which takes about 1-2 minutes. During that time, the paint load operator loads the other bumper styles and does not lose a production cycle.

Small parts for the bumper assembly are brought in pallets to the assembly area. The operators in the assembly area are responsible to replenish parts at the workbenches if necessary. While this activity interrupts standard work loops, it does not lead to a loss of production (see also discussion under balanced work loops FR-DP D3).

Work loops in assembly are generally not very closely defined and can overlap with each other. Operators may be forced to wait on each other (FR-DP T52).

6.2.2.2.5 Direct Labor (FR-DP Dx)

The plant designed detailed work loops for operators to eliminate waiting time, wasted motions, and to achieve balanced work loops (Table 6-10). Whenever direct labor is necessary, it is used very efficiently.

TABLE 6-10: DIRECT LABOR SUMMARY FOR PLANT T.

	FR	DP	Plant T
D1	Eliminate operators' waiting on machines	Human-Machine separation	Injection molding machines have a buffer up to 20 parts between the press and the operator, which decouples the operator from the machine. Operators at paint load continuously loads parts on jigs, paint line conveyor is rarely down. Work content of operators at paint unload and assembly closely matches paint line cycle time.
D2	Eliminate wasted motion of operators	Design of workstations / work-loops to facilitate operator tasks	Little operator walking in plant T considering the size of the parts. Operator at paint load have to walk between 5 racks with molded parts. His work loops is about 60 feet. Operators at paint unload has to walk between different assembly work benches for different part styles. Most walking at bumper assembly is due to loading of bumpers into racks for final car assembly. Clean and orderly work station throughout the plant.
D3	Eliminate operators' waiting on other operators	Balanced work-loops	Overall, very little waiting of operators for other operators. Operators at injection molding are working independently from other operators. Work content of operators in paint (load, paint booth, unload) and assembly closely matches line cycle time. The operator, who delivers molded parts to paint, has a cycle time of 5 minutes, and has about 2 minutes idle time, which he uses to help out at various stages.

	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant T - Direct labor	0	0	1	6	13	0

Operator waiting time (FR-DP D1)

The injection molding machines can run autonomously while the operator trims the part and loads it into a rack. The machines have a buffer of up to 20 parts between the press and the operator, which decouples the operator from the machine. The manual cycle time of operators in the paint system closely matches paint line cycle time, but is always slightly shorter to ensure a smooth operation of the paint system. As a result, operators have to wait for the next part from time to time (FR-DP D11).

The plant emphasizes rotating operators to different jobs, which may even be done across the whole factory not only within the bumper production. All operators in the paint system are cross-trained and could perform any job (FR-DP D12).

Wasted motion (FR-DP D2)

Walking distances are fairly short considering the size of the parts (FR-DP D21). Operations in injection molding load the parts into a rack, which they pull as close to their workbench as possible. At paint load, racks with molded parts form a half circle to reduce walking of the load operator. Paint unload and assembly require the most walking, since operators have to move between the assembly benches, racks for the vehicle assembly line, and EWIP racks.

Balanced work loops (FR-DP D3)

The paint system requires balancing work loops with the speed of the conveyor. The operator work loops are not always closely defined such as in a manufacturing cell. The work content for each operator is slightly shorter than the paint system cycle time to ensure that the paint system can operate smoothly and does not have to wait for the operator.

The paint booth has a cycle time of 46 seconds. The operators are able to finish the cycle in approximately 40 seconds. While the work content and the movements with the paint gun are closely defined, the work cycle has to enable the operator to change color hoses or paint guns during the 46 seconds. The work loops therefore include an allowance between the conveyor speed and the work content.

The work loops of the paint unload operator depend on the bumper style as each style requires different handling. This makes it difficult to balance his work with the conveyor cycle time and leads to some idle time for the operator. For example, the unload operator at paint line 1 performs some assembly, periodically buffs parts, and also has to load molded side door panels to the jigs. The work loops of the operators, who load the assembled bumpers into shipping racks, vary depending on whether they have to walk to the EWIP lanes or not. The work loops have to be flexible enough to accommodate off-standard situations such as buffing and walking to EWIP lanes.

6.2.3 Plant U Case Study

Plant U belongs to the same company as plant M. The overall system design and operation is very similar to plant M except that plant U has no automated material handling system. It was expected that the performance relative to the MSDD would be similar for plants U and M. The goal of the case study was to examine if the MSDD reflects the similarities and also points out differences. The discussion of plant U is not as comprehensive as for plants M and T. The focus is on the differences between plants M and U.

6.2.3.1 Plant Overview

Plant U ships on average 4,700 bumpers per day. It produces 17 different bumper styles and additional service parts for old car models. The bumpers are painted in 45 different colors. Plant U operates 5 days a week with 2 eight-hour shifts. Injection molding operates 3 shifts per day. Additional shifts are scheduled on weekends if necessary. The plant assembles bumpers ILVS and non-ILVS for a total of eight customers. Customers are 30 and 500 miles away from the plant.

6.2.3.1.1 Plant History and Layout

Figure 6-1 illustrates today's layout of plant U. The manufacturing system consists of three main areas: injection molding, paint, and assembly. Assembly cells are not concentrated in one area, but spread out across the shop floor. One assembly line is in another building. The plant stores bumpers in racks on the shop floor, which consumes a large part of the shop floor.

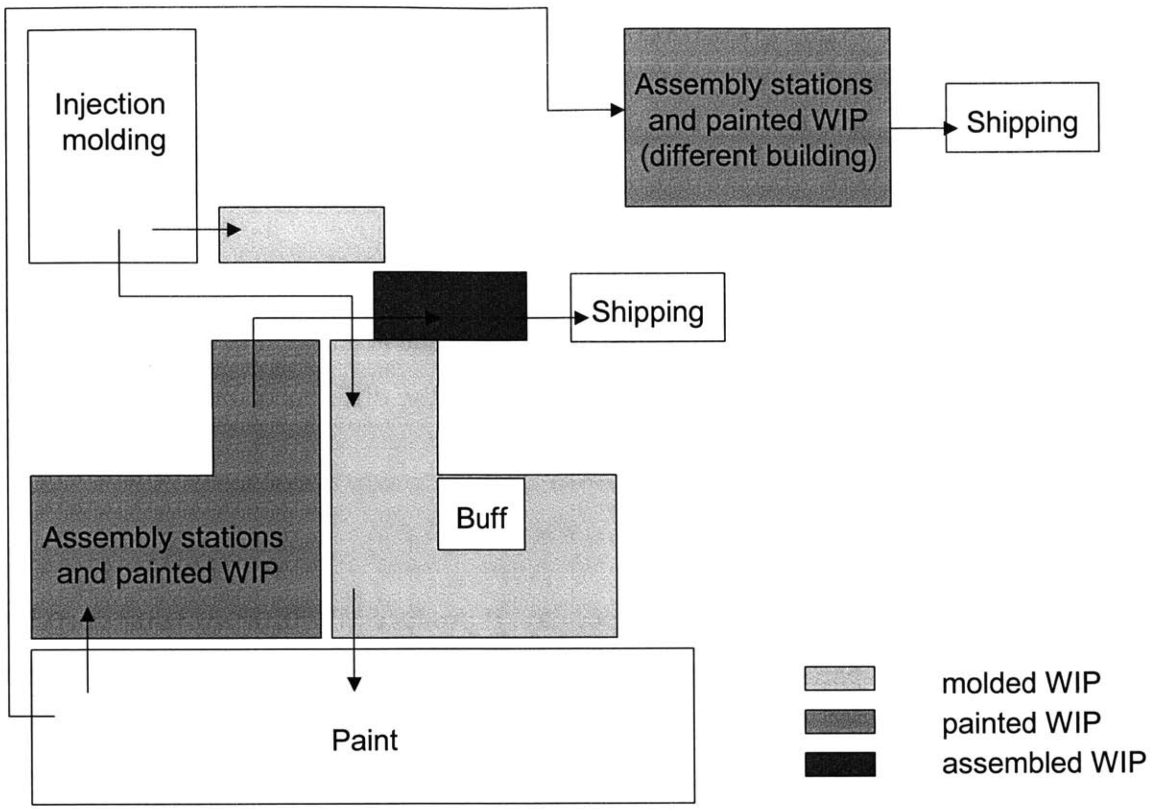


FIGURE 6-17: SCHEMATIC LAYOUT OF PLANT U.

The plant has 7 injection molding machines for 17 different bumper styles. The location of the injection molding area was originally close to the paint system, but was moved to its present location when new equipment was bought. The distance between the injection molding area and paint is about 500 feet. The paint system was installed during the mid eighties. The paint is highly automated and requires no direct labor except for load and unload of the bumpers.

Half of the bumpers are assembled on assembly lines, where several operators progressively assemble the bumper. The other half is assembled as in plant M, where one operator performs the complete assembly of the bumper. All assembly is manual. The plant assembles to ILVS schedules and non-ILVS. To accommodate ILVS assembly, the plant uses a pick-and-place system further described below.

WIP racks dominate the shop floor. The plant has approximately 1.3 day's worth of molded parts, 0.8 day's worth of painted parts, and 0.5 day's work of finished assembled parts at any given time.

6.2.3.1.2 Value Stream

The value stream of plant U is essentially the same as in plant M, with the exception that injection molding determines the schedule itself based on the paint schedule (Figure 6-18). The plant has one scheduling person for the day shift. During the afternoon shift, an operator of the paint system is responsible for schedule changes. High process variability, particularly of the paint process causes frequent changes in the schedules.

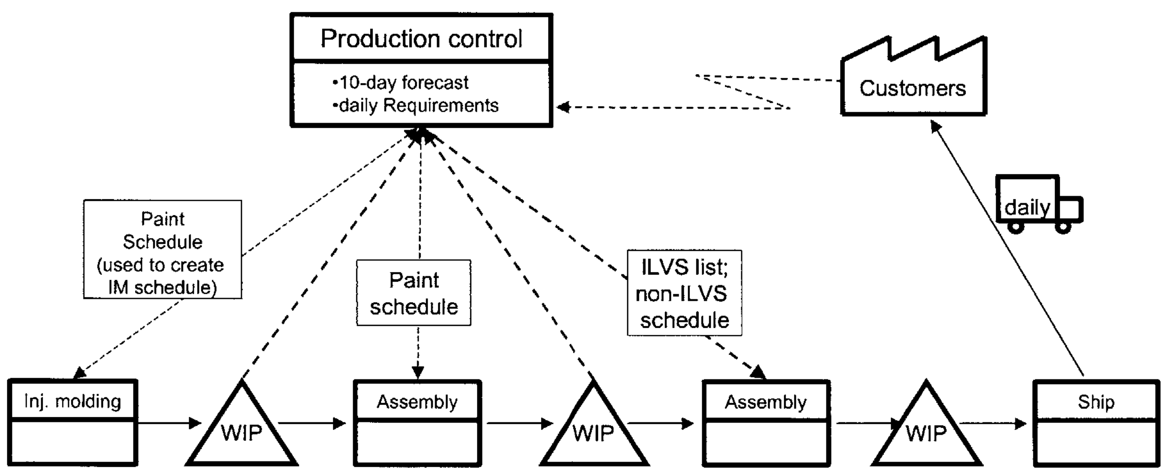


FIGURE 6-18: VALUE STREAM OF PLANT U.

Figure 6-19 shows the complex material flow in plant U. The cycle times and shift patterns mentioned in Figure 6-19 indicate a non-balanced situation between the different operations.

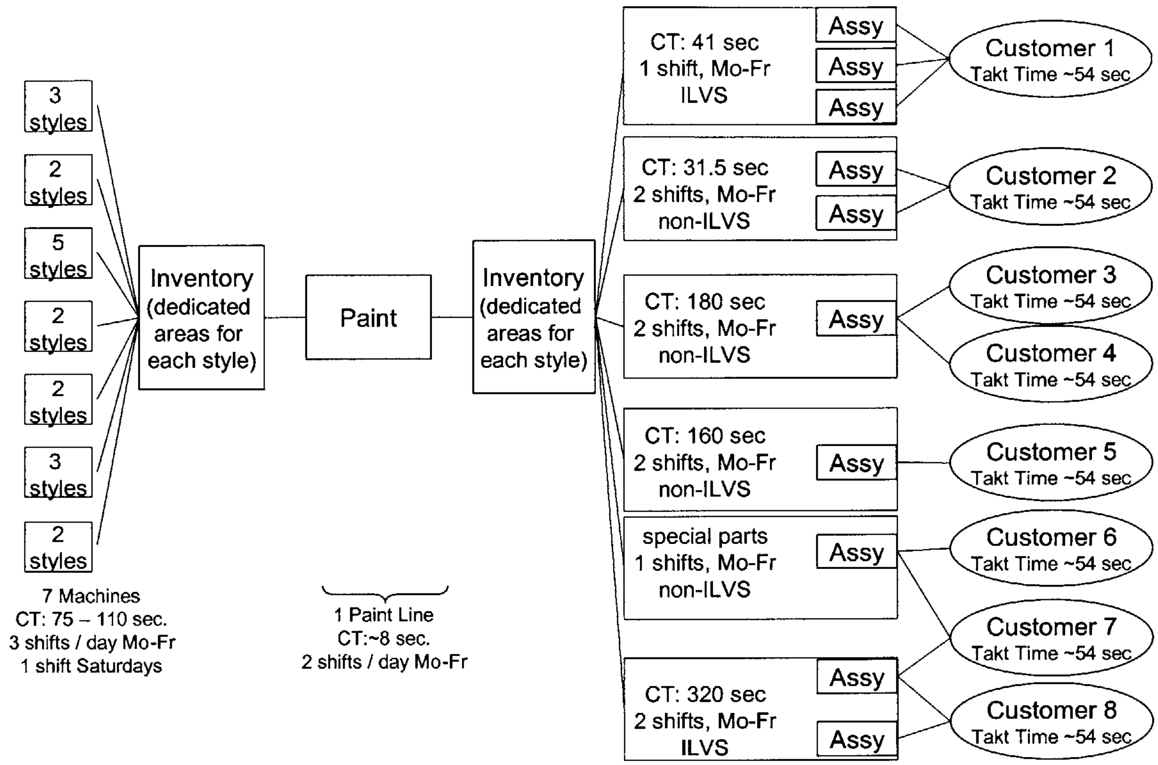


FIGURE 6-19: MATERIAL FLOW IN PLANT U.

6.2.3.1.3 Description of the Processes

Injection Molding

The seven injection molding machines for bumper production are part of an injection molding area, which also produces other parts for the plant. The plant produces 15 different bumper styles plus 2 service parts for a total daily volume of about 5,000 bumpers. The cycle time is between 70 and 110 seconds. Every machine is changed over every day at least once. The defect rate is around 2%. Changeover times are estimated to take between 55 and 90 minutes. Mold repairs are done outside the plant. Regular maintenance is done in-house, though. The parts do not have hidden parting lines, which makes the molds less complex and more reliable than in plant M. The machines have 4000 tons clamping force and the molds require between 3000 and 3800 tons.

The schematic layout of the injection molding area is illustrated in Figure 6-20. A robot unloads the bumper from the machine and drops it onto a conveyor, which can hold up to 10 parts. The operator takes the bumper from the table to his work bench, removes the running gate, deflashes the bumper and loads it into a rack. The number of parts per rack varies between 12 and 18 and depends on the rack type and bumper style. It is possible that the same bumper style is loaded on different type of racks.

The machine cycle time is longer than the manual cycle time. The operator usually works off all parts on the conveyor and then waits until the conveyor is filled up again. This gives him time for breaks and personal allowances. The operator is also responsible to setup the machine and perform the changeovers.

The racks are tugged to the WIP area. The number of racks towed at a time varies between 2 and 4. There is a large number of racks in the aisle, which often block traffic. Molds are stored next to the injection molding machines in a separate corner of the area.

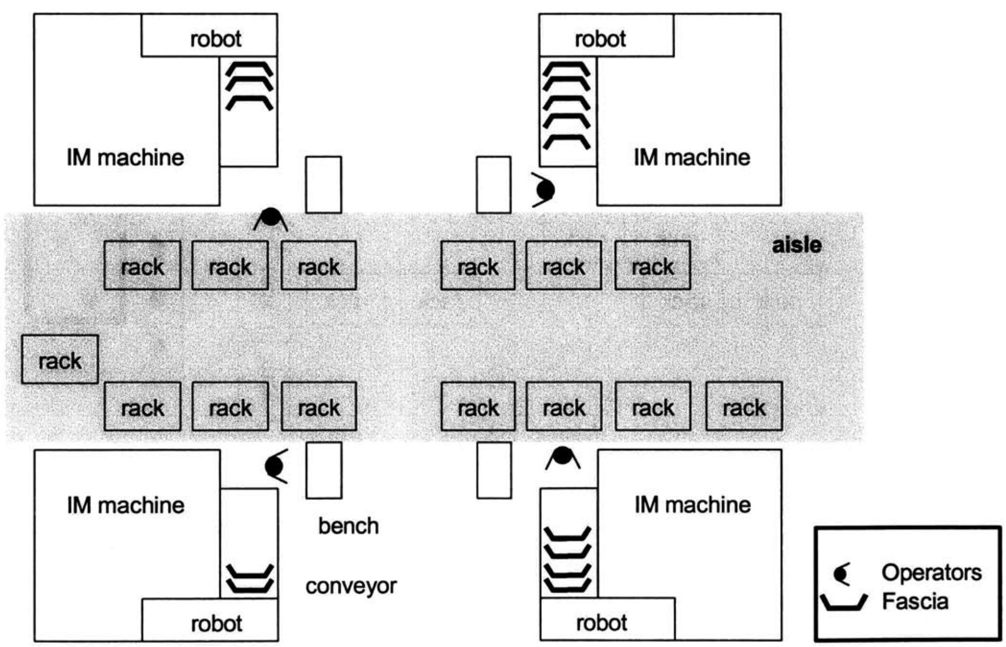


FIGURE 6-20: SCHEMATIC LAYOUT OF INJECTION MOLDING AREA IN PANT M

Paint

The paint line consists of three major areas: (1) loading, (2) paint, (3) inspection and unloading. The overall daily volume is about 6,000 bumpers. The bumpers are painted in 40 different colors. The overall product mix is 95 colored bumpers and 22 different service parts. The minimum cycle time of the paint line is 8 seconds per bumper, if the conveyor is running. The area operates two 8.5 hour shifts per day for five days a week with additional shifts on weekends if necessary. First-time-through yield is between 30% and 95% with an average of 85%. Scrap rate is approximately 3%.

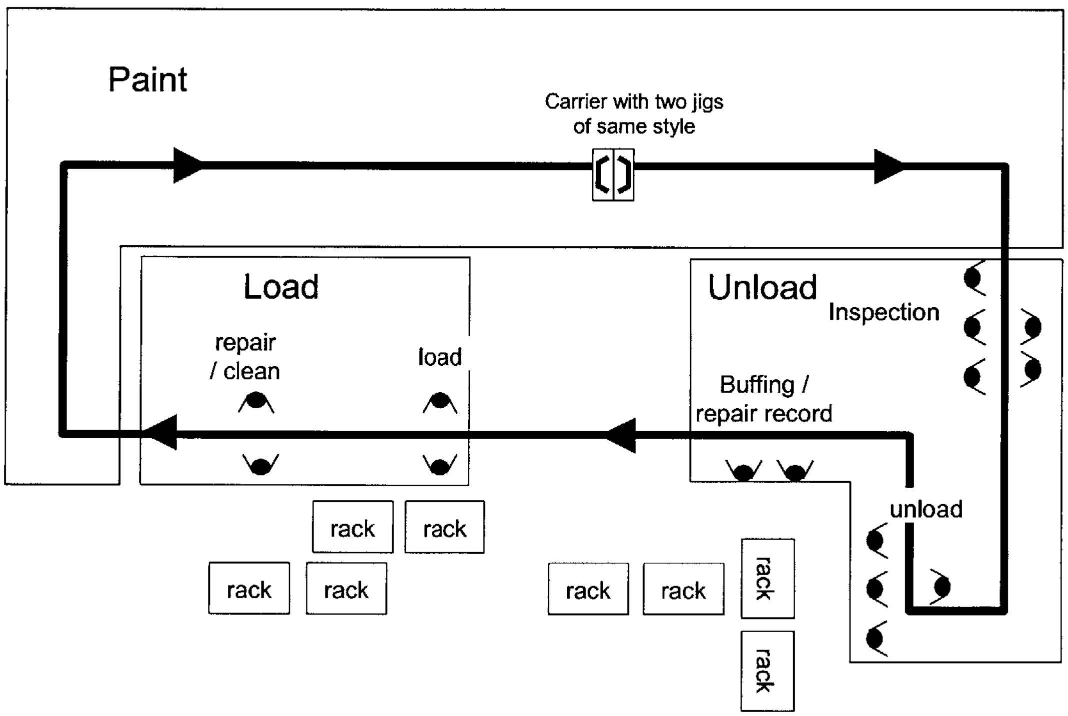


FIGURE 6-21: SCHEMATIC LAYOUT OF PLANT U'S PAINT SYSTEM.

Two operators load molded parts onto jigs. Molded parts are brought to the line in racks. There are usually up to 10 racks waiting in front of paint load. Two jigs of the same bumper style form one carrier. Two other operators wipe off the bumpers. Repaired parts are not taken off the jigs at paint unload, but are sent back to paint load. The two cleaning operators repair the parts while they are moving with the conveyor.

Seven operators inspect the parts for quality problems and color conformity and mark defective parts. It may also happen that a whole batch of bumpers is quarantined when color seems to be of insufficient quality. A supervisor is called to make the final decision, as to whether the parts are good or bad. Four operators unload good parts into racks. Each style can be loaded into different racks that hold various numbers of parts. If no racks are available to unload parts, the paint line is stopped. The two operators after unload buff parts and keep records of defects. They also take off bumpers that need to be scrapped.

Figure 6-22 schematically shows the paint system in more detail. The conveyor consists of nine chains that can move at different speeds similar to the paint system at plant M. It is possible to produce two toned color bumpers by sending bumpers through three optional processes. The system is highly automated with almost no direct work content. Three operators in the paint booth program colors and adjust programs if necessary. Additional support personnel exist for maintenance, engineering, and paint mix.

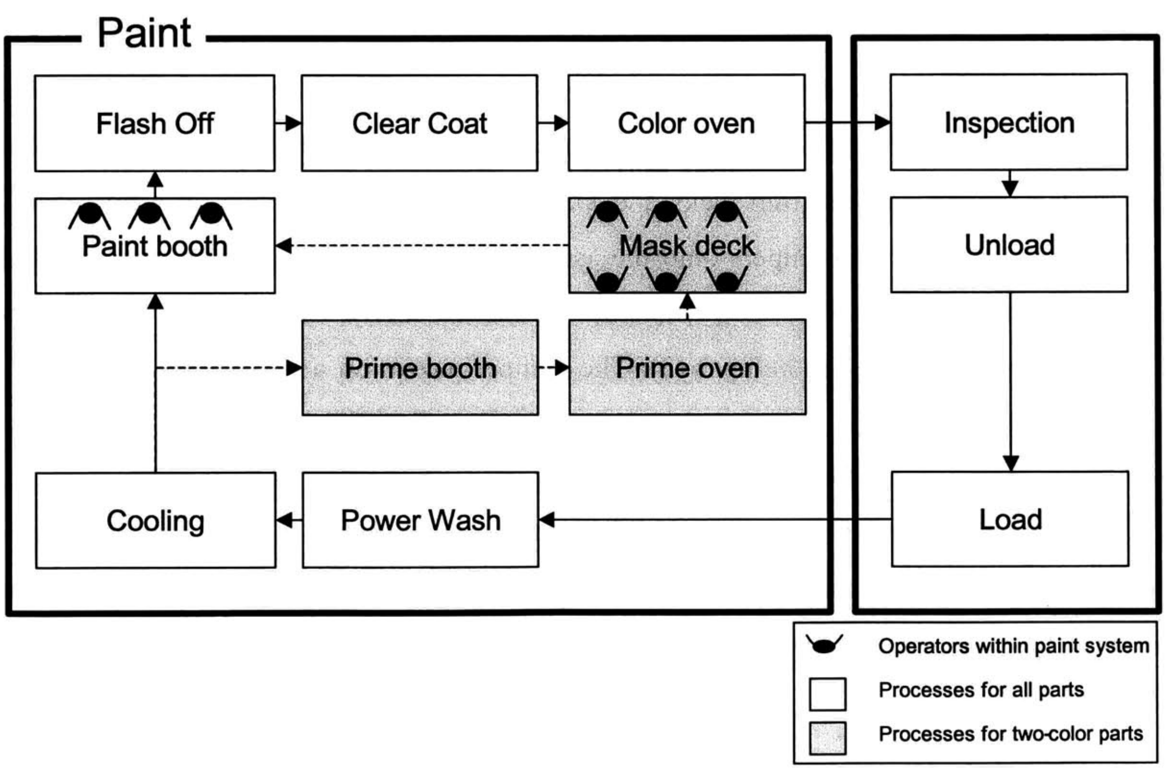


FIGURE 6-22: THE PAINT SYSTEM OF PLANT U HAS THE ABILITY TO PAINT TWO COLOR PARTS.

There are between 20 and 80 jigs of the same style in a row. Jigs are changed over between paint unload and load, which does not require stopping the conveyor. Color batch size is between 12 and 40 parts. Each color changeover requires a gap of 12 feet between the two colors and takes around 30 seconds. The paint robots must flush out the paint gun for the new paint. There are some restrictions for color sequence (for example, no white color after red as some paint particles are still in the paint booth.) Repair parts can be painted in any color.

Assembly

The assembly content per bumper depends on the bumper style. The average assembly content of bumpers in plant U is the highest of the three studied bumper plants. The plant assembles bumpers in an ILVS and non-ILVS mode. The assembly area consists of 10 assembly lines / cells as shown in Figure 6-19. Each bumper style has a dedicated assembly line or station. Assembly stations for low volume parts operate one shift; high volume parts operate two shifts per day for five days a week.

The **ILVS concept** is illustrated in Figure 6-23. Each ILVS line is dedicated to a particular bumper style, since painted bumpers are stored next to the line. Two operators (1) pick painted bumpers from racks and load them in ILVS sequence on a push card. Two operators load the bumpers onto the assembly conveyor (2). They ensure the right sequence and also provide new material to the assembly stations. Five operators progressively assemble the bumper (3). The bumper moves on a pallet with the ends of the bumpers facing up. Operators release the pallet after finishing work tasks. Each assembly line has a different number of operators depending on the assembly content. Two operators at the end of the line (4) inspect the bumpers, wrap them and load them into shipping racks. If a defective bumper cannot be repaired, a new bumper of the same color is brought to the assembly line and immediately assembled.

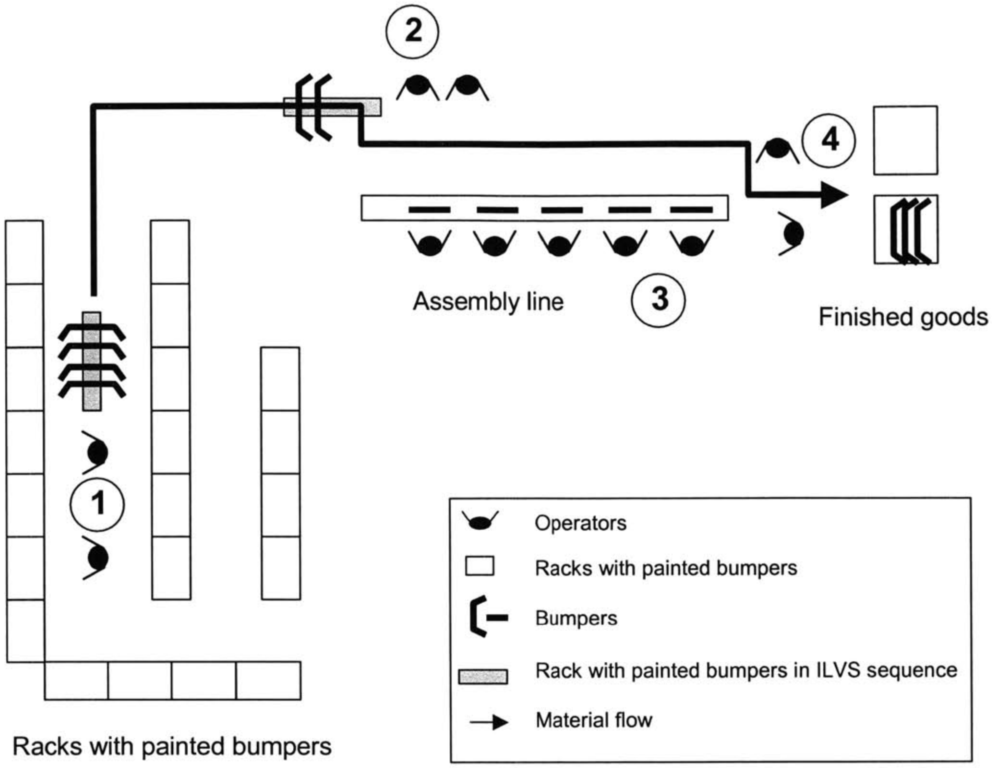


FIGURE 6-23: TYPICAL ILVS ASSEMBLY AREA IN PLANT U.

A **non-ILVS** assembly area is illustrated in Figure 6-24. Three operators pick painted bumpers from racks (1) and bring the bumpers to one of six assembly tables. Each table is dedicated to one bumper style. One operator assembles the complete bumper, wraps it and loads it into a finished goods rack (2). The standard production rate is 20 and 22 bumpers per operator hour depending on the bumper style.

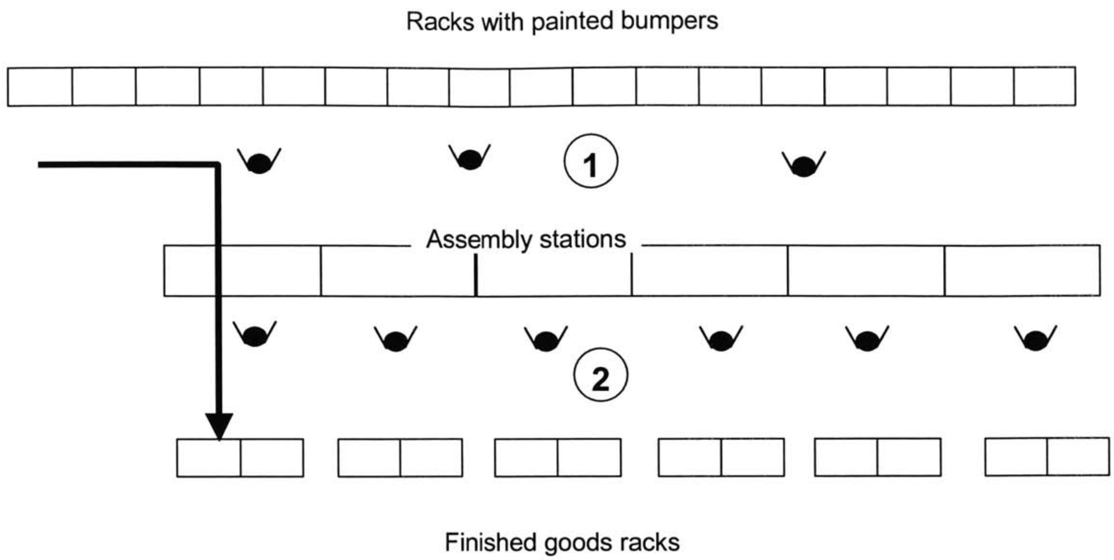


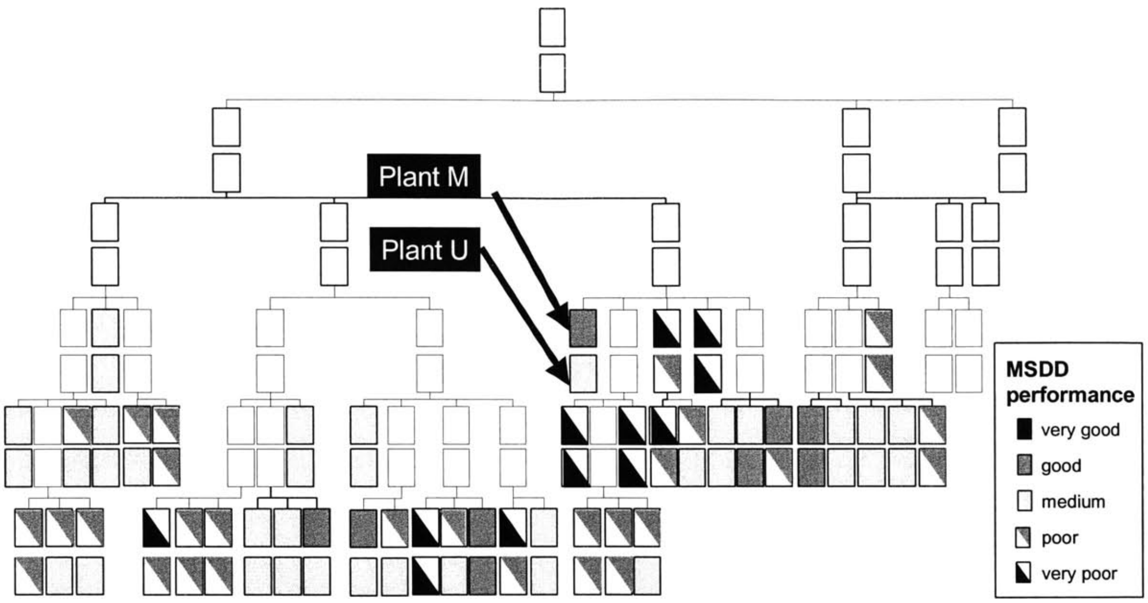
FIGURE 6-24: NON-ILVS ASSEMBLY AREA.

6.2.3.2 Evaluation and Analysis

The overall evaluation of plant U is shown in Figure 6-25. The performance relative to the MSDD is medium to poor. The evaluation summarizes observations made during a two day plant visit, discussions with personnel, and answers of respondents of the questionnaire. Four employees filled out the questionnaire: the area managers of injection molding, paint, and assembly and a supervisor of paint.

Plant U has slightly better performance relative to the MSDD than plant M as illustrated in the lower half of Figure 6-25. Since the overall evaluation of both plants is very similar, the following discussion is focused on major similarities and differences[3]. The differences are based on the analysis of the questionnaire and a reflection of the observations.

[3] The complete questionnaire and evaluation are documented in the MSDD database.



	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M Overall	20	50	38	21	2	1
Plant U Overall	11	38	57	25	0	1

FIGURE 6-25: OVERALL EVALUATION OF PLANT U IN COMPARISON TO PLANT M.

Similarities between plant U and plant M

Both plants show a general lack of designing and enforcing standardized work methods (FR-DP Q122, R111, P131). Work loops are not well designed and lead to idle times among team operators (FR-DP D3).

The overall value stream is very unbalanced between injection molding, paint, and assembly (FR-DP T2). One of the main contributors to this unbalance is the short cycle time of the paint system (see discussion in 6.2.1.2.4). Operators are tied to their work station with sometimes significant idle times in their work loop for example at the paint inspection area (FR-DP D1, D3).

The paint systems in both plants are very similar: the fallout rate is high compared with plant T (FR-DP Q11), process output is unpredictable and has high fluctuations (FR-DP P12), both systems are highly automated with a short cycle time of 5 and 8 seconds (FR-DP T221). The short cycle time leads to unbalanced work loops (FR-DP D3).

The bumper assembly is similar to plant M, but also uses assembly conveyor lines to progressively build up the bumper. Both approaches shows high variation in work completion time and inefficient work procedures.

Both plants have unpredictable and high fluctuations of inventory levels (FR-DP P141), which contributes to frequent schedule adjustments.

Differences between plant U and plant M

In spite of the similarities in the overall system layout and operation, there are some notable differences. Areas in which plant U performs better than plant M are the following:

- Changeover times in injection molding are shorter and more predictable in plant U (FR-DP T32). Plant U produces 17 different styles with 7 injection molding machines, while plant M has 17 machines for 7 different styles. Injection molding equipment is in better condition at plant U (FR-DP P12).
- The paint system in plant U produces in much smaller batch sizes (FR-DP T32). In addition, plant U does not lose the first parts of a new color batch (FR-DP Q11). The paint system only operates two shifts per day, which gives plant U more time to do maintenance and repair (FR-DP P142).
- Plant U is generally better able to meet production schedule (FR-DP T3). There is only one day-shift scheduler as opposed to three schedulers in plant M.
- The automated material handling system in plant M has a strong influence on the work station design (see injection molding and assembly processes). Plant U is more flexible to position racks at convenient locations to minimize walking distances (FR-DP D21). As a result, operators at paint load and unload walk less than in plant M.

Plant U performs worse than plant M in the following areas:

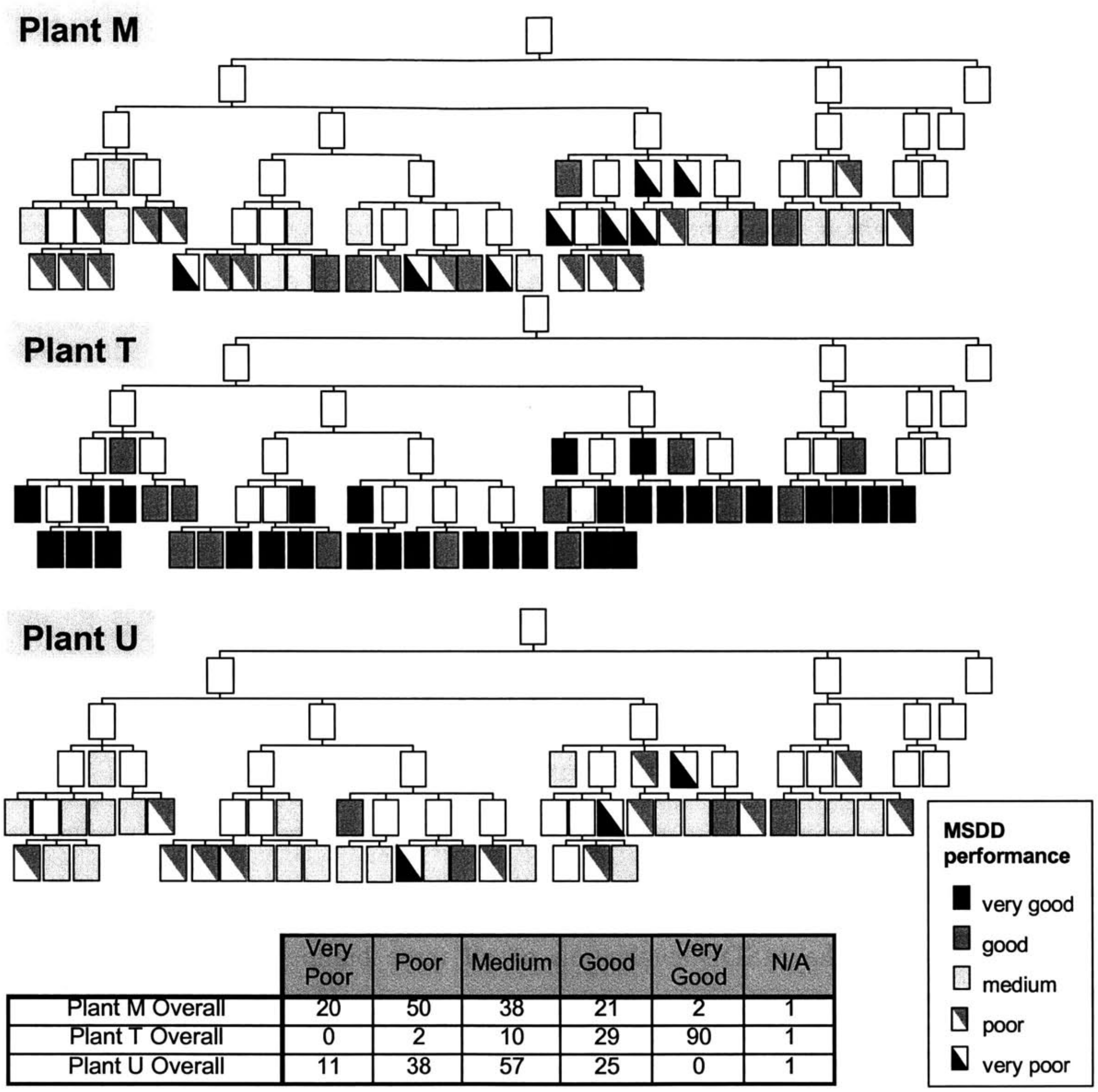
- Material handling is a major challenge in plant U. All bumpers are stored in racks and consume large amounts of floor space. Tugs move racks between processes and inventory areas causing high traffic in the aisles (FR-DP T4, T53). The plant has numerous different racks that hold different numbers of parts. It is therefore difficult to know the exact number of parts in inventory (FR-DP P141). Parts are frequently counted. Plant M uses an automated material handling system with an AS/RS, which consumes less floor space, and coordinates all material movements. However, mislabeled racks cause production disruptions.

- The overall value stream of bumper production is very unbalanced in both plants. Plant U is even less balanced than plant M. Plant U has different shift patterns across the value stream. Injection molding operates three shifts per day and six days a week to minimize equipment investment costs. Inventory is built up over the weekend and consumed during the week. Assembly lines are operated between several hours and 2 shifts per day. Each bumper style has its own assembly line and cannot be changed over.

6.2.4 Comparison of the Three Plants

The following paragraphs provide a comparison of all three plants. It is first summarized how the three plants perform relative to the MSDD. It follows a numerical comparison.

Figure 6-26 shows the MSDD evaluation of all three bumper plants including the distributions of the answers to the questions of the questionnaire. The figure highlights the significant performance differences of plant T compared with plants M and U.



	Very Poor	Poor	Medium	Good	Very Good	N/A
Plant M Overall	20	50	38	21	2	1
Plant T Overall	0	2	10	29	90	1
Plant U Overall	11	38	57	25	0	1

FIGURE 6-26: COMPARISON OF ALL THREE BUMPER PLANTS

Table 6-11 summarizes the quantitative numbers used during the analysis so far. The table highlights that each plant has some specific characteristics that make it difficult to compare the three plants, even though all produce plastic bumpers.

The assembly content per bumper differs greatly among plants M, U and T, which affects the number of operators required. Bumpers assembled in plant U have the highest work content followed by plant M and plant T. In addition, plants M and U must wrap bumpers to prevent damage during truck transport to the customers, while bumpers in plant T are tugged to the next buildings. The product variety in plant U is more than twice as high as in plants M and T in terms of bumper styles, paint colors, and shipped products.

However, the table also points out some areas that demonstrate the superior performance of plant T. Plant T has by far the least WIP. Painted bumpers are immediately assembled and shipped to the vehicle assembly line. Only an EWIP of 400 parts is held after assembly to ensure shipping of parts in the right sequence. The defect rate of the paint system is much lower in plant T than in the other two plants and shows less variation. Plant T is almost able to paint the parts in the sequence in which the customer orders them.

TABLE 6-11: COMPARISON OF PANTS M, U, AND T.

	Plant M			Plant T			Plant U		
	IM	paint	assy	IM	paint	assy	IM	paint	assy
production volume per day	8500	9500	7500	4400	4700	4200	5000	6500	4700
# days per week	5 + overtime (usually every weekend)	5 + overtime (usually every weekend)	5 + overtime	5	5	5	5 + 1 shift Saturday	5 + overtime	5 + overtime
# shifts	3	3	2-3	2	2	2	3	2	1-2
# customers			3			2			8
distance to customer [miles]			30-500			0.1			30-500
WIP (in days of production)	1.3	0.5	0.75	0.3	0.2	0.1	1.5	1	0.5
# machines	17	1	10	7	2	4	7	1	10
cycle time	94-105	7	35-200	55-100	23	0-90	75-110	9	35-300
defect rate	3-8%	5-85%	2-3%	2%	3-4%	<1%	2-3%	5-85%	2-3%
first time through	~96%	~82%	~97%	98%	95%	99%	~97	~87%	~97%
c/o times	45-90 min	30 secs	0-10 min	15 - 30 min	6 sec	0	55-90 min	30 secs	0-10 min
batch size	~ 1day	12-200	1-200	~1 shift	1	1	~ 1day	12-50	1-100
# jigs in paint system		1880			1200			900	
# bumper styles	7 + service			6 + service			17 + service		
Different colors		13			9			40	
Different products shipped			56			38			95

Table 6-12 provides a normalized comparison of the three plants. The normalization takes into account the different volume of good parts shipped per day. Cost data per bumper were not available in any case. The table underscores the superior performance of plant T with respect to WIP and defect rate.

Plant T has fewer direct workers relative to its production volume than plants M an U, but more indirect workers. The ratio for direct workers is largely due to the assembly content of the bumpers. The higher number of indirect workers reflects the emphasis of plant T on maintenance.

The table also illustrates the effect of the automated material handling system in plant M. Plant U stores all bumpers on the shop floor, while plant M uses an AS/RS which consumes much less floor space. Plant T uses virtually no floor space for assembly, but the paint systems are much larger than in plant U and M.

TABLE 6-12: QUANTITATIVE COMPARISON OF THE THREE BUMPER PLANTS.

	Overall		
	Plant M	Plant T	Plant U
Floor Area	0.88	1*	1.39
WIP (between injection molding and shipping)	7.47	1*	8.33
Direct Workers	1.20	1*	1.68
Indirect Workers	0.95	1*	1.04
Line returns (sum of IM, paint, assy)	2.91	1**	2.25
Good Parts/labor-hour (w/o overtime)	0.93	1**	0.73
Assembly content per bumper incl. wrapping (secs)***	35-300	0-90	35-300
Number of fascia styles (w/o service)	1.17	1**	2.50
# different parts shipped	1.47	1**	2.50
Number of shipped good parts per day	1.79	1**	1.12

* (Value Plant M or U / Plant T) / (volume per day Plant M or U / volume per day Plant T)
** (Value plant M or U / value plant T)
*** not normalized

Table 6-13 compares the three paint systems. The paint system in plant T consumes twice as much floor space to produce an equivalent number of parts as plant M or U. All paint systems have essentially the same processes requiring the same floor space for each process. Plant T, however, has two complete paint systems. Each system is dedicated to one vehicle assembly line as described in 6.2.2.1.3. The paint system in plant T has 20 – 30 % more direct workers due to the manual paint process. Plant U has higher direct labor content than plant M as a consequence of the masking process for two-toned bumpers. Defect rate in plant T is 60-70% lower and plant T is able to produce bumpers almost the same sequence as requested by the customer. The high number of indirect workers in plant U is due to tug-drivers for material supply.

TABLE 6-13: COMPARISON OF PAINT SYSTEMS OF THE THREE BUMPER PLANTS.

	Paint System		
	Plant M	Plant T	Plant U
Floor Area(sqft)	0.40	1*	0.50
WIP between paint & assembly & shipping	21.15	1*	15.33
Direct Workers	0.65	1*	0.79
Indirect Workers	0.56	1*	1.27
Line returns	3.82	1**	3.00
Good Parts/labor-hour (w/o overtime)	1.63	1**	1.00
Cycle time in the paint booth [sec] ***	7	46	10
Cycle time at load / unload [sec] ***	5	23	8
Color changeover time [sec] ***	30	6	30
# of Product Models	1.47	1**	2.63
Number of shipped good parts per day	1.79	1**	1.12

* (Value Plant M or U / Plant T) / (volume per day Plant M or U / volume per day Plant T)
** (Value plant M or U / value plant T)
*** not normalized

The differences between plants M and U are less obvious as the MSDD evaluation pointed out already. The higher number of direct workers is largely due to the higher assembly content of the bumpers. The progressive assembly of bumpers on a conveyor line, used for half the production volume in plant U, is less efficient than the stationary assembly and also contributes to the higher number of direct workers. Plant U has fewer line returns particularly in the paint system. In injection molding, output is more stable and molds are in a better state of readiness. The automatic material handling system helps plant M to reduce consumed floor space.

The numerical comparison underscores the superior manufacturing system design of plant T relative to plants M and U. The differences between plants M and U are less obvious. The numerical comparison supports the analysis performed with the MSDD.

6.2.5 Summary

The case studies examined the bumper production of three plants, plant M, T, and U and evaluated each facility relative to the MSDD. Plants M and T were discussed in great detail by describing how the manufacturing system of each plant relates to the FR-DP pairs. All observations and discussions made during plant visits were related to the

MSDD by using the questionnaire. The questionnaire proved to be a very helpful tool for the both data collection and analysis.

The questionnaire was updated based on its application to the case studies. Recommendations for changes in the MSDD and modifications of the questionnaire are documented in Chapter 7 as they include findings from the other case studies as well.

The comparison of the three bumper production plants provided several important insights for the usage of the MSDD:

Reflection of different manufacturing system designs

The three bumper production systems have very different manufacturing system designs and operations. The quantitative comparison showed that plant T has a much lower internal defect rate and much lower WIP levels. In fact, plant T belongs to a company that is a worldwide benchmark for manufacturing efficiency. The analysis and evaluation showed that plant T has very high conformance relative to the MSDD. That means that the analysis of a plant relative to the MSDD can reflect an efficient manufacturing system design.

The evaluation of the three plants relative to the MSDD also shows significant differences between the plants. Plants M and U are less efficient both in terms of numerical comparison and relative to the MSDD. Thus, the case studies illustrated that the MSDD can express system design differences. The analysis of the systems relative to the MSDD provided a detailed understanding of the manufacturing systems.

Dependencies

The three case studies give some valuable insight into the dependencies stated in the MSDD. The dependencies are qualitatively discussed in Chapter 4 and three case studies are not sufficient to statistically prove the dependencies. The case studies add to the confirmation of the dependencies, though, in that they do not disprove them.

The FR-DP pairs in the MSDD are arranged in such a way that they show path dependence when reading from left to right. That is, it should not be possible that a plant shows a high performance on the right side (direct labor efficiency and short throughput times) when having a low performance on the left side (quality and predictable output).

Plants M and U support this premise: Both plants have a medium to poor performance on the left side and do not show strong performance on the right side as illustrated in Figure 6-26.

Simultaneously satisfying all FR-DP pairs

Plant T achieves high performance in all branches of the MSDD. Chapter 4.3.1 discussed the general structure of the MSDD and how core manufacturing competencies (quality, reliability, delivery time) are considered in the MSDD. The performance of Plant T suggests that all three competencies can be achieved simultaneously in car bumper production. A forth core competency (cost) could not be examined since cost data were not available.

6.3 Application Case Study

6.3.1 Introduction

The following section describes the application of the MSDD in a system design project at plant M. The MSDD is used to analyze the existing system and to determine project objectives. The system design process uses the MSDD to ensure that the system objectives are satisfied. The section explains the motivation for the project and describes the steps the design team went through to conceptualize and implement the project. The summary discusses strengths and weaknesses of the MSDD application and provides insight on how the MSDD can be better integrated into a formal design process.

(It is worth noting that the design project overlapped in time with the development of the questionnaire and the case study of the bumper production at plant M.)

6.3.2 Project Motivation and Objectives

Plant M belongs to a large automotive supplier group that is in the process of restructuring its manufacturing practices towards "lean manufacturing." One cornerstone of the "lean" initiative is to operate all manufacturing processes on a pull control basis. Another major initiative in the group is the implementation of an ERP system.

Plant M is a pilot plant for implementing the ERP system. For that purpose, management also wants to apply a pull control approach for bumper production. To illustrate how a pull control approach would alter the plant's manufacturing, the PSD lab developed two physical models of the bumper production. The first model represents the current bumper production system as discussed in section 6.2.1. The second model illustrates a future value stream map as shown in Figure 6-27.

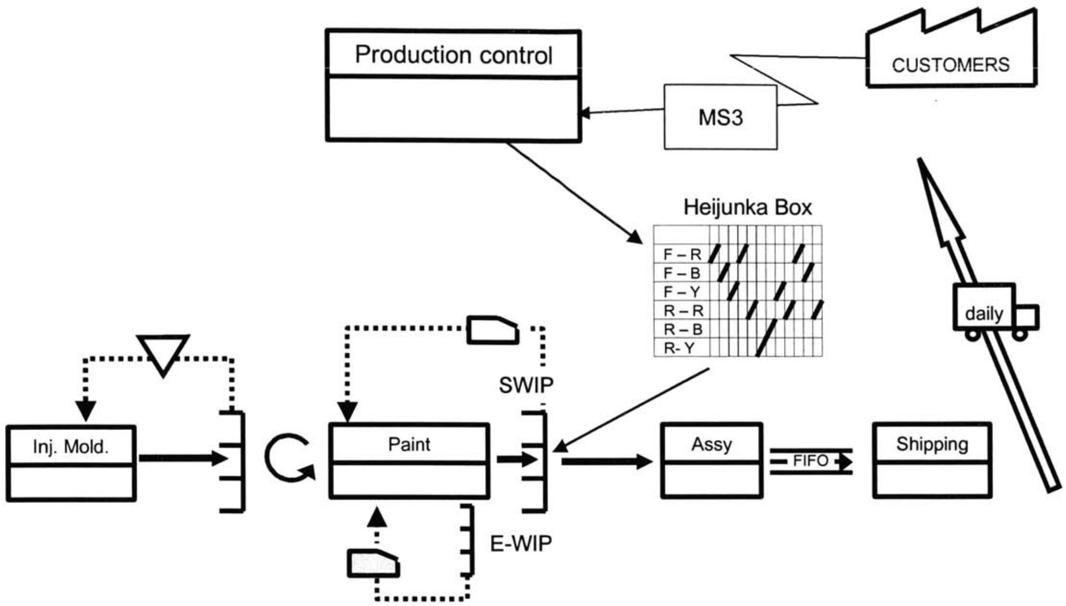


FIGURE 6-27: SIMPLIFYING FUTURE STATE VALUE STREAM MAP.

The models scale down manufacturing parameters such as cycle time, volume, product variety, and inventory to replicate characteristics of the actual plant's operations such as frequent rescheduling, inventory fluctuations, unpredictable output. Lego blocks in different colors and sizes represent bumpers and simple boxes are used as machines. Fallout in paint is simulated by rolling a die (for a detailed description of the models see Cochran et al. [2001]).

The purpose of the model is to illustrate the material and information flow of the whole bumper production value stream. Even though the model is abstract and simplistic, the employees agree that the model reflects the main characteristics of the actual bumper production (frequent rescheduling, unpredictable shipments, hectic). The purpose of the models is not to simulate quantities such as the necessary inventory levels between assembly and paint.

The models provide the starting point for the design project described in this section. The objectives of the project are: (1) schedule only final assembly and schedule paint through a kanban system, (2) produce every demanded part every day in the right quantity, (3) visualize the information flow between assembly, paint and injection molding for the operators and make scheduling information accessible to the operators on the shop floor, (4) improve the ability to quickly recognize problems.

The plant selected the wagon rear bumper style to learn how these goals could be achieved and how the bumper production system would be affected by implementing the new value stream. The daily demand of the wagon bumpers is around 200 parts per day (less than 3% of the total bumper production). As a constraint, the company wants to avoid major physical rearrangements in the plant and cannot afford to invest in a new paint system. However, it was possible to reconfigure assembly.

The following paragraphs describe how the MSDD is used during the design project. The design project focused on the design of a new assembly line for the wagon bumpers and the information linkage of assembly with paint. Injection molding is not considered during the project and postponed for the second phase of realizing the new value stream. The design team consists of the assistant plant manager, an industrial engineer, a manufacturing engineer, operators, union representatives and two students of the PSD lab.

6.3.3 Application of MSDD

The application of the MSDD can be summarized in four steps as illustrated in Figure 6-28. Step 1 analyzes the existing system relative to the MSDD. The second step clarifies the project goals and matches those with the MSDD. Step 3 determines dependent objectives based on the decomposition and the dependencies stated in the MSDD. Step 4 leads to a realization of the project.

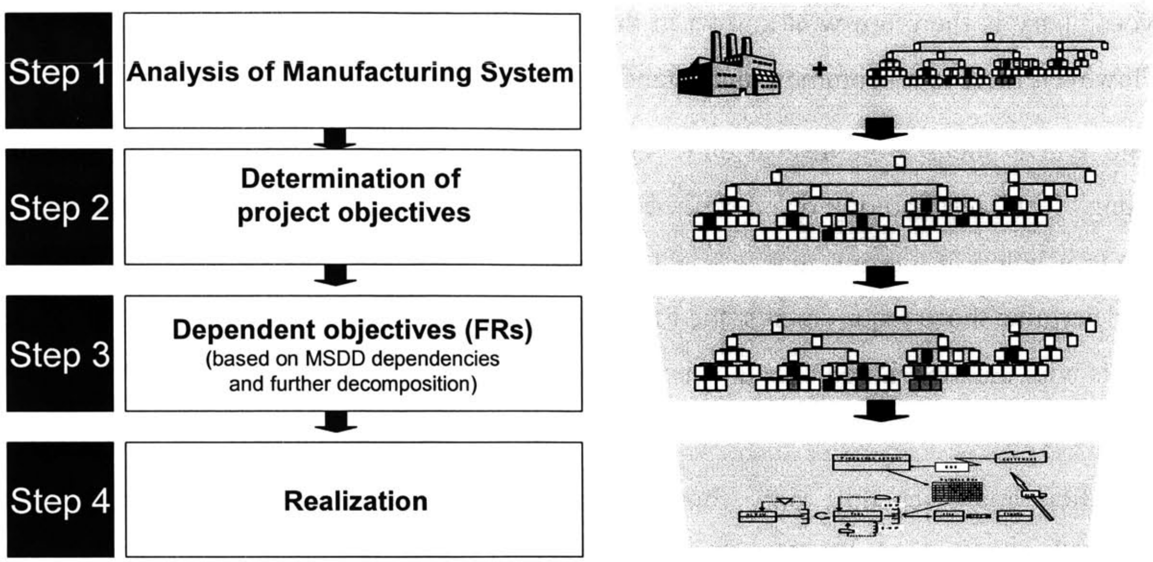


FIGURE 6-28: 4 STEP APPLICATION PROCESS FOR MSDD.

The steps are not performed in strict sequence, but involve iterations. The following paragraphs describe the steps in more detail.

Step 1 – Analysis

The analysis of the current bumper production includes drafting a current value stream map and evaluating it relative to the MSDD. The evaluation of FR-DP pairs is based on discussions, interviews, and observations. At the beginning of the case study, the evaluation process was only loosely defined and sometimes ambiguous. Chapter 5 describes the difficulties in developing a standardized tool for evaluating and analyzing a manufacturing system relative to the MSDD. This project greatly contributed to the development of the questionnaire by clarifying the meaning of the FR-DP pairs and by testing various methods for measuring (see Chapter 5).

After the questionnaire was developed, the analysis was reviewed and documented with the help of the questionnaire as described in 6.2.1.

Step 2 – Determination of Project Objectives

The company is in the process of transforming the manufacturing environment to "lean production." Major initiatives are underway to restructure the shop floor. "Lean" vocabulary is therefore well known in the plant and frequently used during the project. However, there is no common understanding of what "lean" means.

The MSDD focuses the discussion on concrete objectives for the design project without using "lean" terminology or prescribed physical design solutions. The MSDD facilitates the translation of the four management goals into concrete project requirements. In order to determine those requirements, the four goals are mapped with the MSDD. Mapping the goals with the MSDD requires the design team go through the entire MSDD and compare the FR-DP pairs with the goals.

The first goal "schedule only final assembly and schedule paint through a kanban system" matches with FR-DP T31 "Provide knowledge of demanded product mix (part types and quantities)" – "Information flow from downstream customer." The second goal "Produce every demanded part every day in the right quantity" relates to FR-DP T3 "Reduce run size delay" – "Production of desired mix and quantity during each demand interval." Interestingly, the MSDD states the project goal as a design parameter and not as a design objective. The objective is to reduce run size delay, which contributes to delay reduction.

The ability to produce every demanded bumper every day requires predictable material availability (FR-DP P14 "Ensure material availability" - "Standard material replenishment system"). FR-DP P14 captures the need of having the right mix of painted bumpers available for assembly to produce every demanded part every day. Goal 3 "Visualization of the information flow" has to do with FR-DP P11 "Ensure availability of relevant production information" –"Capable and reliable information system." The design team must decide how the information is communicated and how the operators access the information. Quickly identifying problems (goal 4) matches with FR-DP R11 "Rapidly recognize production disruptions" – "Subsystem configuration to enable operator's detection of disruptions."

Step 3 – Determination of Dependent Project Objectives

The next step is to clarify other FR-DP pairs that must also be achieved in order to satisfy the objectives determined in step 2. The clarification follows the decomposition of FR-DP pairs and the dependencies stated in the MSDD.

FR-DP T3 "Reduce run size delay" – "Production of desired mix and quantity during each demand interval" is decomposed into two FR-DP pairs, from which one (FR-DP T31) is already considered as a project objective. The second FR-DP T32 "Produce in sufficiently small run sizes" – "Design quick changeover for material handling and equipment" requires that paint is able to distribute the jigs on the paint conveyor in a way that facilitates painting several colors every day.

The MSDD states that achieving FR T3 depends on DP T2. It is therefore necessary to examine which FR-DP pairs of the T2-decomposition branch are relevant for the project. The following three pairs define additional requirements: FR-DP T21 "Define takt time(s)" – "Definition or grouping of customers to achieve takt times within an ideal range" requires defining the assembly shift patter and rate at which the bumpers are assembled. FR-DP T222 "Ensure that manual cycle time <= takt time" – "Design of appropriate operator work content/loops" requires designing the work content of the operator so that she can finish the work cycle on time. FR-DP T23 "Ensure that part arrival rate is equal to service rate" – "Arrival of parts at downstream operations according to pitch" enforces the coordination of the AS/RS with the assembly cell to ensure timely delivery of parts. The other two pairs of the FR-DP T2 decomposition are not applicable: The equipment cycle time at paint or injection molding could not be influenced (FR-DP T221), and leveling the cycle times is not applicable as the cycle times for all bumpers of a chosen style were the same (FR-DP T223).

Another dependency for FR T3 is DP T1 "Reduction of transfer batch size." Since the transfer batch size in plant M is already very small (6 bumpers at a time), FR-DP T1 is not considered a design objective for the project.

FR P14 is affected by DP-P13 "Motivated workforce performing standard work." Predictable operator output is necessary to ensure the operation of a standard replenishment system (FR-DP P131), which in turn requires thoroughly training the operators to ensure that they understand the system (FR-DP Q121 and Q122). Furthermore, the decomposed FR-DP pairs of FR-DP P14 and FR-DP R11 provide more detailed objectives.

The ability to completely redesign the assembly line led to two more objectives: reduce walking distances (FR-DP D21) and achieve balanced work loops (FR-DP D3).

Figure 6-29 summarizes the mapping of the project objectives with the MSDD. It shows a wide spread of the objectives across the MSDD and highlights that the design project must consider objectives from all branches of the MSDD.

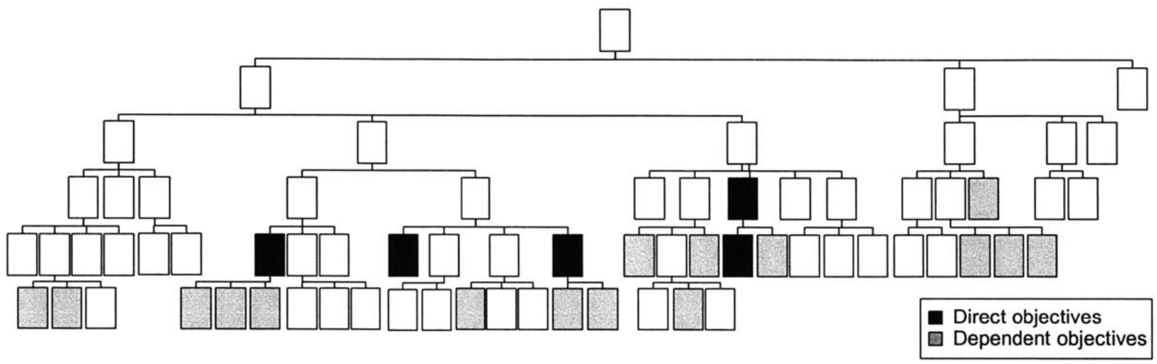


FIGURE 6-29: MAPPING OF PROJECT OBJECTIVES WITH MSDD.

Step 4 –Realization

The following paragraphs describe the new design. The description refers to FR-DP pairs that are affected by design decisions and refers to them in brackets.

The first step in the design process is to decide how many shifts per day the assembly cell should operate. This determines the takt time for the assembly cell (FR-DP T21), the number of operators and the work content per operator (FR-DP T222). The decision to operate two shifts per day leads to a takt time of 220 seconds per bumper. The two-shift operation is a compromise considering the operating pattern of paint and the assembly cycle time for the bumpers. Ideally, assembly would operate the same time per day as paint, i.e. three shifts per day (FR-DP T23). However, the resulting takt time of 330 seconds would exceed the assembly content per bumper causing significant operator idle times. On the other hand, one shift operation at assembly would lead to increased inventory between paint and assembly to buffer painted bumpers for two shifts.

The design of the information flow between assembly and paint (FR-DP P11, T31) has to consider several constraints of the existing system. Kanbans cannot be attached to AS/RS racks. Therefore, it is necessary to separate the kanban flow from the material flow. Considering that wagon bumper production represents only 3% of the overall production volume, it would be too disruptive to integrate the kanban handling in the regular work loops of operators who load and unload the paint booth. The final solution is a result of close cooperation between operators from assembly and paint. In addition, the physical model is used to verify suggestions and clarify how the kanban loops could be designed. Eventually, one operator would be responsible to manage the complete kanban loop between assembly and paint.

The following paragraphs describe how the information flow satisfies the project objectives. Figure 6-30 illustrates the extended value stream.

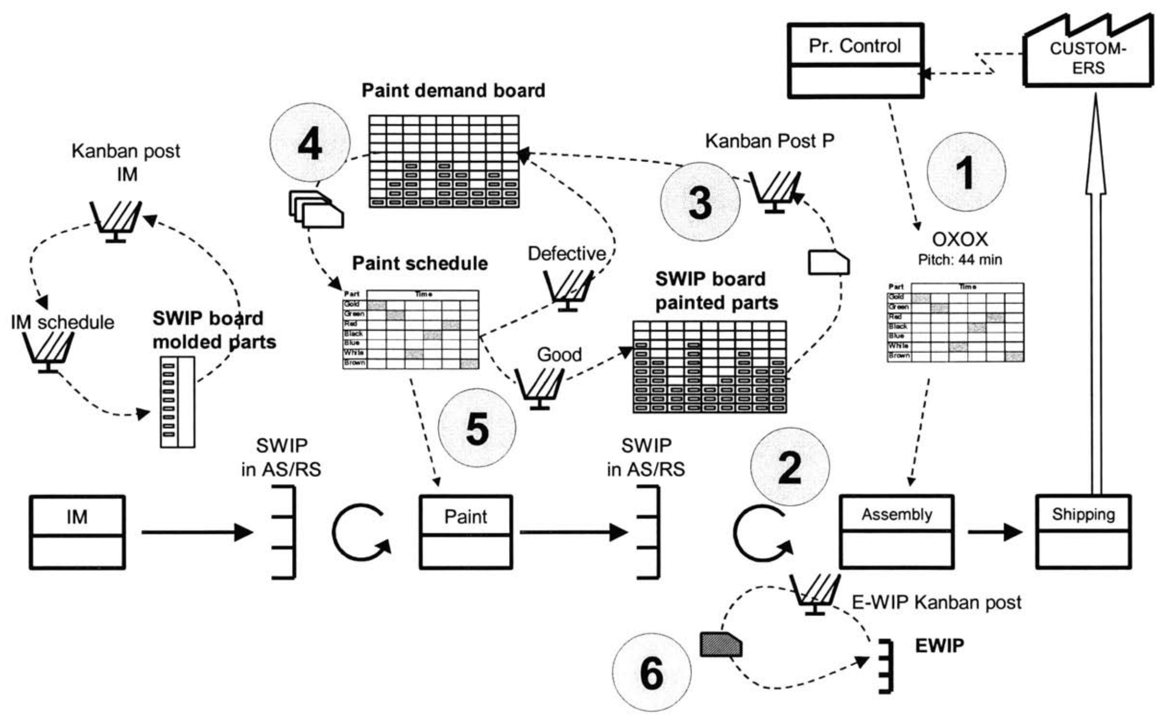


FIGURE 6-30: EXTENDED VALUE STREAM MAP FOR NEW BUMPER PRODUCTION.

(1) Production control issues a daily schedule for assembly. The schedule is divided into increments of 44 minutes during which the operators assemble twelve bumpers of the same color. The shipping rack of assembled bumpers holds twelve parts and the customer requires that all parts in one shipping rack be of the same color. Therefore, the minimum

batch size in assembly is twelve. Every time assembly finishes a batch of twelve parts, an operator crosses off one batch on the schedule list. The 44 minute increments mentioned on the schedule also enable the operator to immediately recognize whether he is ahead or behind schedule (FR-DP R111).

The assembly schedule levels the demand for high-volume colors over the course of the day. For example, silver bumpers have a daily demand of 48 bumpers. The assembly schedule then schedules 4 batches of 12 bumpers rather than 48 bumpers in a row to avoid peak demand for a given bumper color (FR-DP T32). Finally, the operator programs the AS/RS to order the next set of painted bumpers (FR-DP P142, FR-DP T23).

(2) For each delivered AS/RS rack, an assembly operator removes one kanban of the "SWIP board painted parts". The "SWIP board" reflects how many painted bumpers are in the AS/RS and gives the assembly operators an overview of the inventory status at any given time (FR-DP P11).

Assembly receives parts from a standard level of painted bumpers (FR-DP P141). The inventory between paint and assembly has defined levels for every color (FR-DP P141). The calculation of the inventory levels between paint and assembly uses a formula that considers variation of both process output and demand fluctuation [Graban, 1999].

(3) The kanbans are collected in a kanban post. In regular time intervals, an operator brings the kanbans to the "Paint demand board." This board shows the demand for painted wagon bumpers for each color (FR-DP P11, T31).

(4) The jigs on the paint conveyor are set up for two batches of 36 parts for each conveyor revolution. Thus, it is necessary to collect six kanbans to release one batch of bumpers. When the "paint demand board" has a set of six kanbans for a particular color, the set is removed from "paint demand board" and released to the "paint schedule" board. The paint schedule board shows the color sequence for the next batches.

(5) Paint inspection determines good and defective parts when a batch of 36 bumpers leaves the paint system. Defective parts lead to an immediate new demand by sending kanbans to the "Paint demand board" (FR-DP R111). For every AS/RS rack with good parts, one kanban is sent to the "SWIP board painted bumpers."

(6) The assembly operators pull parts from the Emergency Work In Process (EWIP), when the AS/RS does not send twelve parts (FR-DP P141). This can happen when AS/RS racks are only partially filled or when the assembly operator detects defective parts. If the operator has used 6 painted bumpers from EWIP, he programs the AS/RS to send six bumpers to replenish the EWIP. In addition, he removes one kanban from the "SWIP board" to signal additional demand for the paint system.

The new system design decreases feedback delays and improves the recognition of production disruptions in the following ways (FR-DP R11). Whenever the kanban boards show possible part shortages, the operators contact the supervisor, call the scheduler, and interact with the operators of the paint system to discuss next steps. High fallout rate at paint is quickly communicated to assembly operators (FR-DP R12). Previously, possible part shortages could only be recognized when the scheduler printed out the AS/RS status report and compared it with the assembly schedule.

The physical model serves as a training tool for all employees of the bumper production – hourly and administrative – to demonstrate the new information flow (FR-DP Q121). The value stream map is used to introduce the general concept of the kanban system.

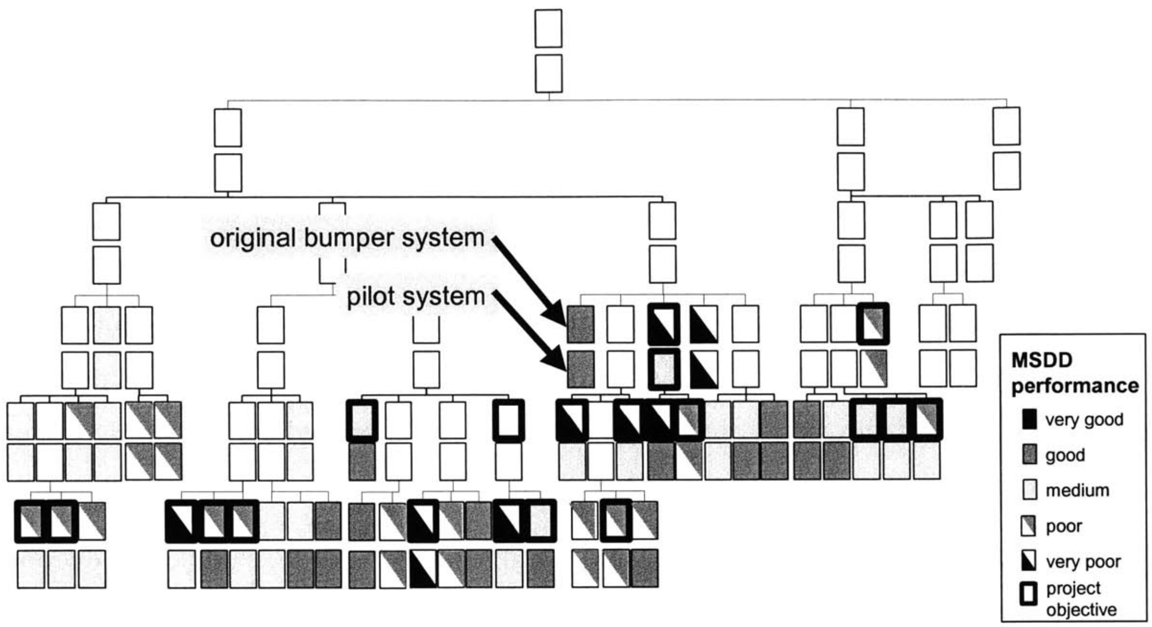
The plant considers computerizing the kanban loop once the high volume bumpers are integrated in the new system. The computer system would automatically update the kanban status with the available information from the AS/RS system. However, the manual version described here is very useful to make employees familiar with the system. It greatly contributed to the increased communication on the shop floor.

Evaluation of the new system

The new system was evaluated with the questionnaire approximately eight weeks after the initial implementation (the questionnaire had been developed in the meantime). The system is not fully functioning yet by the time of the evaluation as the plant is still in the process of becoming familiar with the new system.

Figure 6-31 shows the comparison of the new and old system in the lower and upper boxes respectively. The tables below the graph show how the answers for the old and new system changed. The new system achieves a better score for most questions.

However, there are areas in which the system has not changed yet or does not achieve the desired improvements.



All answers to questionnaire

	Very Poor	Poor	Medium	Good	Very Good	N/A
Old system	20	50	38	21	2	1
New system	7	30	37	45	12	1

Answers to questions related to design objectives

	Very Poor	Poor	Medium	Good	Very Good	N/A
Old system	18	29	11	6	0	0
New system	6	14	15	24	5	0

FIGURE 6-31: COMPARISON OF ORIGINAL BUMPER PRODUCTION AND PILOT SYSTEM INCLUDING DISTRIBUTION OF ANSWERS TO QUESTIONS RELATED TO DESIGN OBJECTIVES.

Table 6-14 contains all questions related to those FR-DP pairs that are determined design objectives, and shows the answers for the new and old system. The comment field describes how the new system changed relative to the existing system.

TABLE 6-14: EVALUATION FOR QUESTIONS OF FR-DP PAIRS, WHICH WERE DESIGN OBJECTIVES.

FR-DP	Question from Questionnaire	Old *	New *	Explanation of changes
Q121	We have standard training procedures for each operation.	2	2	No change.
Q121	Operators know upstream and downstream processes.	2	5	Very good training of system coherences for all participants of the system with the physical model.
Q121	Operators are usually trained on the job.	4	4	No change.
Q121	We continuously improve training procedures.	2	2	No change.
Q122	Operators are involved in creating the work methods.	2	4	Assembly operators participated in the layout of the assembly area and the work sequence.
Q122	Work methods have been defined for each operation and contain information about required quality standards.	4	4	No change
Q122	A written copy of operator's standardized work is available at each station.	2	4	Yes, all instructions are now displayed in the assembly cell. (not all of them are updated, though)
Q122	Variation in quality is reduced either by adjusting the work method or through operator training.	2	3	Increased operator involvement will likely lead to adjusting the work standards as well to reduce quality variation.
Q122	We enforce that every operator performs the tasks according to the work method.	1	1	No change
R111	Machine downtimes are immediately noticed (e.g. through information technology or process design)	2	4	Downtimes in paint are noticed more quickly now due to better communication. Injection molding is not linked yet.
R111	We use devices such as Andon boards or radio communications to signal the occurrence of disruptions.	2	4	Yes, there are alarm devices start playing music and Andon lights in assembly.
R111	Operators can easily see whether they are ahead or behind schedule.	1	4	Yes for assembly. Schedule shows time increments of 44 minutes, i.e. operators can see every 44 minutes if they are ahead or behind schedule.
R111	Variation in work completion time is easily identified.	1	1	No change.
R112	We can always determine which upstream machine is responsible for a defect.	4	4	No change
R112	Process lay out allows immediate detection of disruptions (e.g. downstream operations are quickly starved).	1	3	Fallout in paint is recognized faster due to better information feedback and standardized inventory levels.
R112	Machine downtimes can be unnoticed by downstream processes because processes are separated from each other either physically or through large buffers.	4	2	Much better communication between paint and assembly. Injection molding not integrated yet.
R113	We have standard procedures for determining the root cause of disruptions.	2	3	Formal capturing of problems in assembly. No established standard program yet.
R113	Our system exposes disruptions and makes them easy to recognize.	2	4	The whole system supports the exposition of disruptions much better than before (e.g. by having schedules on the floor, defined inventory levels).
R113	Breakdowns in equipment are easy to diagnose.	3	3	No change
P11	Our operators have access to all information regarding their tasks.	3	4	Yes in assembly. Board in the middle of the assembly area shows all work sequences etc. Production schedules are clearly displayed.
P11	The operator always understand what to produce, when to produce, and how to produce.	3	4	Better communication of schedules and system coherences.
P11	Operators have easy access to process information.	4	4	No change
P11	We often have production disruptions due to missing information.	2	1	The operator, who is dedicated for the kanban loop interacts frequently with paint. Feedback from paint to assembly and vice versa is more frequent now.
P131	We time each operating step in detail and include the information in the work instructions.	2	2	No change. Operator work content has not been defined yet.
P131	Variation in work completion time is being solved either by adjusting the work method or through operator training.	1	1	Not yet. System is not stabilized yet. But it is a goal to make variation more visible.
P131	If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other).	3	3	No change
P131	Work completion time of the same task often varies between operators.	4	4	No change
P131	There is high variation of work completion time between cycles of the same operator.	5	5	No change
P141	We have standard levels of inventory between sub-systems for each part.	1	3	The levels were defined, but they are not maintained. Scheduling still schedules assembly in large batches. Standard levels not achieved yet.
P141	Operations are frequently starved due to unavailability of incoming parts.	4	2	This still happens, but not frequently. The whole process of producing according to consumption is not completely stabilized yet. After all, wagon bumpers are a low volume product and adjustments in the paint system unlikely to support such a low volume part.

* 1 = strongly disagree with question, 2 = disagree, 3 = neither nor, 4 = agree, 5 = strongly agree

FR-DP	Question from Questionnaire	Old *	New *	Explanation of changes
P142	Our part suppliers deliver on a just-in-time basis.	2	2	No change
P142	The frequency of material delivery is based on consumption as opposed to preset delivery times.	4	5	Operators call for AS/RS racks real time.
P142	Part deliveries are independent of downstream consumption.	3	2	No major change, as AS/RS only delivers what is requested. No change in delivery of purchased parts.
T21	We determine takt time at an early stage of a manufacturing system design project.	1	3	Takt time was defined weeks after the first implementation on the shop floor. Schedule did not reflect time initially.
T21	We have clear customer - supplier relations throughout the value stream and production pace is based on takt time.	2	3	Production pace is somewhat based on takt time, but not really established yet. But it is the goal.
T222	We design each operator's work loop to run as close to takt time as possible.	2	2	No change, as work loops were not designed yet.
T222	When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two operators performing the same operation in parallel)	3	3	No change yet: Must be considered during design of operators work loops.
T23	We are well balanced across the process flow.	1	2	Shift pattern in assembly tries to balance production between paint and assembly.
T23	We use a Heijunka box or some other means to communicate the pace of customer demand into the value stream.	1	5	Yes, the schedule is now presented in a Heijunka box. Assembly operators can see pace of production.
T3	We usually meet the production schedule every day.	2	4	Yes, this is true most of the time. However, there are still some difficulties with painted bumpers due to fallout. Inventory levels may have to be increased.
T3	We frequently produce more (or less) than scheduled.	4	3	The assembly schedule is met most of the time. Problems occur when scheduling releases a peak demand for a particular color.
T3	We frequently produce more (or less) of a particular part type per day than the downstream customer consumes per day.	5	4	This has not been eliminated completely yet. Scheduling does not consider the real customer demand, but aggregates several days.
T31	We schedule only one operation in the value stream. Upstream operations are scheduled based on the consumption of the scheduled operation.	1	4	Yes, only assembly is scheduled. Paint color schedule determined based on consumed parts.
T31	We use a pull system for production control.	1	4	Yes, between assembly and paint. It doesn't work perfectly yet.
T31	Our operators have easy access to the production schedule.	2	5	Yes, the operators have the schedule at the assembly cell. Schedule also contains information when a particularly part is supposed to be assembled.
T32	We are working aggressively to reduce setup times.	2	2	No change
T32	We have converted most of the setup time to external time while the machine is running.	2	2	No change
T32	We have low setup times for equipment in the evaluated value stream.	1	1	No change
T32	We tend to have large run sizes in our master schedule.	4	2	Run sizes for assembly and paint have been standardized. No large color batches anymore.
D21	When the shop floor layout is designed, equipment and material are placed so as to minimize walking distances.	2	4	Yes, it was considered and continuously updated. No change in paint.
D21	We usually arrange equipment first and then consider the work loop of the operator.	4	3	This improved a bit, but work loops have not been considered well yet.
D21	We design equipment to minimize walking of the operator.	3	3	No change
D21	Most of our operators are bound to one station and do not have to walk at all.	2	2	No change
D22	We have defined locations for all tools.	3	4	Some improvements based on operator input. But different operators put tools to different spots indicating the tool position is not optimal yet and not strictly defined.
D22	Tools to perform a task are frequently missing.	3	3	No change, since tools in assembly are seldomly missing in the existing system.
D22	We enforce keeping work stations in clean and orderly condition.	3	3	No change
D23	We continuously improve workplace ergonomics by rearranging equipment, tools, material presentation etc.	1	4	Operators give more input now and suggestions are implemented.
D23	We use time studies to update standard work sheets.	1	1	No change yet. Time studies are not performed yet.
D23	Ergonomic interfaces among worker, machine, and fixture are an important consideration during initial layout design.	3	4	Operators gave a lot of input for the new design to incorporate their experience.
D3	Balancing work loops of operators is an important system design objective.	2	2	Not considered yet.
D3	It is often the case that within a team of operators some are idle for part of the cycle, while others are busy for the entire cycle.	4	4	No change yet

* 1 = strongly disagree with question, 2 = disagree, 3 = neither nor, 4 = agree, 5 = strongly agree

Improvements are made in the following areas:

- Assembly production pace is based on takt time (FR-DP T21). The pace is clearly communicated (FR-DP T23) and operators can easily see whether they are ahead or behind schedule, since the schedule shows production goals in 44 minutes increments (FR-DP R111).
- The general communication between assembly, paint, and scheduling improved by the kanban boards. Fallout rates at paint are quickly communicated to assembly (FR-DP R112, R113).
- The only scheduling point is assembly. Paint determines the bumper color based on downstream consumption (FR-DP T31).
- Operators have a very good understanding of the overall value stream through training with the physical model (FR-DP Q121) and are involved in the design of the assembly cell and work methods (FR-DP Q122).
- The assembly cell is frequently rearranged based on operator input to improve ergonomic interfaces (FR-DP D23).

Areas in which the new system has not yet succeeded are:

- There is no written documentation of operator training procedures and work methods (FR-DP Q121, Q122). The kanban loop is not clearly written down yet and there is no formal training for the kanban operator. While one operator during the day shift understands the system very well, another operator in the afternoon shift occasionally misses removing kanbans from the boards. Kanban boards, therefore, do not always reflect the current system status and paint does not always have the right demand information, which leads to sporadic inventory starvation (FR-DP P141).
- The clear definition of standardized work is not done yet in the new system (FR-DP P131). The plant hesitates to determine the number of operators required to operate the assembly cell and the kanban loop. It believes that it is first necessary

to become familiar with the system and eliminate problems before designing standardized work. As a result, it generously overstaffed the cell with two assembly operators and one operator for the kanban loop. Operator work loops are therefore not balanced (FR-DP D3).

The assembly schedule does not reflect customer demand, but batches the demand for colors over several days (FR-DP T3). For example, one assembly schedule observed on the shop floor showed a demand of 168 silver bumpers for one day. The average demand for silver bumpers is 48 with a maximum daily demand of 72 over a three month period. As a result, the calculated inventory levels for silver are too low and the paint system cannot replace silver bumpers fast enough. The plant still investigates the reasons for the demand peaks. An examination of the daily demand at the customer site did not confirm such drastic demand fluctuation. There could be two main reasons for the peak demand in scheduling: first, the defect rate for silver bumpers at the paint system could have been very high the previous days so that demand of those days accumulated. Second, the scheduling department does not schedule the daily customer demand, but also considers available parts in the pipeline between the plant and the customer and creates a "hot-list" with items urgently needed. If the "hot-list" does not utilize the assembly capacity, the scheduler fills the schedule up with colors that most likely will be used in the near future (see discussion in 6.2.1.1.2).

6.3.4 Discussion

This section reviews the sequence in which the FR-DP pairs have been considered in the development of the design process and discusses the applicability of the DPs stated in the MSDD.

Sequence of considering FR-DP pairs

The FRs and DPs in the MSDD are arranged in such a way that the FR-DP pair whose DP affects the most FRs are organized first. As a result, the MSDD shows path dependence when reading from left to right. The path dependence means that FR-DP pairs on the left side must be satisfied in order to achieve the FRs on the right side. This sequence suggests that the FR-DP pairs on the left side should be considered first during the design process.

Table 6-15 lists the FR-DP pairs of project objectives in the order they appear in the MSDD when reading it from left to right. It quickly becomes evident it is not possible to follow the sequence shown in the table. The first FR-DP Q121 "Ensure that operator has knowledge of required tasks" – "Training program" presumes that the operator tasks have already been defined. This is not the case at the outset of a system design project. Another example is FR-DP P142 "Ensure proper timing of part arrivals" – "Parts moved to downstream operations according to pitch." A pitch is a time increment and a multiple of the takt time. Thus, it is necessary to first define the takt time before the DP can be considered. Takt time, however, is defined in FR-DP T21 "Define takt time(s)" – "Definition or grouping of customers to achieve takt times within an ideal range," which is further right in the MSDD.

The precedence given in the MSDD is therefore not applicable for the design of manufacturing systems. The sequence in which a manufacturing system is designed is different from the order in which the FR-DP pairs are arranged in the MSDD. It is necessary to link the FR-DP pairs to a procedural design approach such as one provided by Kettner [1984] as discussed in the Chapter 2. The procedural design approach presents a step-by-step sequence in which design decisions are made. The MSDD could be used to define objectives that must be met during each design step. Chapter 8 discusses in more detail how a linkage between a procedural design approach and the MSDD could be realized.

TABLE 6-15: FR-DP PAIRS OF PROJECT OBJECTIVES IN THE ORDER THEY APPEAR IN THE MSDD.

FR-DP	FR	DP	Design solution in new system
Q121	Ensure that operator has knowledge of required tasks	Training program	Physical model to teach operators system coherences.
Q122	Ensure that operator consistently performs tasks correctly	Standard work methods	Standard work methods have not been defined yet.
R111	Identify disruptions when they occur	Increased operator sampling rate of equipment status	Time increments in Heijunka box allow operators to see whether they are ahead or behind schedule. Fallout in paint quickly recognized and communicated through kanban boards.
R112	Identify disruptions where they occur	Simplified material flow paths	Increased communication between assembly, paint, supervisors, scheduling.
R113	Identify what the disruption is	Context sensitive feedback	
P11	Ensure availability of relevant production information	Capable and reliable information system	Detailed design of information flow between assembly and paint (kanban loop, schedule at assembly cell, kanban boards)
P131	Reduce variability of task completion time	Standard work methods to provide repeatable processing time	No standard work methods are defined yet.
P14	Ensure material availability	Standard material replenishment system	(see P141, P142)
P141	Ensure that parts are available to the material handlers	Standard work in process between sub-systems	Defined inventory levels for painted bumpers in front of paint and EWIP at assembly.
P142	Ensure proper timing of part arrivals	Parts moved to downstream operations according to pitch	Assembly operator programs the AS/RS to order next parts.
T21	Define takt time(s)	Definition or grouping of customers to achieve takt times within an ideal range	Definition of shift pattern to determine available time and takt time.
T222	Ensure that manual cycle time <= takt time	Design of appropriate operator work content/loops	Constraint for operator work task design (not designed yet!)
T23	Ensure that part arrival rate is equal to service rate	Arrival of parts at downstream operations according to pitch	Assembly operator programs the AS/RS to order next parts.
T3	Reduce run size delay	Production of the desired mix and quantity during each demand interval	(see T31, T32)
T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer	Heijunka box with leveled schedule for assembly. Kanban board at paint.
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment	Standardization of run sizes to batches of 36 bumpers.
D21	Minimize wasted motion of operators between stations	Configure machines / stations to reduce walking distance	Operator involvement in designing the assembly cell.
D22	Minimize wasted motion in operators' work preparation	Standard tools / equipment located at each station (5S)	Operator involvement in designing the assembly cell.
D23	Minimize wasted motion in operators' work tasks	Ergonomic interface between the worker, machine and fixture	Operator involvement in designing the assembly cell.
D3	Eliminate operators' waiting on other operators	Balanced work-loops	Operator work loops are not defined yet.

Using the DPs as design solutions

The section discusses to what extent the DPs stated in the MSDD helped the design team to develop solutions for their manufacturing system. The goal is to examine if DPs are too narrow or too broad to be applicable. In both cases, it would be recommended to either reformulate the DP or to further decompose the DP as discussed in Chapter 7. As described in Chapter 4, the decomposition stopped at a level that was specific enough to support design decisions without interfering with the intent to make the MSDD applicable to a wide range of manufacturing companies.

The right column in Table 6-15 summarizes how the new design attempts to achieve the FR. The description of the new design in the previous section provides more detailed information about how each FR-DP pair has been considered in the design.

In some cases, the design solution is similar to the stated DP indicating that the DP provides ideas on how to achieve an objective (for example, DP Q121 "Training program" or DP P141 "Standard work in process between sub-systems.") However, the DPs were only a starting point and more detailed design was necessary to implement them. Some DPs are very specific, such as DP P131 "Standard work methods to provide repeatable processing time." Once all tasks are determined it is possible to define standard work methods.

DP R111 "Increased operator sampling rate of equipment status" is too narrow to be useful. There is no need for assembly to sample equipment status, as it does not involve any equipment. Nevertheless, the new design has several characteristics supporting the detection of disruption: the kanban boards indicate possible material shortages, and operators can quickly recognize if they are ahead or behind schedule.

Some DPs are very abstract making it difficult to derive any ideas for the actual design. DP P11 "Capable and reliable information system" is too broad to provide any guidance for the design. DP T31 "Information flow from downstream customer" is very broad as well. While the general intent of the DP is clear, it may take considerable effort to implement the DP. However, any further decomposition of the DP is likely to be very company specific, which would limit the general applicability of the MSDD.

In summary, the DPs offer a starting point for determining design solutions. It is necessary to further specify the DPs considering the circumstances in which a manufacturing system operates. Overall the level of detail of the MSDD was helpful in providing ideas for the design. Most DPs were not too specific or broad to be applicable.

The questionnaire increased the applicability of the MSDD by providing more detailed explanations of the meaning of the FR-DP pairs. It was easier to imagine how a new system could improve relative to the questions than relative to an FR-DP pair. The explanations in Table 6-14 illustrate how the new design can be related to the questions. Future applications should therefore use the questions as a starting point for defining design solutions rather than the FR-DP pairs.

The MSDD database enables documenting project specific design solutions. The documentation of future system design applications could eventually lead to a knowledge database that helps designers to create design solutions considering company or industry specific circumstances.

6.3.5 Summary

The described case was the first time the MSDD has been used in the design of a manufacturing system. The application process was not defined at the outset of the project and evolved during the project. Several conclusions and recommendations can be made based on the experience of the described design project.

(1) The MSDD proved to be a useful tool to discuss and determine project objectives. It provided a platform for the team members to discuss their understanding of the project goals. By referring to objectives and means stated in the MSDD, it was possible to avoid ambiguous terms such as “lean” manufacturing. The dependencies stated in the MSDD helped to consider system design aspects that were critical for success, but were not obvious at the beginning of the project.

(2) The interpretation of the FR-DP pairs to determine the project objectives was difficult and required a deep understanding of the MSDD. It was necessary to reflect on how each FR-DP pair compared with the project goals stated by the company management. In addition, while the determination of dependent objectives was easy within a decomposition branch, for example within the delay reduction branch, it was more difficult to determine dependent objectives across branches. It would be desirable to

facilitate the mapping process. The MSDD database described in chapter 8 allows the search for keywords such as "schedule", or "standardized work" and highlights related FR-DP pairs.

(3) The questionnaire was not developed when the project started, but it became a very useful tool later in the process. It detailed the analysis of the system and made it easier for the team members to understand the complete scope of the FR-DP pairs. Furthermore, the questionnaire was valuable for documenting how the new system improved compared with existing bumper production. It also facilitated pointing out remaining weaknesses.

(4) The design process suggests that the MSDD does not provide precedence for system design decisions. The decisions did not follow the MSDD from left to right by first satisfying objectives related to quality then identifying and resolving problems and so forth. The first consideration was the determination of takt time expressed by FR-DP T21 in the delay reduction branch. This starting point was in line with procedural manufacturing system design approaches presented in Chapter 2 [Kettner, 1984]. It is desirable, however, to provide a sequence for considering the MSDD objectives during a system design process. Chapter 8 outlines a process how the MSDD could be integrated with a procedural design approach.

6.4 Electronics Assembly Case Studies

6.4.1 Introduction

The following section compares two different value streams for the assembly of the same product families at the same company. The products consist of approximately 20 parts and are manually assembled. The value streams consist of kitting, assembly, and boxing of the products. The value streams are referred to as value stream C and value stream P.

The goal of the case studies is to examine whether the MSDD can explain the differences of the value streams and how the MSDD can be used to derive suggestions either for improvement of the existing systems or to yield an alternative value stream design.

Section 6.4.2 describes the two value streams. It follows an analysis of both lines using the MSDD questionnaire in section 6.4.3.1. In order to determine which of the two value streams, C or P which of the FR-DP pairs satisfies the MSDD requirements best, section 6.4.3.2 categorizes the questions of the questionnaire into two groups. Group 1 consists of questions in which the choice of the value stream is irrelevant to the answer to the question. Group 2 consists of questions in which the choice of the value stream does influence the answer to the questions. Both groups of questions are discussed separately. Section 6.4.5 develops a third value stream design which could best satisfy the requirements of the MSDD. Finally, 6.4.6 summarizes the findings and discusses insights to the use of the MSDD.

6.4.2 Description of Value streams

Value stream C follows the idea that one operator assembles the entire product at one assembly station. Value stream P distributes the assembly to 28 assembly stations. 25 operators progressively assemble the product.

Value stream C was the standard way of assembling products at the company. Value stream P was introduced by a new production manager to better deal with high volume fluctuations and to reduce the need for operator training. The company typically experiences demand increase of up to 40% at the end each fiscal cycle. Since most assembly operations in value stream P are very simple, it is possible to add temporary workers with very little training.

6.4.2.1.1 Value Stream C

Value stream C assembles six different types of products. Each type has multiple configuration options. Two shifts per day assemble around 3,700 units. The throughput time from kitting to boxing is between 5 and 8 hours.

The overall layout of value stream C shown in Figure 6-32 consists of a kitting line, assembly area, and boxing line. A conveyor system connects the different areas. The first station of the kitting line prints out the bill of material or travel sheet for each product. The travel sheet stays with the product until the last step of boxing. The kitting line commissions all parts necessary for the complete assembly of the product and sends the kit to the assembly cells. The kitting line consists of 9 work zones with one operator per work zone. A conveyor automatically moves the pallet from one work zone to the next.

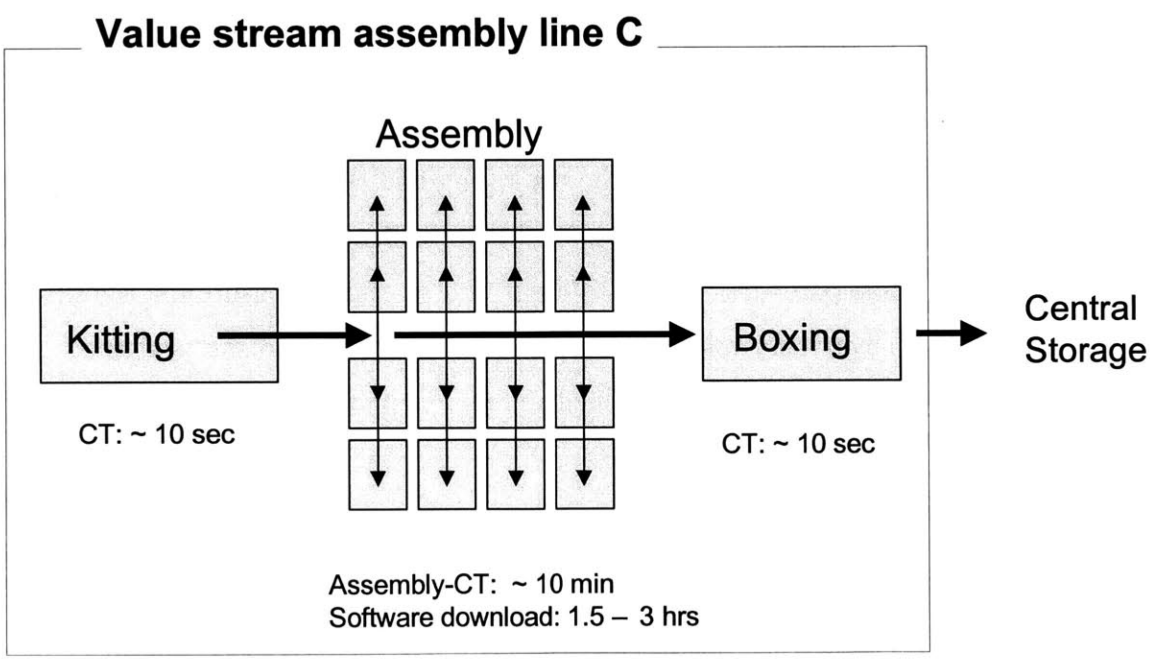


FIGURE 6-32: SCHEMATIC LAYOUT OF VALUE STREAM C .

Operators pick parts according to the travel sheet. When a kit arrives at a particular work zone, lights at the shelves indicate which parts need to be picked. This is called "pick-to-light." The operator picks and scans the parts. Not all parts are "picked-to-light" and scanned, though. The conveyor only releases the kit to the next operator, when all parts requiring scanning are picked. The conveyor system distributes the kits to the assembly cells depending on cell availability and product configuration. Each cell can assemble each product type except for special configurations which are only assembled at dedicated cells. An automated system called "selective distribution" can route orders with specific configuration requirements to specific cells capable of performing those rare operations. The assembly operators receive off-site training before they assemble the first product on-line. Each operator is capable of assembling each product type with exception of some special configurations.

The assembly area consists of 16 assembly cells. Each cell has six operators: four assembly operators, one operator for functional test and software download, and one operator for final product cleaning. Each assembly operator assembles a complete unit. Assembly cycle time per product is on average around 10 minutes. Diagnostics, functional tests, and software download takes between 1.5 and 3 hours. In addition, four cells share one operator, who repairs units that failed the functional test.

The conveyor system transports the assembled products to the boxing line. The configuration of the boxing line is similar to the kitting line. 32 operators pick necessary parts such as manuals, software packages, and other miscellaneous parts and add them to the shipping box. Most parts are "picked-to-light" and scanned to ensure the right parts are boxed. The conveyor only releases the box from one station to the next when the operator at each station has added and scanned all required parts.

6.4.2.1.2 Value Stream P

Figure 6-33 illustrates the overall layout of value stream P. The complete system consists of 7 assembly lines, seven software download areas, two clean and wrap areas, and two boxing lines. The lines assemble 6 different product families. Each family has multiple configuration options. The total output of all seven lines is around 7,800 units per day produced in two shifts. The throughput time from assembly to boxing is around 4 hours.

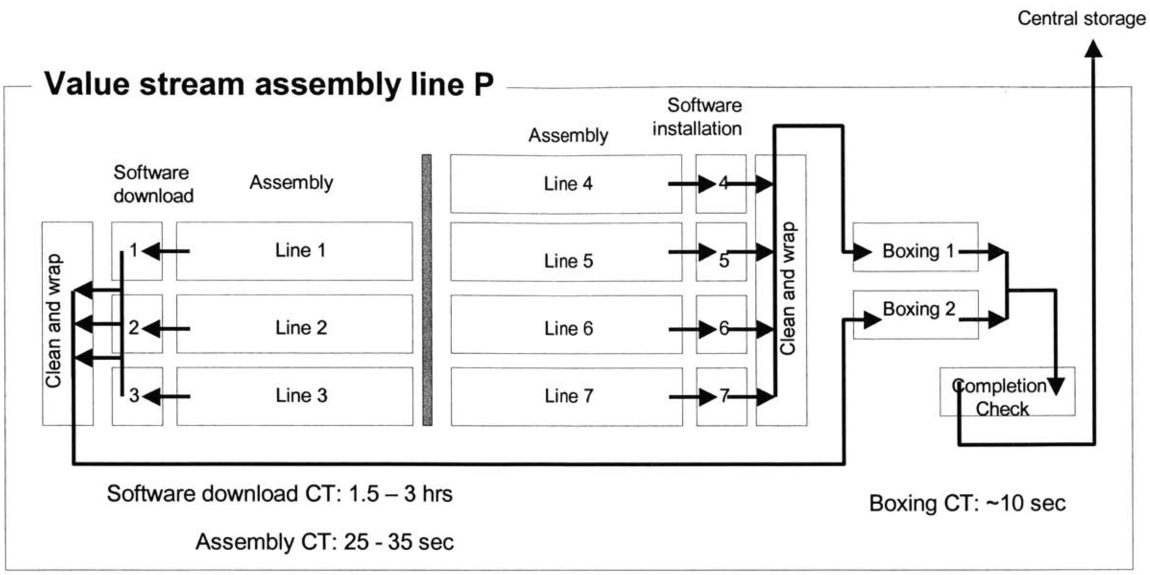


FIGURE 6-33: SCHEMATIC LAYOUT OF VALUE STREAM P.

Each assembly line consists of 28 stations. 25 operators assemble the product on 24 build stations. Two operators at stations at the beginning of the line print out the travel sheets. At the end of the line are a test station and a repair station with one more operator. A conveyor moves parts on a pallet from workstation to workstation. The build stations progressively assembly the product. Operators pick parts from the shelves according to the travel sheet and assemble them. Some parts are picked-to-light and scanned similar to value stream C. If the operator has finished his tasks, the conveyor releases the pallet to the next station. The last station of the assembly line is an "in-line" repair station. The operator repairs defects such as misaligned parts, which are evident even before the functional test and replaces parts if an operator installed a wrong part. If an assembly operator detects a defect during the built-up of the product, he pulls the part of the line and puts it on a shelf adjacent to his workstation. The repair operator collects defective parts, repairs them and brings them back to the same assembly station.

Each assembly line has a dedicated area with 450 racks for downloading software to the products. If the download fails the product is sent to a functional repair station which is shared by the two to three assembly lines. Nine operators per assembly line visually control, clean and wrap the products in the clean and wrap area. If they recognize scratches or other defects, they send the units to the functional repair area. A conveyor transports the parts from the cleaning area to the boxing lines. An operator at the end of the boxing line randomly checks the boxes for completeness. Furthermore, some products are selected for a complete functional test after boxing.

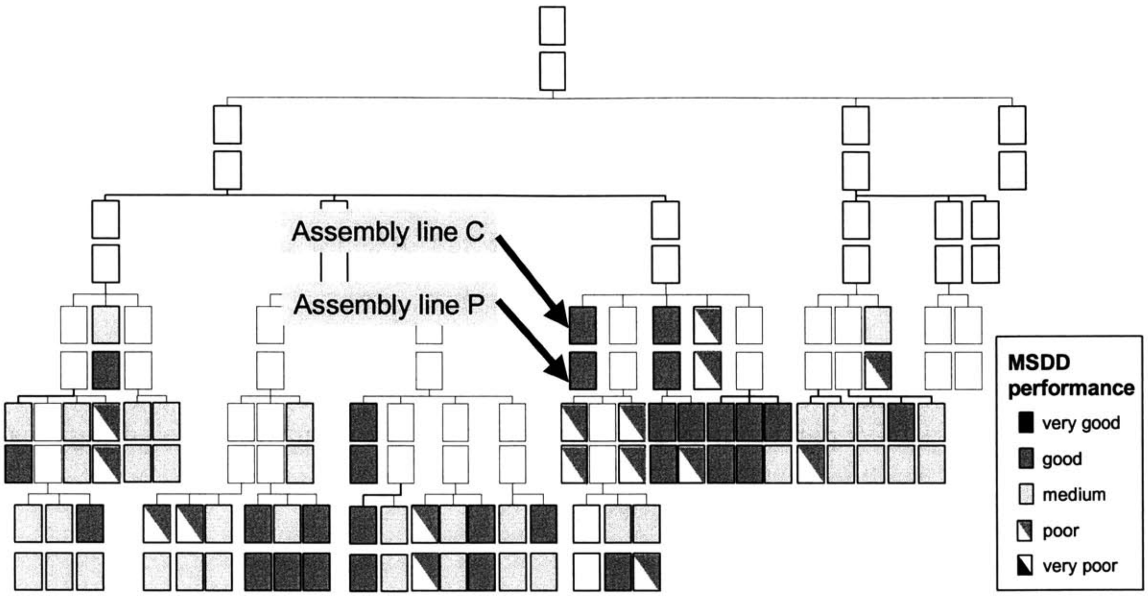
The assembly line in value stream P has four job classifications: entry level, senior level, technician, and senior technician. The entry level requires only minimal training of about 15 minutes and is performed on-the-job. The next levels require work experience of 6 to 36 months. Operators learn the jobs of the next higher level during the operation and also receive additional training. 15 operators belong to the entry level, 8 operators to the second level, 4 operators are technicians and 1 is senior technician.

6.4.3 Evaluation and Analysis

The following sections compare and analyze the two value streams. Section 6.4.3.1 provides a summary of the evaluation relative to the MSDD. The subsequent analysis distinguishes aspects which are independent of the value stream design, i.e. can be achieved / improved without conceptual changes, and aspects, where the conceptual differences influence how well the requirements of the MSDD are achieved. Section 6.4.3.2 explains how the two groups have been determined before discussing each group in more detail.

6.4.3.1 MSDD Summaries

The overall evaluation of two value streams is shown graphically in Figure 6-34. The evaluations reflect observations made during plant visits, discussions with personnel, and answers of all respondents of the questionnaire. Four and three manufacturing engineers filled out the questionnaire for value stream C and P, respectively.



	very poor	poor	medium	good	very good	N/A
Assembly line C	1	25	43	40	10	13
Assembly line P	1	27	50	32	9	13

FIGURE 6-34: COMPARISON OF VALUE STREAM C AND P.

The performance of both value streams relative to the MSDD is medium with several good and poor aspects for each line design. The two value streams had the same answer for 91 out of 132 questions with value stream C performing slightly better than P.

The analysis of the questionnaires showed some major similarities:

+ reliable and capable equipment
+ good documentation of defects in central database
+ simple information flow
+ good access to process information for assembly operators
+ material deliveries based on consumption (some starvation of operations possibly due to double consumption, miss picking of parts, defective parts)

- lack of defining and adhering work methods
- high variation in work completion time
- poor ability to recognize problems quickly which limits ability to improve
- unpredictable throughput times due to fall out at various stations
- departmental layout: kitting, assembly, boxing (value stream C); assembly, software download, clean, boxing (value stream P)
- relatively inefficient operator work

Some specific observations of value stream C are:

+ high product mix flexibility. No changeover between a given product families. Value stream P requires a flushing out of incoming material between two product families.
+ high competence of assembly operators.
+ defects are detected within the assembly cell and allow immediate feedback to the assembly operators.

- assembly operators tend to create own assembly sequence.
- difficult to deal with incoming defects, as they disrupt the work at the assembly cell. A defective part requires a person to pick up a new part from the kitting area, while the assembly operator is idle.
- selective distribution can starve assembly cells.

Some specific observations of value stream P are:

+ fast recognition of disruptions in the assembly process, since disruptions can cause line stoppage.
+ variation in assembly work completion time easier to recognize than in value stream C
+ no starving of assembly line through material handling system

- high operator fluctuation (~ 100% per year).
- requires batch production, since changeover of incoming material necessary.
- no transparent material flow between assembly, burn, wipe down.
- sensitive to absenteeism as the assembly line requires minimum number of operators.

The following tables summarize the findings with respect to FR-DP pairs in the MSDD.

TABLE 6-16: QUALITY RELATED ISSUES

	FR	DP	Summary	Value stream C	Value stream P
Q11	Eliminate machine assignable causes	Failure mode and effects analysis	C=P Mainly manual assembly. Most defects due to material and operator handling. Equipment generally in good condition, capable and not causing defects.	Equipment is in good condition. Defects are recorded. Most defects due to material and operator handling.	see value stream C
Q12	Eliminate operator assignable causes	Stable output from operators	C>P Value stream C has advantages here. Assembly operators in value stream C receive more formal training and are more knowledgeable about the product. Faster feedback of quality problems between assembly, burn, test and repair.	Assembly operators require and receive thorough training. Operator procedures are accessible through the intranet. Operators tend to create their own assembly sequence, which hinders achieving consistent and high operator output. Fast quality feedback within the cell between assembly, burn, test, and repair. Sophisticated Pick-To-Light (PTL) system reduces chances to mis-pick parts in kitting and boxing.	No formal training for assembly operators except for high sensitive parts such as LCD screen assembly. High operator fluctuation leads to loss of knowledge. Frequent control if work standard is followed may lead to additional training of operators. However, stable operator output is not well achieved yet.
Q13	Eliminate method assignable causes.	Process plan design	C=P Both value streams perform detailed studies of tasks. More accurate studies for value stream P to balance the assembly line work. More encouragement to improve methods in value stream C.	Detailed study of work tasks, particularly for kitting and boxing. Not so much for assembly, as one operator assembles whole unit.	Detailed study of every work tasks required to layout the assembly line. Low encouragement to improve the work methods.
Q14	Eliminate material assignable causes	Supplier quality program	C=P Neither system is robust in dealing with incoming defects.	In general, the perception was that there are too many defective parts coming in from the suppliers. However, this is independent of the concept.	see value stream C

TABLE 6-21: GROUP I QUESTIONS (INDEPENDENT ON CHOICE OF VALUE STREAM)

FR-DP	Question
Q11	We use cause and effect analysis tools to determine the source of defects caused by machines.
Q11	We keep records of manufacturing defects for every machine.
Q11	We have eliminated most machine assignable causes
Q121	Operators are usually trained on the job.
Q121	We continuously improve training procedures.
Q121	Operators know upstream and downstream processes.
Q122	We enforce that every operator performs the tasks according to the work method.
Q122	A written copy of operator's standardized work is available at each station.
Q122	Work methods have been defined for each operation and contain information about required quality standards.
Q123	Poka-Yoke devices are frequently used to prevent errors.
Q123	Operators call for help or stop the line when they recognize a quality problem.
Q13	We have detailed process descriptions for all operations.
Q14	Incoming material is defect free.
Q14	Quality is our number one criterion in selecting suppliers.
Q14	We cooperate with suppliers to ensure defect free deliveries of parts.
Q2	Process mean is only set within tolerances, but not necessarily on target.
Q2	We operate processes on target.
Q2	We continuously monitor processes to check whether they are staying within tolerance specifications (e.g. through SPC).
Q31	Disturbances from outside the process are detected before they can affect the process output.
Q31	We have procedures that enable operators to detect a change in the process inputs rapidly.
Q31	We have procedures to distinguish between common and assignable causes of variation in process quality.
Q32	We have made our processes insensitive to disturbances from outside (e.g. material or environmental influences).
Q32	We have standard procedures to eliminate root causes of quality variation.
R111	We use devices such as Andon boards or radio communications to signal the occurrence of disruptions.
R112	We can always determine which upstream machine is responsible for a defect.
R113	Breakdowns in equipment are easy to diagnose.
R113	We have standard procedures for determining the root cause of disruptions.

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TABLE 6-18: PREDICTABLE OUTPUT

	FR	DP	Summary	Value stream C	Value stream P
P11	Ensure availability of relevant production information	Capable and reliable information system	C=P Reliable and sophisticated information system provides necessary production information. No real times display of schedule adherence.	Assembly operators can pull up process information and work descriptions at the work place through the intranet. Good tracking system. Rarely production disruption due to missing information. No need to communicate part sequence, as operators assemble what comes down the line. No real times display of schedule adherence.	Assembly operators have limited access to process information as the assembly task is mostly simple. Intranet provides access to relevant information at various stages in the process. Good tracking system. No need to communicate part sequence, as operators assemble what comes down the line. No real times display of schedule adherence.
P12	Ensure predictable equipment output	Maintenance of equipment reliability	C=P No major difference. Material handling system major part of equipment and major source for downtime. Preventive maintenance not necessarily done on a regular basis.	Preventive maintenance is done, but not necessarily with a regular schedule. Material handling system fairly complex (selective distribution) and major source for downtimes.	Preventive maintenance is done, but not necessarily with a regular schedule. Material handling system less complex than in value stream C.
P13	Ensure predictable worker output	Motivated work-force performing standard work	C=P Predictable operator output is not well achieved in either value stream. Work methods are not defined and task completion time varies between operators and cycles. Absenteeism affects production.	Work methods do not contain timing information. Work completion time varies between operators and between cycles of the same operator. Assembly operators tend to create their own assembly sequence.	Work methods do not contain timing information. Work completion time varies between operators and between cycles of the same operator. Regular inspection of assembly operations tries to enforce assembly sequence. High turnover of operators (~100% per year)
P14	Ensure material availability	Standard material replenishment system	C=P No major differences in the value streams. Material shortages and inventory fluctuations exist in both value streams. Material deliveries linked to order release and consumption through tracking. No defined inventory levels. between subsystems as both value streams basically represent flow-through systems.	Material availability in the value stream refers to purchased parts. Standard levels of inventory defined to some degree. Some starvation of operations due to unavailability of material. Unpredictable fluctuation of material. Incoming material not delivered in standard quantities. Part counting on the floor necessary to some degree.	Material availability in the value stream refers to purchased parts. No defined standard levels of inventory as material is flushed out between product families. Some starvation of operations due to unavailability of material. Unpredictable fluctuation of material. Incoming material not delivered in standard quantities. Part counting on the floor necessary to some degree.

TABLE 6-19: DELAY REDUCTION

	FR	DP	Summary	Value stream C	Value stream P
T1	Reduce lot delay	Reduction of transfer batch size (single-piece flow)	C=P No transportation batching in the system in either concept.	No batching of units within the value stream. Some purchased parts are delivered in larger boxes.	see value stream C
T2	Reduce process delay	Production balanced according to takt time	C=P There are no clear customer-supplier relationships in the either system. Each department (kitting, assembly, burn, boxing) has different capacity and cycle times. Production pace is not well communicated in the system. No production leveling to ensure smooth flow through the system.	The system does not have clear customer-supplier relations: one kitting line feeds 16 assembly cells, feeds one boxing line. The pace of production is not communicated well throughout the system. Production pace of the operations is not related to takt time or customer demand other than an overall daily demand. It is unclear if assembly cycle times for different units are determine the number of units to be produced per day, i.e. a cell should produce x units per day, but when the selective distribution system sends mostly long-cycle time units to a cell, the cell can't meet the desired daily volume. It does not seem to be possible to level out different cycle times to created a leveled schedule for each assembly cell.	The system does not have clear customer-supplier relations. Three assembly lines feed one burn area, feed 9 wipe out operators, feed one boxing line. The pace of production is not communicated well throughout the system. Production pace is not related to takt time or customer demand other than an overall daily demand. It is unclear how the desired cycle time of the assembly line has been determined. However, it served as the determinant for the line layout.
T3	Reduce run size delay	Production of the desired mix and quantity during each demand interval	C>P Only one scheduling point in each system at the beginning of line. Communication of schedule through travel sheet. value stream C more flexible for product mix as no changeover between product families involved. Neither system achieves desired daily output every day.	Value stream C more flexible in product mix. No changeover between product families. Basically, run size can be one. Restrictions apply for combination of PC's and laptops in one line. Communication of schedule is not necessary as the first point in the line receives all important information about mix and quantity (travel sheet). However, system is not able to produce desired quantity every day.	Value stream P requires changeover between product families (flash out of incoming material). Thus, the system operates in batch mode. Communication of schedule is not necessary as the first point in the line receives all important information about mix and quantity (travel sheet). However, system is not able to produce desired quantity every day.

T4	Reduce transportation delay	Material flow oriented layout design	C=P No major difference. Both systems are structured in departments. A sophisticated material handling system transports units between the departments in both systems.	Separation of kitting, assembly, boxing requires transportation. Sophisticated material handling system allows "selective distribution" to send units to assembly cells.	Separation of assembly, burn, boxing requires transportation. Manual transportation from assembly to burn. Conveyor from wipe out to boxing.
T5	Reduce systematic operational delays	Subsystem design to avoid production interruptions	C=P No major difference. In general good separation of production and support resources. Some interference in value stream P as material is partially stored within the work path of the operators. Material handling system in value stream C can cause congestions and starve assembly cells.	Material handling system can cause congestion. Delivery of raw material does not interrupt production (feeding material from the back in kitting, virtually no material feeding in the assembly cells). In general good separation of production and support resources.	Raw material is mostly fed to assembly stations from the back of the work stations and does not interrupt production. Some material stored within the cell forcing operators to leave work station to pick up new material. In general good separation of production and support resources.

TABLE 6-20: DIRECT LABOR

	FR	DP	Summary	Value stream C	Value stream P
D1	Eliminate operators' waiting on machines	Human-Machine separation	C>P No major difference between the line value streams. No automatic machines are involved in either system. Operators at conveyor lines (kitting, boxing, and - for value stream P - assembly) are somewhat paced by the conveyor - also due to some unbalancing of work loops. Operators rotate jobs within their subsystem, but not between subsystems.	Operators at the kitting and boxing line are mainly paced by the conveyor transporting the assembly kit. However, the conveyor only releases the kit, when the operator has finished his cycle. Thus, the operator is not purely paced by the machine. On the other hand, operators often wait for the next kit coming down the line as the conveyor is congested. Operators within the assembly cell can perform all tasks (incl. assembly, burn, wipe out?). Not sure how the rotation works between subsystems.	Operators at the assembly line are mainly paced by the conveyor transporting the assembly kit. However, the conveyor only releases the kit, when the operator has finished his cycle. Thus, the operator is not purely paced by the machine. On the other hand, operators often wait for the next kit coming down the line as the conveyor is congested. This is also true for the boxing line. Some cross training within a subsystem (e.g. within the assembly line). 5 operators form one group and operators rotate within their group.
D2	Eliminate wasted motion of operators	Design of workstations / work-loops to facilitate operator tasks	C=P Both concept mostly bind operators to one work stations and thus have eliminated the need to move. The overall layout is equipment dominated, ergonomic interfaces seem to be of secondary importance.	Most operators are bound to a particular station (assembly line, boxing, wipe out) and don't have to move at all - thus motion is minimized by eliminating need to move. The overall layout is equipment dominated. Good ergonomics for loading units into the burn compartments, but no height adjustable tables for assembly.	Most operators are bound to a particular station (assembly line, boxing, wipe out) and don't have to move at all - thus motion is minimized by eliminating need to move. The overall layout is equipment dominated, ergonomic interfaces seem to be of secondary importance.
D3	Eliminate operators' waiting on other operators	Balanced work-loops	C=P Balancing work loops is important in both value streams, but frequent line stoppages lead to waiting times among operators. Work loops don't really exist in either concept.	Balancing operator work loops is an important consideration during layout, work tasks in kitting and boxing are split to evenly distribute work among line workers. However, frequent line stoppages at various stations leads to waiting times of operators. No work loop design in assembly cell.	Balancing operator work loops is an important consideration during layout, work tasks in assembly and boxing are split to evenly distribute work among line workers. However, frequent line stoppages at various stations leads to waiting times of operators. No work loop design in burn and wipe out.

6.4.3.2 Categorization of MSDD

The goal of the case studies is to compare the two value streams and derive improvements for the existing lines or suggestions for the development of a third value stream design. It is therefore necessary to point out areas in which one of the value streams can satisfy the MSDD requirements better than the other due to conceptual differences.

In order to compare the two lines and to determine the strengths and weaknesses, it became evident that the questions had to be categorized into two groups: Group 1 consists of questions for which the choice of value stream is irrelevant to the answer to the question. For example, both value streams have the ability to maintain equipment in-house (FR-DP P121). Group 2 consists of questions which emphasize conceptual differences and in which the characteristics of the concept influence the score. For example, the ability to quickly recognize problems is influenced by the physical design of the system (FR-DP R111).

The process of deciding, which question belongs in which group, reflects each question with respect to the two value streams and with possible alternative configurations. The distinction does not take into account if value streams C and P have different scores for any given question. The question "Poka-Yoke devices are frequently used to prevent errors", for example, is answered differently for concepts C and P, but does not necessarily have to be. Poka-Yoke devices can be applied regardless of value stream design. Thus, the question is assigned to group 1. On the other hand, the question "The shop floor layout has functional departments" depends upon the value stream design. Although lines C and P employ a functional layout, another concept might integrate all processes into one manufacturing cell avoiding functional departments. Therefore, the question falls into group 2.

85 out of 132 questions are assigned to group 1 (choice of value stream is irrelevant for achieving high score) and 47 questions were in group 2 (choice of value stream matters for achieving high score). Table 6-21 and

Table 6-22 show the questions for each group. For the remaining of this chapter, the two groups are referred to as group I (for Independent of choice) and group D (for Dependent on choice).

TABLE 6-21: GROUP I QUESTIONS (INDEPENDENT ON CHOICE OF VALUE STREAM)

FR-DP	Question
Q11	We use cause and effect analysis tools to determine the source of defects caused by machines.
Q11	We keep records of manufacturing defects for every machine.
Q11	We have eliminated most machine assignable causes
Q121	Operators are usually trained on the job.
Q121	We continuously improve training procedures.
Q121	Operators know upstream and downstream processes.
Q122	We enforce that every operator performs the tasks according to the work method.
Q122	A written copy of operator's standardized work is available at each station.
Q122	Work methods have been defined for each operation and contain information about required quality standards.
Q123	Poka-Yoke devices are frequently used to prevent errors.
Q123	Operators call for help or stop the line when they recognize a quality problem.
Q13	We have detailed process descriptions for all operations.
Q14	Incoming material is defect free.
Q14	Quality is our number one criterion in selecting suppliers.
Q14	We cooperate with suppliers to ensure defect free deliveries of parts.
Q2	Process mean is only set within tolerances, but not necessarily on target.
Q2	We operate processes on target.
Q2	We continuously monitor processes to check whether they are staying within tolerance specifications (e.g. through SPC).
Q31	Disturbances from outside the process are detected before they can affect the process output.
Q31	We have procedures that enable operators to detect a change in the process inputs rapidly.
Q31	We have procedures to distinguish between common and assignable causes of variation in process quality.
Q32	We have made our processes insensitive to disturbances from outside (e.g. material or environmental influences).
Q32	We have standard procedures to eliminate root causes of quality variation.
R111	We use devices such as Andon boards or radio communications to signal the occurrence of disruptions.
R112	We can always determine which upstream machine is responsible for a defect.
R113	Breakdowns in equipment are easy to diagnose.
R113	We have standard procedures for determining the root cause of disruptions.

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R121	We have standard communication paths to contact support staff.
R122	Our communication devices allow rapid correspondence (e.g. walkie talkies, andon boards).
R123	We have information devices (e.g. a display at the machine panel), which show the cause of a disruption.
R123	We document disruptions and create a knowledge base to understand recurring problems.
R13	To keep production moving, we usually solve problems only temporarily. Reoccurrence of the disruption is likely, since the root cause is not eliminated.
R13	We follow standard procedures for resolving problems.
R13	We have frequent group sessions where we discuss problems and develop solutions to prevent reoccurrence.
P11	Our operators have access to all information regarding their tasks.
P11	We often have production disruptions due to missing information.
P11	Operators have easy access to process information.
P11	The operator always understand what to produce, when to produce, and how to produce.
P121	Maintenance: our own employees maintain our equipment.
P121	Repair: equipment is usually repaired by outside contractors or the equipment vendor.
P121	The ability to easily service equipment determines requirements for its design (e.g. accessibility, controllability, ability to monitor the process, exchangeability of components).
P121	We are able to perform standard service checks without interrupting production (e.g. from the back of a machine).
P122	We emphasize proper maintenance as a strategy for achieving schedule compliance.
P122	We are usually behind production schedule and have no time for preventive maintenance. Repair is our maintenance.
P122	Our equipment and tools are in a high state of readiness at all times.
P122	We dedicate a portion of every day solely to preventive maintenance and follow the preventive maintenance schedule.
P131	We time each operating step in detail and include the information in the work instructions.
P132	Our operators are at their work station, when they are supposed to be there.
P132	Unplanned absenteeism often affects our ability to produce to schedule.
P133	We have standard procedures in place for mutual relief.
P133	Operator allowances (e.g. for personal hygiene) usually lead to production disruptions.

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P141	We have standard levels of inventory between sub-systems for each part.
P141	Operations are frequently starved due to unavailability of incoming parts.
P141	There is unpredictable fluctuation in our inventory levels.
P142	Our part suppliers deliver on a just-in-time basis.
P142	The frequency of material delivery is based on consumption as opposed to preset delivery times.
P142	Part deliveries are independent of downstream consumption.
T1	We usually transport small parts in large containers or large bins.
T1	We are transporting standard quantities between operations - i.e. each trip transports the same number or parts).
T221	When automatic cycles time are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two machines performing the same operation).
T221	We design our manufacturing processes so that the cycle time closely matches the takt time.
T221	We usually try to minimize the number of machines by decreasing the cycle time per machine regardless of takt time.
T223	The team leader or line supervisor is capable of creating a leveled schedule.
T23	We use a Heijunka box or some other means to communicate the pace of customer demand into the value stream.
T3	We usually meet the production schedule every day.
T3	We frequently produce more (or less) than scheduled.
T3	We frequently produce more (or less) of a particular part type per day than the downstream customer consumes per day.
T31	Most operations are centrally scheduled.
T31	We schedule only one operation in the value stream. Upstream operations are scheduled based on the consumption of the scheduled operation.
T31	Our operators have easy access to the production schedule.
T31	We use a pull system for production control.
T32	We are working aggressively to reduce setup times.
T32	We have low setup times for equipment in the evaluated value stream.
D11	Machines are designed to eliminate the need for operators to watch the machine cycle.
D11	Eliminating non-value added time spent at each station is a priority of station design.
D12	We rotate operators to other jobs within their subsystem.
D12	We have a formal suggestion program for all employees.
D12	Plant employees are rewarded for learning new skills.
D21	We design equipment to minimize walking of the operator.
D22	We have defined locations for all tools.
D22	Tools to perform a task are frequently missing.
D22	We enforce keeping work stations in clean and orderly condition.
D23	We use time studies to update standard work sheets.
D23	Ergonomic interfaces among worker, machine, and fixture are an important consideration during initial layout design.

Table 6-22: Group D questions (dependent on choice of value stream)

FR-DP	Question
Q121	We have standard training procedures for each operation.
Q122	Variation in quality is reduced either by adjusting the work method or through operator training.
Q122	Operators are involved in creating the work methods.
Q123	We immediately detect defects and do not send them downstream.
Q13	We encourage our operators to improve work methods.
R111	Variation in work completion time is easily identified.
R111	Machine downtimes are immediately noticed (e.g. through information technology or process design)
R111	Operators can easily see whether they are ahead or behind schedule.
R112	Machine downtimes can be unnoticed by downstream processes because processes are separated from each other either physically or through large buffers.
R112	Process lay out allows immediate detection of disruptions (e.g. downstream operations are quickly starved).
R113	Our system exposes disruptions and makes them easy to recognize (e.g. accumulating material shows that a production unit is falling behind).
R122	Disruptions are quickly conveyed (e.g. by starting an alarm, information technology).
R13	Operators on the shop floor have the authority to take necessary steps for resolving disruptions.
P131	Variation in work completion time is being solved either by adjusting the work method or through operator training.
P131	There is high variation of work completion time between cycles of the same operator.
P131	Work completion time of the same task often varies between operators.
P131	If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other).
P132	Operators can work ahead of schedule and take an unplanned break.
T1	The internal transfer batch size is usually larger than 2 hours of production material.
T21	We determine takt time at an early stage of a manufacturing system design project.
T21	We have clear customer - supplier relations throughout the value stream and production pace is based on takt time.
T222	We design each operator's work loop to run as close to takt time as possible.
T222	When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two operators performing the same operation in parallel)
T223	If a manufacturing unit produces several parts and the parts have different cycle times, we stagger the parts to produce on average to takt time.
T223	Our run sizes depend on consumption rate not only on the optimal run lot size per machine.

continued from previous page

T23	We are well balanced across the process flow.
T32	We tend to have large run sizes in our master schedule.
T32	We have converted most of the setup time to external time while the machine is running.
T4	We have laid out the shop floor so that our machines and processes are in close proximity to each other.
T4	The shop floor layout has functional departments.
T51	Delivery of material does not interrupt production.
T51	Material handling and transportation equipment does not limit the pace of the production.
T51	Operators have to leave their work station to pick up new material.
T51	Operators frequently perform activities, which disrupt the standardized work.
T51	Picking up outgoing material interrupts production (e.g. due to the need for fork lifts to move large bins).
T52	Operators work loops are laid out so that one operator does not interfere with another.
T52	The coordination and separation of production work patterns is considered during the design phase - it does not just evolve during operation.
T53	The coordination and separation of support work patterns is considered during the design phase - it does not just evolve during operation.
T53	The process design ensures that support resources do not interfere with each other.
D11	Operators usually wait at a machine until the machine cycle is finished.
D12	The operators are capable of performing more than one task.
D21	We usually arrange equipment first and then consider the work loop of the operator.
D21	Most of our operators are bound to one station and do not have to walk at all.
D21	When the shop floor layout is designed, equipment and material are placed so as to minimize walking distances.
D23	We continuously improve workplace ergonomics by rearranging equipment, tools, material presentation etc.
D3	It is often the case that within a team of operators some are idle for part of the cycle, while others are busy for the entire cycle.
D3	We often design work loops for one operator independent from work loops of other operators on the same team.
D3	Balancing work loops of operators is an important system design objective.

6.4.3.3 Aspects Independent of the Line Configuration

The following paragraphs analyze the two lines with respect to questions of group I. The distribution of the answers in shown in Figure 6-35. Both lines achieve mostly medium to good scores with line C performing better than P. The two value streams have the same score for 69 of the 85 questions in group I. Value stream C reached a higher score in 11 questions, while value stream P had a better score in 5 questions as shown in the lower half of Figure 6-35. The similarity in the answers indicates that neither system does satisfy some basic system design issues very well. The next paragraphs analyze the two lines with respect to the questions of group I. The sequence of discussion follows the MSDD from left to right and refers to FR-DP pairs in brackets.

Distribution of answers for group I questions

	very poor	poor	medium	good	very good	N/A
Assembly line C	0	7	33	28	5	12
Assembly line P	0	10	36	22	5	12

Number of questions in which a line performed better than the other			
	by 1 point	by 2 points	by 3 points
Assembly line C better than P	8	3	0
Assembly line P better than C	5	0	0

FIGURE 6-35: ANWERS TO GROUP I QUESTIONS

Defects are mainly due to defective incoming material and operator mistakes. Defects due to equipment are rare as the assembly is manual (FR-DP Q11). It is not clear, how much operator involvement is desired in either value stream, i.e. how much operators participate in designing work sequences, laying out the system, and improving the system. Industrial engineers design the work sequences supported by computer tools. From discussions and the answers in the questionnaire, assembly operator involvement is higher in value stream C, but was generally fairly low (FR-DP Q122, FR-DP R13).

Stable operator output (FR-DP P13) is not well achieved in either system mainly due to variation in work completion time (FR-DP P131). The information system in both lines is good and supports the manufacturing system well (FR-DP P11). Information is available through the intranet at critical points in the system. The travel sheet ensures that the configuration of the unit was known across the value stream.

Main part of the equipment is the material handling system (FR-DP P141). Downtime in value stream C is in the order of 10% mainly due to the material handling system. Maintenance is mainly done in response to repair requests. Both value streams have a pool of maintenance workers who respond to requests from supervisors. Preventive maintenance is not scheduled (FR-DP P122).

Material availability and deliveries are reliable and tightly integrated with order releases (FR-DP P14). Material is sent from warehouses to the lines. Value stream C has defined levels of material in front of the kitting line (FR-DP P141), while this is not the case in value stream P. Value stream C has to keep a large number of parts available at any given time to accommodate high product variety without material changeover in the kitting line. Value stream P runs one product family at a time and has to replace any remaining parts from the previous family with the parts for the next family. Inventory levels unpredictably fluctuate in both systems and operations are starved every now and then due to unavailability of incoming parts.

Delivery frequency of purchased parts depends on consumption (FR-DP P142). Whenever material is consumed, it is scanned and reduced from material available at the lines. Additional deliveries are released based on consumption and upcoming jobs. However, in spite of the sophisticated information system, it is necessary to count parts on the shop floor occasionally to account for double consumption of parts, defective parts, and wrongly picked parts.

Lot delay (FR-DP T1) is insignificant as parts moved one by one through the system. Both systems are centrally scheduled. Orders are released to the point in the value stream, where the travel sheet is printed (FR-DP T3). There is no additional need for scheduling any other points in the value stream as the products simply flow through the value stream. The MSDD emphasizes the need to clearly communicate the schedule (FR-DP T31) which is achieved in both value streams as the travel sheet contains all important information for the unit to be built.

The coordination and separation of production and support activities (FR-DP T5) is well done in both systems. Gravity chutes present the material to the operators and are refilled from outside without interfering the operators. Value stream P experiences some interference, when operators have to leave their workstation to pick up new material which is stored within the work path of the operators. In addition, reentering of repaired products disrupts the regular work pattern of assembly operators in line P. The selective distribution system in value stream C occasionally causes congestions and starves the assembly cells.

Operator efficiency is not very good in either value stream (FR-DP D1 – D3) mainly due to waiting times at various stages. Both designs essentially eliminated walking by binding operators to one station (FR-DP D12). Ergonomic interfaces can be improved in both value streams (e.g., height adjustable tables in value stream C). Operators in kitting and boxing have to perform a wide variety of different jobs depending on the product configuration, i.e. picking more or less parts. The most frequently picked items are presented at the most convenient locations to facilitate short cycle times. As a result, picking less frequently used parts often leads to delays in releasing the pallet to the next workstation which subsequently causes idle times at downstream operators.

The assembly line in value stream P experiences similar problems and operators are frequently idle for part of the cycle. In addition, the first workstation of the assembly line had a cycle time of 35 seconds, while the cycle times gradually fall to 25 seconds at the last station. Work loop balancing in the assembly cells of value stream C is not applicable, since each operator assembles a complete unit independently of other workers.

Generally, both lines lack defining and enforcing standardized work which relates to numerous FR-DP pairs in the MSDD: quality and time related aspects (operators do not perform work according to work methods (FR-DP Q122, FR-DP P131, FR-DP D23), identifying and resolving problems (FR-DP R111, FR-DP R13), ways to capture knowledge and improve the system (FR-DP Q32)). Defined work sequences do not contain time information. No man-machine charts exist for any operation. In addition, standards are often defined but not enforced or followed.

6.4.3.4 Aspects Dependent of the Line Configuration

The evaluation of the two value streams is less uniform for group D questions. Only 24 of 47 questions show the same score. Value stream P has a better score in 11 questions and value stream C in 12 questions. This indicates that each value stream has features which could help to achieve a good performance relative to the MSDD and a combination of the positive features could provide a basis for a third value stream design. The following paragraphs discuss the FR-DP pairs in the order they appear in the MSDD.

Distribution of answers for group D questions

	very poor	poor	medium	good	very good	N/A
Assembly line C	1	18	10	12	5	1
Assembly line P	1	17	14	10	4	1

Number of questions in which a line performed better than the other			
	by 1 point	by 2 points	by 3 points
Assembly line C better than P	9	2	1
Assembly line P better than C	9	2	0

FIGURE 6-36: ANWERS TO GROUP I QUESTIONS (CONCEPT IRRELEVANT)

Several features influence the <u>quality output from operators</u>. Operator involvement is lower in value stream P (FR-DP Q12). Few operators know all processes. Improvement suggestions in value stream P are very rare according to discussions. Value stream C requires very skilled operators, since each operator assembles the complete unit. In addition, operators in the assembly cells rotate between assembly, software download and cleaning. Operators are therefore very knowledgeable about all processes and can provide good feedback for improvements. However, there is not formal capturing of improvement suggestions. The company discusses possible improvements for the assembly tasks based on the performance of individual assembly cells. The company measures the performance of each assembly cell in number of units produced per day. If a cell shows a good performance, the company may study how the operators assembly the product and alter the assembly sequence. However, the performance measure can be misleading, since the number of assembled units greatly depends on the product configuration. If a cell receives mostly products that have a low assembly content, the output of the cell is automatically higher than for cells that receive parts with high assembly content. Furthermore, the material handling system may starve a cell for several minutes idling the operators. Thus, high output rate is not necessarily due to efficient assembly of the operator and studying a cell with high output rate may not capture the best practices.

Both value streams send defects to downstream processes sporadically (FR-DP Q123), but for different reasons. In value stream C, it can happen that kitting sends wrong or defective parts to the assembly cells. The assembly operator cannot continue his job, until a new part is picked from the kitting area and brought to the assembly station. On the other hand, value stream C provides fast feedback within the assembly cell when a defect occurs (FR-DP R111), since one assembly cell performs all operations necessary to manufacture a complete unit including software download, functional test and cleaning. However, since recorded defects decrease the performance measure of each cell, there is a tendency to fix defects without recording them. This behavior is counterproductive for a structured system improvement process (FR-DP R13).

In value stream P, operators do not receive immediate feedback when they cause a defect (FR-DP Q123, R111). The repair workstation at the end of the line fixes defects and releases the product to the software download area. While all defects are recorded, the company does not use the data for improvement activities (FR-DP R13).

Exposing disruptions can be enhanced in either system for example by using Andon lights or starting alarm (FR-DP R111, FR-DP R122). It is said that line stoppages at value stream P are encouraged. However, stoppages also penalize the performance of the line. Therefore, operators have an incentive to keep the line moving in spite of problems. Products are sent to the repair station to fix problems off-line. In value stream C, disruptions can be hidden. Assembly cells can be starved or be down without being noticed by upstream or downstream processes.

Repeatable task completion time is not well achieved in either value stream (FR-DP P131). In value stream C, operators in the assembly cells tend to create their own assembly sequence. Consequently, it is virtually impossible to improve existing assembly sequences, as the sequence is normally not followed, abnormalities are not visible and improvements are more difficult to define. Assembly tasks in value stream P are simpler and the assembly sequence is more closely defined. Deviations are easier to recognize as operators see if an adjacent operator has problems with the assembly. In addition, inspectors regularly control if operators follow the work instructions.

Absenteeism affects both systems (FR-DP P132). In most cases, operators are at their workstations, when the work starts after breaks. Value stream P exposes, when operators at the assembly line are missing, while it might be unnoticed for several minutes if an assembly cell in value stream C is unmanned. Operators in value stream C are able to work ahead and take unplanned breaks.

Both value streams divide the total system into departments: value stream C has kitting, assembly, and boxing; value stream P has assembly, software download, cleaning, and boxing. The departments are not designed to operate at the same cycle time throughout the value stream leading to an unbalanced system (FR-DP T21). There is no clear customer-supplier relationship in either value stream. Takt time or customer demand rate is not communicated within the system. The goal is merely to produce a given number of parts per day, but this number is not translated into a pace of production (e.g., one unit every 10 minutes in each assembly cell) to enable fast feedback.

A good example for the unbalanced operation of value stream C is the fact that administrative staff works at the boxing line during lunch breaks, while all assembly cells are shut down. Thus, assembly works faster than boxing during regular operating hours. The overall throughput time in value stream C is 5 to 8 hours. However, the overall processing time is between 2 and 3.5 hours with software download being the main contributor with 1.5 to 3 hours. Therefore, the system has as much as 6 hours work in process between operations. Throughput time in value stream P is in the order of 4 hours. Considering that the processing time is the same as in value stream C, the system holds only 0.5 to 2 hours work in process between operations.

The physical separation of the departments in both value streams increases transportation requirements (FR-DP T4). The conveyor system in value stream C connects all departments. Value stream P uses manual transportation between the assembly lines, the software download stations, and the cleaning stations. A conveyor system similar to the one in value stream C transports the parts to the boxing area.

Value stream P needs material changeover between two production families. Changeover times are very unpredictable and take between 15 and 60 minutes (FR-DP T32). Operators are idle during the changeover time. As a result, the line produces in batches (FR-DP T3). Value stream C holds all parts for all part families in the kitting area and is therefore capable of producing a greater variety without changing over.

In both value streams, operators are able to perform more than one task (FR-DP D12). All operators in kitting and boxing are able to perform different jobs within their sub-system and rotate positions frequently. In value stream C, all operators within the cell rotate their positions. Operators in value stream P only rotate within their job category. Operators re mostly bound to one station and do not have to move at all (FR-DP D21). Improvements in work ergonomics are not common in either value stream (FR-DP D23). All operators are standing. However, height adjustable tables in the assembly cells would require major adjustments with the conveyor system. As described earlier, the layout of both systems seem to be equipment dominated.

Observations Beyond the Questionnaire

The following paragraphs discuss aspects that are not well covered by the MSDD, but are important for the company. The first aspect relates to the assembly cycle time and the second aspect relates to volume flexibility.

Assembly times in value stream P are between 25 and 35 seconds. The tasks are highly divided and often boring. Operators lose ownership of the product. In contrast, assembly operators in value stream C are sometimes overloaded with the tasks to assemble one unit. The assembly of one unit takes on average 10 minutes and can be as high as 30 minutes for special configurations. Manufacturing engineers of the company said that neither cycle time is well suited to achieve stable operator output. As a result, it would be desirable to design assembly stations with a cycle time somewhere between 35 seconds and 10 minutes. Further studies are necessary to determine an "ideal" range of cycle time.

The ability to accommodate demand surges at the end of fiscal cycles it very important for the company. The complete system of value stream P is shown in Figure 6-33. It consists of 7 assembly lines, seven software download areas, two clean and wrap areas, and two boxing lines. Each assembly line produces currently around 550 units per eight hour shift. Therefore, it is possible to add or remove capacity in increments of 550 units per shift by operating or not operating an assembly line. Every assembly line has dedicated staff for software download and cleaning so that those units would also be operated or not. Adding or removing an assembly line is likely to lead to unbalanced work loops at the shared resource boxing, though.

The ability to vary the output rate within one assembly line is limited. The line has a maximum speed when one operator is at each station, which is the regular operating mode described earlier. The line also seems to have a minimum speed as the number of defects increases when fewer than 19 operators are on the line (as opposed to 25 during regular operation). It is not clear what the exact reasons are for the quality loss: it could be that low-skilled operators have to perform tasks they are not trained for, or that work loops become unbalanced leading to long idle times and a loss of concentration.

Value stream C consists of one kitting line, one assembly area with 64 assembly cells, and one boxing line. The total capacity is approximately 1,850 units per shift. Thus, adding or removing a complete line affects more than three times as much volume than adding or removing an assembly line in value stream P. However, value stream C can increase or decrease production volume in smaller increments by activating or deactivating single assembly cells. For the full benefit, it should be possible to add or remove operators in kitting and boxing as well.

The ability to accommodate demand surges during end of fiscal cycles is similar in both systems. The company runs all systems at full capacity and adds overtime during the week and on weekends. The company also enlists the help of volunteers from engineering and other company areas to work remedial tasks. During the plant visit for this research of value stream C, for example, administrative staff operated the boxing line, while kitting and assembly was on break. The boxing line was working off WIP between assembly and boxing.

The company depends on high-skilled operators in both value streams to perform critical assembly tasks. It is therefore necessary to have a pool of high-skilled people in either case. Manufacturing engineers of value stream P did not confirm that the simpler assembly tasks increased flexibility in terms of adding or removing operators.

6.4.4 Numerical Comparison

The following paragraphs provides a quantitative comparison of the two value streams. Table 6-23 underlines that each value stream has some areas in which it performs better than the other value stream. Defect rate and throughput time show the largest differences. The defect rate is significantly higher for value stream P both for inline repair and for defective parts shipped to the customer. Throughput time in contrast is higher in value stream C.

TABLE 6-23: NUMERICAL COMPARISON OF VALUE STREAM C AND P.

	Normalized	
	Value Stream C	Value Stream P
# product families	1**	1.00
Floor Area	1*	1.26
Throughput time until end of boxing [hours]	1**	0.62
Direct workers	1*	1.13
Indirect workers	1*	0.95
Parts/labor-hour	1**	0.92
In line repair	1**	2.13
Shipped defects (appr.)	1**	9.00
Number of built parts per day	3,758	7,800

* (Value of Value Stream P / Value Stream C) /
(volume per day of Value Stream P / volume per day of Value Stream C)
** (Value of Value Stream P / value of Value Stream C)

The following paragraphs examine if the analysis with the MSDD supports the understanding of the differences in defect rate and throughput time. The purpose of the discussion is to provide a starting point how quantitative performance measures can be linked to the evaluation with the MSDD.

Defects in both value streams are mainly caused by operators or defective material. Since both systems receive material from the same suppliers, the following discussion concentrates on operator related defects, which is considered in FR-DP Q12 "Eliminate operator assignable causes" – "Stable output from operators." Table 6-24 contains distribution of answers to questions related to FR-DP Q12 separated by group I and D. Value stream C has a higher evaluation in four out of twelve questions most importantly related to operator training and the ability to detect defects before sending them to downstream operations. However, considering that 8 out of 12 questions belong to group I, both concepts should be able to reduce operator related defects without changing the physical layout.

The analysis with the MSDD supports the fact that value stream C has a lower defect rate and points out starting points for further analysis to reduce defects in both systems.

TABLE 6-24: ANSWERS TO Q12 "ELMINATION OF OPERATOR ASSIGNABLE CAUSES" FOR VALUE STREAM C AND P.

			Very Poor	Poor	Medium	Good	Very Good	Null
Q12	Value Stream C	Group D	0	2	0	2	0	0
Elimination of operator assgn. causes		Group I	0	2	2	4	0	0
	Value Stream P	Group D	0	2	2	0	0	0
		Group I	0	3	3	2	0	0

The analysis of throughput time with the help of the MSDD is challenging. There it not one single area in the MSDD that deals with throughput time. Production disruptions contribute to throughput time and are covered by the quality, identifying and resolving problems, and predictable output branch. In addition, the delay reduction branch considers sources of delays that are predictable consequences of the design and operation of the system. It is therefore necessary to consider a wide range of FR-DP pairs to understand causes for long throughput times.

The following paragraphs first discuss aspects related to production variation followed by an analysis of the delay branch. The focus of the production variation is again on operator related issues since the equipment consists mainly of conveyors in both systems. Three areas in the MSDD consider variation in operator output: FR-DP Q12, which was discussed above, FR-DP R11 "Rapidly recognize production disruptions" – "Subsystem configuration to enable operator's detection of disruptions" and FR-DP P13 "Ensure predictable worker output" – "Motivated work-force performing standard work." Table 6-25 shows the distribution of answers for questions related to FR-DP R11 and FR-DP P13 and also distinguishes between group I and group D questions. Value stream C has a lower evaluation particularly for group D questions indicating that some of the problems with respect to FR-DP R11 and P13 are due to the value stream design (see also discussion in 6.4.3.4).

TABLE 6-25: ANSWERS TO R11 AND P11 BRANCHES FOR VALUE STREAM C AND P.

			Very Poor	Poor	Medium	Good	Very Good	Null
R11 Recognize problems	Value Stream C	Group D	1	3	2	0	0	0
		Group I	0	0	1	3	0	0
	Value Stream P	Group D	0	1	4	1	0	0
		Group I	0	1	1	2	0	0
P13 Predictable operator output	Value Stream C	Group D	0	4	1	0	0	0
		Group I	0	1	3	0	1	0
	Value Stream P	Group D	0	3	1	1	0	0
		Group I	0	0	4	0	1	0

The analysis of the delay reduction branch does not reveal differences between value stream C and P. Both systems perform equally poor. The MSDD deals with the aspect of continuous flow under the delay reduction branch and more specifically under the decomposition of FR-DP T2 "Reduce process delay" – "Production balanced according to takt time." The evaluation of FR-DP T2x points out that neither value stream achieves a balanced production as shown in Table 6-26. (Value stream P has one very good rating for "When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation," since it is necessary to avoid parallel operations for the design of the progressive assembly lines. Value stream C has a rating of medium at this question).

The distribution for the complete delay reduction branch is given in the lower part of Table 6-26 and shows a higher evaluation for value stream C. The main reason is the ability of value stream C to produce in smaller run sizes by avoiding changeover times between families. However, the effect of smaller run sizes does not affect the throughput time between kitting and boxing and is therefore not reflected in the throughput time of Table 6-23.

TABLE 6-26: DISTRIBUTION OF ANSWERS TO THE T-BRANCH FOR VALUE STREAM C AND P.

			Very Poor	Poor	Medium	Good	Very Good	Null
T2 Balanced production to takt time	Value Stream C	Group D	0	3	3	0	0	0
		Group I	0	1	0	0	0	4
	Value Stream P	Group D	0	3	2	0	1	0
		Group I	0	1	0	0	0	4
			Very Poor	Poor	Medium	Good	Very Good	Null
T-branch Delay reduction	Value Stream C	Group D	0	6	3	6	5	0
		Group I	0	1	4	3	3	6
	Value Stream P	Group D	0	7	6	3	4	0
		Group I	0	1	5	2	3	6

The differences in throughput time are not well explained by the MSDD. While operator related issues indicate a slightly better performance for value stream P, the questions for the delay reduction branch do not point out differences. Further applications are necessary to establish a better link between established performance measures and the analysis with the MSDD. The potential benefit would be that the MSDD can explain performance differences in more detail and can also be used to derive improvement suggestions as shown in the next section. It might also be possible, though, to define performance measure based on the evaluation of the MSDD.

In summary, the numerical comparison supports the analysis of the MSDD in that both value streams have advantages and disadvantages. The clear relation from quantitative numbers to the analysis of the MSDD is still difficult.

6.4.5 Development of a Third Value Stream Design

The analysis showed that both value streams have similar strengths and weaknesses with respect to the MSDD. Each value stream also has some unique advantages. A third value stream design can combine the advantages and eliminate common weaknesses.

The prior discussion distinguished between group I and group D questions. Group D questions deal with aspects in which the value stream affects how well an FR-DP can be satisfied, while group I deals with aspects in which the line concept is irrelevant for satisfying an FR-DP. Resolving problems with respect to group I issues is not a matter of the value stream design but can be achieved in any value stream. The following discussion focuses on group D aspects to develop a third value stream design that improves MSDD performance.

Table 6-27 describes the specific ways in which a third value stream design can improve the performance for each of the questions of group D. It is tried to find a solution, which could improve the evaluation of a question by reflecting on the existing line designs and drawing from other manufacturing system design experiences. The following paragraphs describe how the various solutions to each of the questions can be implemented in one physical configuration.

TABLE 6-27: GROUP D QUESTIONS FOR THIRD VALUE STREAM DESIGN.

FR-DP	Question	Third value stream design
Q121	We have standard training procedures for each operation.	Core team of high-skilled people, which can perform every task - from kitting to boxing.Low-skill jobs with easy job-training for temporary workers at end-of-quarter.
Q122	Variation in quality is reduced either by adjusting the work method or through operator training.	Variation in quality is exposed in the new system as all operators work in one cell and can see the upstream operator who caused a quality variation. The cell is better able to self-regulate and control itself.
Q122	Operators are involved in creating the work methods.	Capturing of operator input for continuous improvement. This should also happen across cells.
Q123	We immediately detect defects and do not send them downstream.	Extensive use of pick-to-light (PTL) to avoid picking wrong parts. In addition, third way has all processes adjacent to each other, which provides fast feedback similar to cellular approach, where defects are detected within one work group.
Q13	We encourage our operators to improve work methods.	Standard improvement procedure to capture operator knowledge and suggestions.
R111	Variation in work completion time is easily identified.	Detailed work instructions for every operation, for every combination of work loops.Thorough training and enforcing standards. One may work with a time clock counting down times. It may also be necessary to create a leveled schedule to ensure that on average takt time is achieved.
R111	Operators can easily see whether they are ahead or behind schedule.	Production counter at both ends of the cell show actual production and scheduled production. All operators can see if the cell is ahead or behind schedule at any given time.
R111	Machine downtimes are immediately noticed (e.g. through information technology or process design)	The idea here it to have an integrated manufacturing environment, in which all processes are tightly connected. Downtimes are quickly recognized and conveyed.
R112	Process lay out allows immediate detection of disruptions (e.g. downstream operations are quickly starved).	All operations integrated in one cell. Disruptions can easily communicated from last to first operation and vice versa. Counter at beginning and end of cell.
R112	Machine downtimes can be unnoticed by downstream processes because processes are separated from each other either physically or through large buffers.	Since all operations are tightly integrated in one manufacturing cell, disruptions at any points are more visible and quickly noticed.
R113	Our system exposes disruptions and makes them easy to recognize (e.g. accumulating material shows that a production unit is falling behind).	This is layout in the small scale: defined buffers between sub-systems (e.g. decouplers between operator work loops). Accumulating material is visible and triggers an alert.
R122	Disruptions are quickly conveyed (e.g. by starting an alarm, information technology).	Andon lights throughout the cell, quick recognition of deviations from standards; balanced work loops between operators allow for quick detection, if an operator falls behind.
R13	Operators on the shop floor have the authority to take necessary steps for resolving disruptions.	General consideration. Operators should be seen as core element of the manufacturing system.
P131	If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other).	Operators from different work loops can support each other.
P131	Variation in work completion time is being solved either by adjusting the work method or through operator training.	Enforcement of standards. Update of standards and training.
P131	Work completion time of the same task often varies between operators.	The new system exposes variation in work completetion time that can subsequently be eliminated.
P131	There is high variation of work completion time between cycles of the same operator.	(see above)
P132	Operators can work ahead of schedule and take an unplanned break.	Counter at each end of cell. No sub-subsystem is able to work ahead or take unplanned break - only complete cell.

FR-DP	Question	Third value stream design
T1	The internal transfer batch size is usually larger than 2 hours of production material.	The new value stream design is still a flow through system with no transportation batching.
T21	We determine takt time at an early stage of a manufacturing system design project.	Determine production pace to meet customer demand. What is the range of output you want to achieve between lowest volume at beginning of quarter to highest volume end of quarter? Then also consider "ideal range" of assembly cycle time - not too boring, not too complex.
T21	We have clear customer - supplier relations throughout the value stream and production pace is based on takt time.	One cell including all operations. No physical separation of kitting, assembly, boxing. Everything close together to enable fast feedback.
T222	When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two operators performing the same operation in parallel)	Must consider the range of possible operating points of the cell. For example, during low demand periods, an assembly operator may work on 5 work stations with a work loop of 5 minutes. During high demand periods the operator works on 2 stations with a work loop of 2 minutes. For each desired output rate of the cell, it is necessary to define work loops for all operators and balance the work loops.
T222	We design each operator's work loop to run as close to takt time as possible.	see above
T223	If a manufacturing unit produces several parts and the parts have different cycle times, we stagger the parts to produce on average to takt time.	Create a level schedule, which produces on average according to takt time. This requires to know all assembly times for each unit upfront. It may be sufficient to distinguish between short, medium, and long cycle time units and level those out to reach on average medium cycle time units. That is, avoid releasing 20 long cycle time unites in a row.
T223	Our run sizes depend on consumption rate not only on the optimal run lot size per machine.	Combine kitting with having all parts at the assembly station. The goal is to produce a wide variety of products without the need to change over, I.e. deflashing the incoming parts. It may be required to have several stations within the cell dedicated to particular families. The stations hold some key parts of the family.
T23	We are well balanced across the process flow.	All process cycle times interact in one cell. Balanced work loops from kitting to boxing to accommodate desired output rate of the cell.
T32	We tend to have large run sizes in our master schedule.	Goal is to produce in single-unit increments with not changeover (material or otherwise) between any family the cell is capable to produce. This requires material management and equipment management to accommodate different product sizes and weights.
T32	We have converted most of the setup time to external time while the machine is running.	see above
T4	We have laid out the shop floor so that our machines and processes are in close proximity to each other.	One large cell has all processes integrated eliminating the need for conveyors.
T4	The shop floor layout has functional departments.	All processes are integrated in one manufacturing processes.
T51	Material handling and transportation equipment does not limit the pace of the production.	No complex and long conveyors, which can cause congestion. Sliding tables can make it easy to move products between assembly stations. The transportation of units to the software download racks can be done similar to concept P or with the help of racks as they are used in concept C.
T51	Operators frequently perform activities, which disrupt the standardized work.	Detailed design of material presentation, re-entry points of repaired products or re-routed products (if that happens at all).
T51	Operators have to leave their work station to pick up new material.	Feed material from back to the assembly station.
T51	Delivery of material does not interrupt production.	Feed material from back to the assembly station.
T52	Operators work loops are laid out so that one operator does not interfere with another.	Detailed work loop design for various staffing modes of the cell.
T52	The coordination and separation of production work patterns is considered during the design phase - it does not just evolve during operation.	(see above)
T53	The coordination and separation of support work patterns is considered during the design phase - it does not just evolve during operation.	Defined work loops for delivering material to the cell.
T53	The process design ensures that support resources do not interfere with each other.	Defined material supply routes and times.

FR-DP	Question	Third value stream design
D11	Operators usually wait at a machine until the machine cycle is finished.	
D12	The operators are capable of performing more than one task.	Core team of high-skilled people, which can perform every task - from kitting to boxing. Frequent rotation during low-demand periods to avoid that work gets boring. Temporary workers should also be rotated to gradually improve their capabilities.
D21	Most of our operators are bound to one station and do not have to walk at all.	Operators should move between stations. Even the assembly operators should move from one station to another to perform specific assembly steps. The assembly task is divided into several stations and several operators assembly the complete unit. As volume goes down, fewer operators work on more station, but do not perform more tasks at one station. As volume goes up, more operators work on fewer stations. But the work content per work station should keep constant as the stations is designed to accommodate particular tasks including the necessary raw material.
D21	When the shop floor layout is designed, equipment and material are placed so as to minimize walking distances.	Operators walk between assembly stations. Stations should be in close proximity.
D21	We usually arrange equipment first and then consider the work loop of the operator.	Integrated cell applies concurrent engineering for the human-machine interface.
D23	We continuously improve workplace ergonomics by rearranging equipment, tools, material presentation etc.	The physical structure of the cell should be flexible enough to realize improvement suggestions.
D3	Balancing work loops of operators is an important system design objective.	Must consider the range of possible operating points of the cell. For example, during low demand periods, an assembly operator may work on 5 work stations with a work loop of 5 minutes. During high demand periods the operator works on 2 stations with a work loop of 2 minutes. For each desired output rate of the cell, it is necessary to define work loops for all operators and balance the work loops.
D3	We often design work loops for one operator independent from work loops of other operators on the same team.	Balancing work loops requires concurrent design of all work loops in the cell. It may be necessary to reallocate tasks to different work stations to achieve a balanced system.
D3	It is often the case that within a team of operators some are idle for part of the cycle, while others are busy for the entire cycle.	see T222

Figure 6-37 illustrates schematically the basic ideas of a third value stream design. All operations necessary to build a unit are integrated to one large manufacturing cell covering all operations of the value stream. There is no physical separation of kitting, assembly, and boxing. The assembly of the unit is divided into several stations to achieve an assembly time in the range of 2-5 minutes depending on the outcome of the studies about the "ideal" cycle time. The discussion of the third value stream follows the sequence of the questions in Table 6-27.

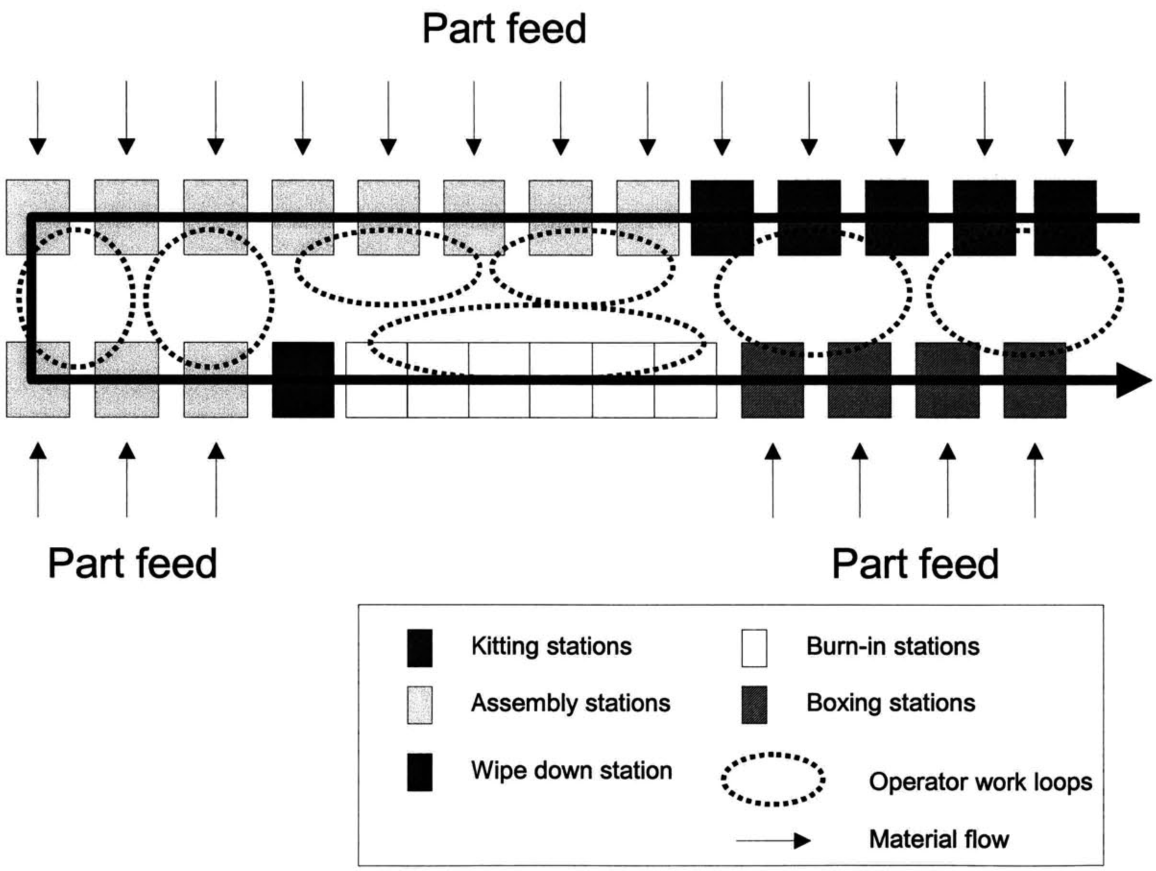


FIGURE 6-37: THIRD WAY – CONCEPTUAL STRUCTURE.

A core team of highly skilled operators can perform all tasks within the cell – from kitting to boxing (FR-DP Q12). Those operators run the whole cell during low-volume periods. The cell has some tasks which require high skilled operators such as technicians, and other simple tasks such as kitting, boxing, and possibly some assembly tasks. During high demand periods, it is possible to quickly train temporary workers for simple tasks, while the core team performs all demanding operations.

Operator training (FR-DP Q121) is very important in the system, particularly for the core team. Detailed work instructions for every operation and for every combination of work loops define standards that every operator must be able to meet (FR-DP T222, FR-DP D3).

Designing and adhering to standardized work methods to perform tasks is critical element for the new design (see discussion under 6.4.3.3). Line supervisors are responsible that standards are followed, training is provided, and work standards are updated. Operators should not develop their own assembly sequence. Operator involvement is important in designing and updating standards (FR-DP Q13). It should also include feedback to product design procedures.

The cell configuration supports identifying and resolving problems in various ways. Disruptions are quickly recognized as all processes are tightly linked with each other (FR-DP R11x). If defects are sent to a downstream process, immediate feedback is possible between all operations. A counter at the end of the cell displays if the cell is ahead or behind schedule and all operators in the cell can see the counter.

Variation in work completion time is recognized quickly as defined buffers between workstations (or work loops) provide a visual display if an adjacent operation cannot follow the production pace (FR-DP P131). Let us assume there is a buffer of three parts between assembly operators A and B. If B does not keep up with the production pace, material fills up the buffer and production must stop which immediately indicates an abnormality.

The manufacturing cell includes all operations of the value stream. The operating cycle time is designed to accommodate an "ideal" range (FR-DP T21). All operations produce essentially at the same pace achieving a balanced production across the value stream (FR-DP T23). A leveled schedule produces on average according to takt time (FR-DP T223). Production control must know the assembly times for all units. It may be sufficient to distinguish between short, medium, and long cycle time units and level those out (see 6.5) to ensure that for example 20 long cycle time units are not released in sequence.

Small buffers between operations accommodate for variations in the required assembly time for the different product configurations (see above). The design of the manual work content (FR-DP T222) considers the possible range in which the cell can operate during high and low demand phases.

It is desirable to avoid any changeover between product families (FR-DP T32). This could be done either by having a kitting area which holds all required parts, or by holding commonly used parts at the assembly stations and all other parts in the kitting area.

The suggested layout of the concept reduces distances between operations and eliminates the need for conveyors to transport parts (FR-DP T4). Sliding tables can be used to carry parts between assembly stations. The transportation of units to the software download racks can be done similar as in value stream P or with the help of racks as they are used in value stream C.

The cell design accommodates various work loops to facilitate volume flexibility within one assembly cell. It is necessary to design work loops for each capacity scenario to achieve balanced production across the whole cell (FR-DP D3). Assembly operators should move from one station to another to perform specific assembly steps (FR-DP D11). The assembly task is divided into several stations and several operators assemble the complete unit. As volume goes down, fewer operators work on more stations, but do not perform more tasks at one station. As volume goes up, more operators work on fewer stations. But the work content per assembly station does not change as the stations are designed to accommodate particular tasks including feeding of raw material.

It is also possible to add complete cells more easily than in value stream C or P, since each cell performs all operations necessary to build and box a product and has no shared resources with other operations. Each cell has a maximum capacity of 20 units per hour or 145 units per shift considering a minimum cycle time of 3 minutes and an effective working time of 7.25 hours per shift. Thus, it is possible to add and reduce capacity in smaller increments than in value stream C and P.

The third value stream design is very rough and schematic. It is hoped that it provides a platform for discussions about future ways to manufacture at the company based on the knowledge derived from the MSDD questionnaire and analysis.

6.4.6 Summary

The case study examined two distinctive value streams for an electronic product. The analysis showed that both value streams have similar performances relative to the MSDD with slight advantages of value stream C. Neither value stream satisfied the requirements stated in the MSDD very well.

In order to better understand the differences of the two value streams, all questions of the questionnaire were categorized into two groups: group I represented aspects that either system could satisfy well (e.g., detailed time studies of assembly tasks). Group D dealt with aspects in which the value stream plays an important role in achieving a high performance.

Both value streams performed medium in the first group which indicates that both value streams could improve in some basic system design aspects. The performance in the second group was less uniform suggesting that each value stream had features that could help to achieve high performance relative to the MSDD and a combination of the positive features could provide a basis for a third value stream design.

A schematic third value stream design was proposed based on the findings of the analysis. The development of the concept was guided by the questions of the second group. The concept is very schematic, but includes aspects from rough physical layout (arranging processes – FR-DP T21) to detailed operational aspects (leveled order release FR-DP T223).

Findings relative to the MSDD

The study of the two assembly value streams provided several important insights for the usage of the MSDD:

(1) The evaluation relative to the MSDD did not clearly favor one of the two value streams. The company management itself was not sure which value stream design was favorable. The quantitative comparison of both systems confirmed that neither system had clear advantages. Thus, the analysis with the respect to the MSDD provided a fair evaluation of both systems, which was also confirmed by company employees.

(2) The detailed analysis of the questionnaire pointed out strengths and weaknesses of both value streams and guided the development of a third value stream design.

(3) It was often the case that both systems satisfied an FR-DP pair equally well, but for different reasons. This suggests that the FRs and DPs are not prescriptive in terms of how objectives can be satisfied. In fact, many aspects of the MSDD can be satisfied independent of the system configuration as suggested by the categorization of the questions.

(4) The questions of the questionnaire were categorized into two groups, which greatly facilitated the analysis and understanding of both systems. The grouping provided significant support in understanding and explaining the differences and similarities of both systems. The grouping was also the basis for the development of the third value stream. The third value stream design was developed in order to better satisfy the objectives and means stated in the MSDD. The design was guided by the questions of group D.

(5) The developed third value stream design was very schematic, but covered aspects from rough physical layout to operational settings. This suggests the MSDD implicitly contains a wide array of manufacturing system design aspects and principally covers all phases of the systems engineering process discussed in Chapter 2.

(6) It was tried to link the MSDD evaluation with performance measures for defect rate and throughput time. While the linkage for the defect rate was possible, it was more difficult to do for throughput time. Further applications are necessary to establish a better connection between established performance measures and the analysis with the MSDD.

(7) The MSDD does not support decisions with respect to volume flexibility, which is a very important system design criterion for the company. However, the degree of desired volume flexibility greatly depends on the company's business environment. Making specific recommendation with respect to volume flexibility would limit the portability of the MSDD to a wide range of manufacturing companies. The discussion of the third value stream design pointed out that volume flexibility is partially considered in the delay reduction branch.

6.5 Industrial Goods

6.5.1 Introduction

The following case study describes a manufacturing line at United Electric Controls (UE), a family owned company in the Boston metropolitan area. UE manufactures automatic process controllers for pressure and temperature. The company has a very efficient manufacturing system and has made tremendous improvements compared with 1987, when it started to implement Toyota Production System techniques. The company won the Shingo prize for manufacturing excellence in 1990 and cooperated with the Toyota Supplier Support Center for several years.

The purpose of the case study is to examine how well the MSDD reflects the efficiency of UE's manufacturing system. The case study intends to support logical replication, since the outset of the case study predicts a high performance relative to the MSDD. Furthermore, the case study verifies the applicability of the MSDD in a small manufacturing company with lower production volume than the previous companies. It also applies the MSDD in a third industry after automotive and electronic goods.

The PSD lab worked with the plant for several years and developed a deep understanding of the design and operation of its production system. The company used to be very open for outside companies and universities to visit the shop floor, but has recently cut back on those contacts. As a result, it was not possible to perform an MSDD evaluation of the most recent system and to discuss the evaluation with current employees of the company.

The analysis of the manufacturing system draws from experiences from extensive visits between 1997 and 1999. The visits included advising projects for MIT classes, detailed studies of the machining and assembly areas, and a study of the information system [Linck et al., 1998]. The evaluation was discussed in detail with a former vice-president of UE in April 2001. The former employee was a driving force behind the restructuring of the manufacturing system. She left the company in 1999, when the company had to downsize its operation due to a decreasing market for its products.

The section first provides background information about UE and describes the improvements UE achieved over the last years. The evaluation then focuses on one product line on which the company has concentrated its improvements. The product line is referred to as the "120 line." The production line is introduced before the evaluation is briefly discussed. A complete description of the 120 line can be found in Fox [1999].

6.5.2 Company Background

UE started to transform its manufacturing system in 1987. Three years later, the company has achieved major improvements [Chin, Rafuse, 1993]. From 1987 to 1990, it reduced quoted lead delivery time from 12-16 weeks to two weeks. On-time delivery improved from 60% to 90%. The company dramatically reduced floor space and merged two buildings into one. Inventory was reduced from $9.5 million to $5 million. An automatic storage and retrieval system was eliminated. Most WIP moves in small bins and fits on assembly table tops.

The company started with the assembly processes and worked its way upstream to the CNC area. All assembly operations were grouped into manufacturing cells. CNC became a focus for improvements only in the recent years.

In addition, the company emphasizes employee involvement. Every employee is involved in continuous improvement activities and shows pride in the achievements of the manufacturing system. Administrative departments such as customer service, production planning, and purchasing have been moved to the shop floor to reduce employee travel distances and to improve information flows.

6.5.3 The 120 Product Line

The following section describes the shop floor of UE and the manufacture of the 120 line products. The statements and discussions are based on plant visits between 1997 and 1999. The 120 line consists of pressure and temperature controls for potentially explosive or highly corrosive atmospheres. Customers can chose from a variety of options such as operating range, pipe fittings, size, etc. In 1999, the company produced more than 500 different products of the 120 series. The daily production volume was between 120 and 140 units. The company operates one shift per day.

The overall floor layout and the material flow for the 120 line is shown in Figure 6-38. All areas are connected by one material supply route. The manufacture of the 120 products involves CNC machining and assembly. One operator walks through the whole plant, collects empty kanban and bins, picks up new material, and supplies the material to the manufacturing areas. The operator repeats that loop every 45 minutes.

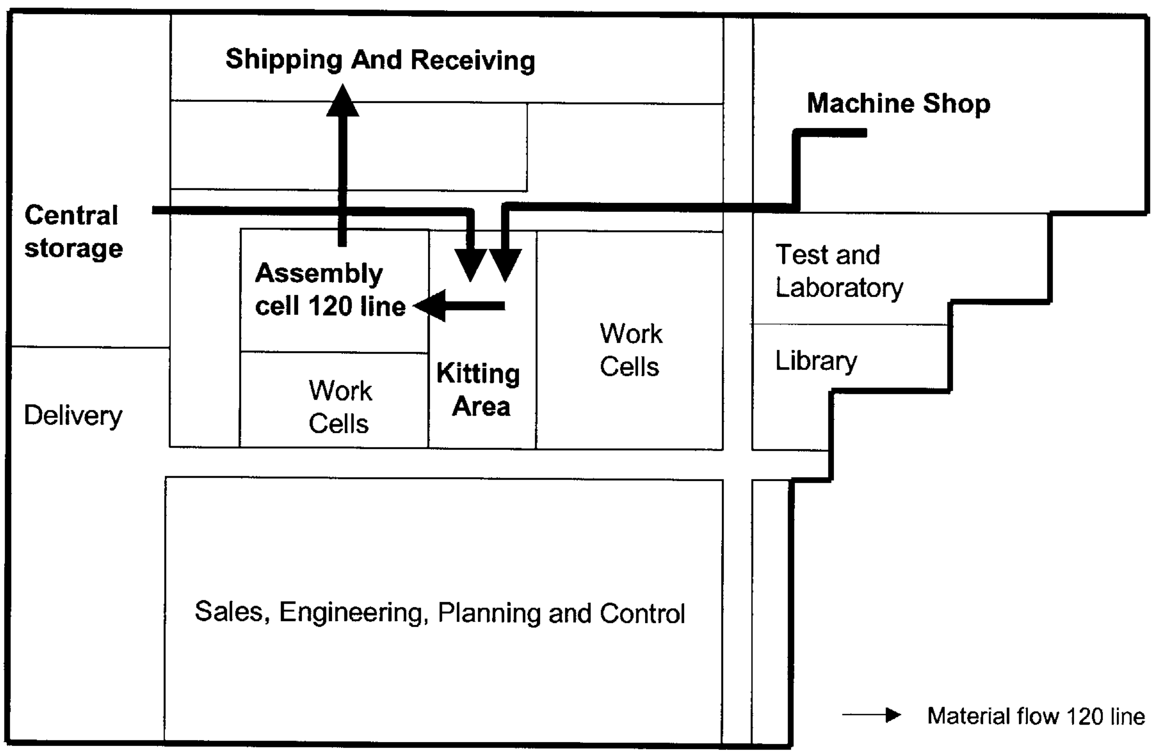


FIGURE 6-38: SHOP FLOOR LAYOUT OF UE WITH MATERIAL FLOW 120 LINE.

The information flow is shown in Figure 6-39. UE receives orders with a delivery lead-time from 3 days to more than 8 weeks. Suppliers deliver parts in various time intervals. Raw material for CNC is sometimes delivered in up to 6 month periods. Purchased parts such as housings are delivered daily.

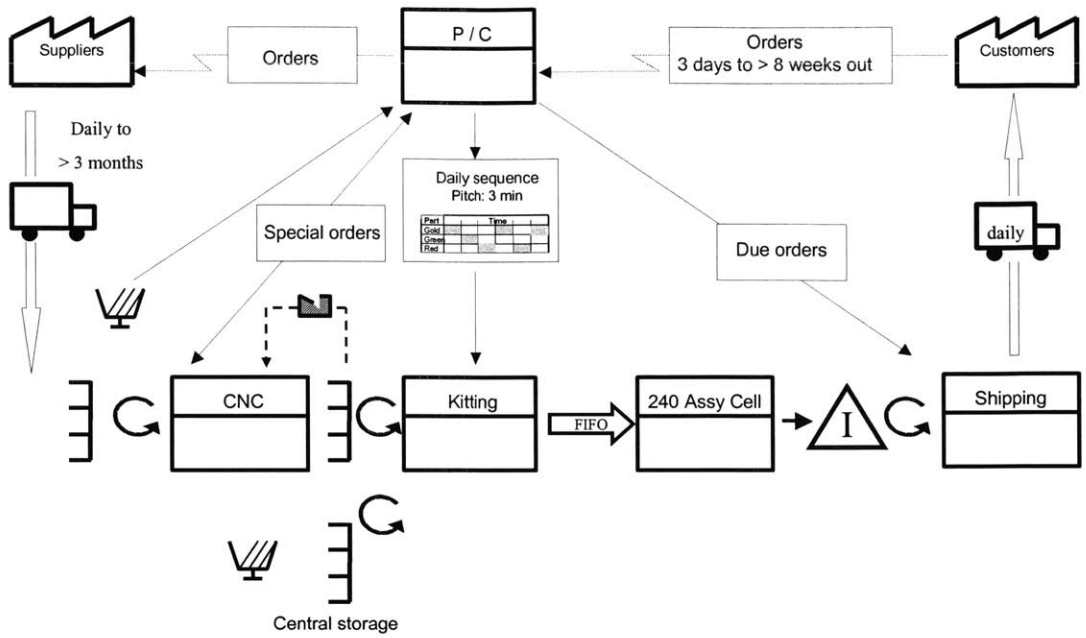


FIGURE 6-39: VALUE STREAM UE 120 LINE

Production control creates a leveled schedule for the assembly cell. As mentioned above, the 120 product family offers a wide range of configuration options. Depending on the options, the assembly time varies between 2 and 6 minutes and can be as high as 15 minutes. The assembly usually operates at a takt time between 3 and 3.5 minutes depending on customer demand. Production control groups all products into short, medium, and long assembly times. The daily schedule mixes the orders in such a way that no two short or long cycle time units are released in a row to ensure that the cell can operate, on average, to takt time.

Kitting collects all necessary parts and sends the kit to the 120 assembly cell. The cell assembles the parts and sends them to a storage area for finished goods. Each customer has dedicated shelves in the shipping area for finished goods. Shipping receives a daily list from production control with the products that must be shipped that day. UE can track all orders and their status from order release to shipping.

Kitting receives parts from CNC and from the central storage. Both areas are linked through a kanban system. Central storage sends kanbans back to production control for reordering. CNC machines are not dedicated to particular products. Some orders of 120 line products require customized CNC parts. Those orders show up on the computer screen of the scheduler 2 weeks prior the due date of the order. The scheduler issues a special order to CNC with a due date 2 days prior to planned assembly. When CNC has machined the part, it sends the parts directly to the 120 assembly cell and notifies production control that the part is manufactured. Production control then releases the order for final assembly.

Figure 6-40 shows the 120 assembly line in more detail. It involves 8 operators: 3 operators in the assembly cell, 1 operator for pressure testing, 1 operator for temperature testing, one operator for packaging and labeling, 1 kitting operator who also delivers parts to and from the 120 cell, and 1 operator who prints and product name plates for the parts. The last operator is shared with the rest all other areas of the shop floor.

The kitting operator picks two orders from the Heijunka box (1). Each order is in a time slot with an associated time so that the kitting operator can see if she picks the parts according to the scheduled time. She picks up finished goods from the ship rack (2), collects the BOM and name plate for the next two parts (3), collects all necessary parts for the next two orders in the kitting area (4), and drops off the kits in the kit rack at the assembly cell (5). She repeats this cycle every two takt time intervals. Production control determines the takt time for the next two weeks based on customer demand.

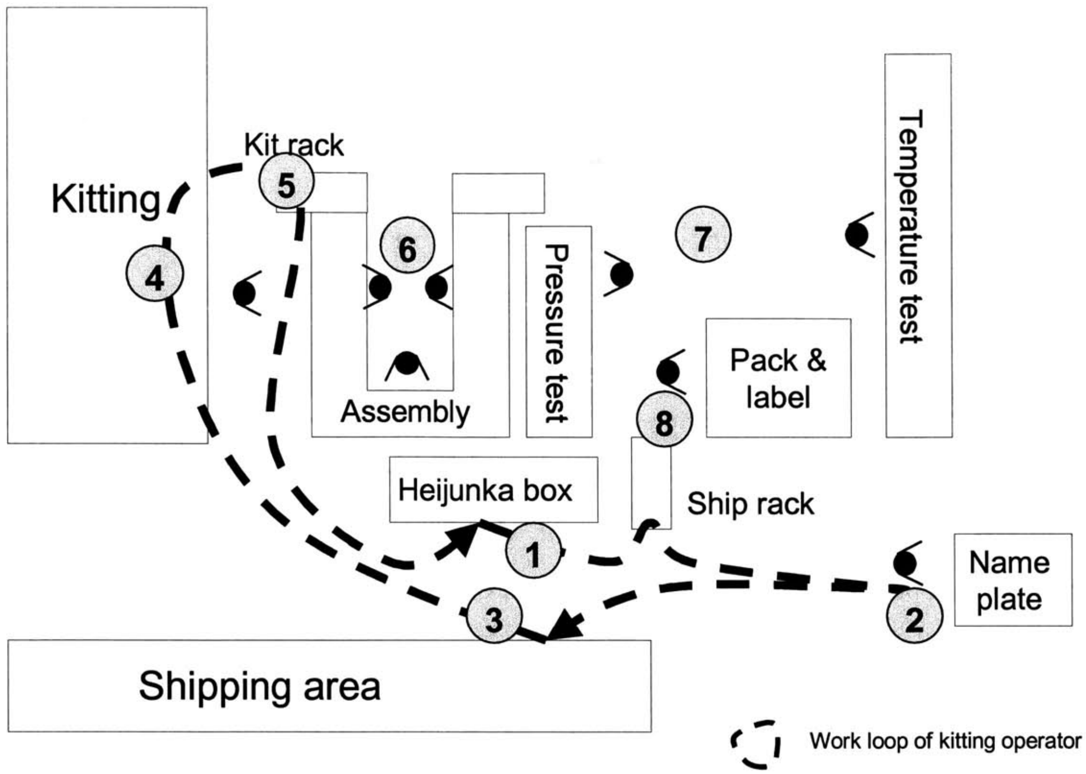
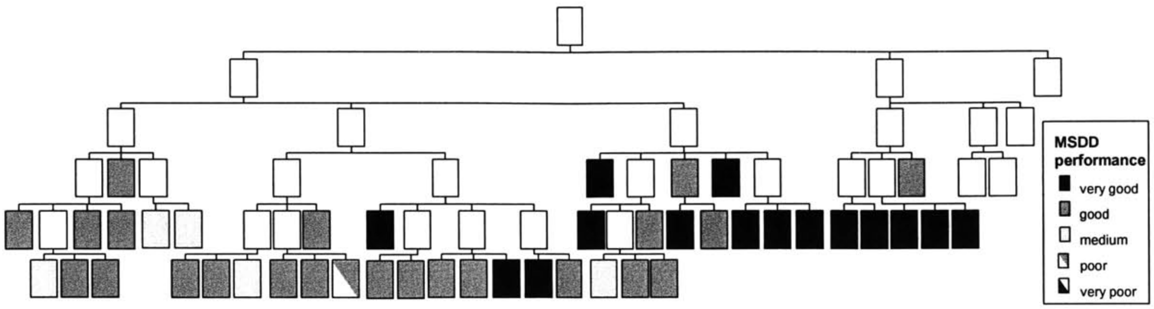


FIGURE 6-40: 120 ASSEMBLY LINE AT UE

Three assembly operators perform all assembly (6). Each operator works on two to three workstations. The last assembly operator drops the parts into the test-chute. The parts need either a pressure test or a temperature test (7). Each test has one dedicated operator. The last operator packs the parts into cartons, adds manuals, and attaches bar-code stickers (8) before releasing the part to the ship rack.

6.5.4 Evaluation and Analysis

The overall evaluation of UE's 120 line is shown in Figure 6-41. The performance of the complete value stream relative to the MSDD is good to very good. The table in the lower half of the Figure 6-41 shows the distribution of the answers for all branches of the MSDD. Figure 6-41 illustrates a very interesting aspect: UE has very high values on the right side of the MSDD, while still having some weaknesses on the left side. The following paragraphs discuss the evaluation starting with the positive achievements before reflecting on the weaknesses.



	Very Poor	Poor	Medium	Good	Very Good	Null
120 line overall	**0**	**3**	**18**	**57**	**51**	**3**
Quality	0	2	8	14	4	0
Identi./Resolve problems	0	1	3	15	0	0
Predictable output	0	0	5	10	13	0
Delay Reduction	0	0	2	11	21	3
Direct labor	0	0	0	7	13	0

FIGURE 6-41: OVERALL MSDD EVALUATION OF UE'S 120 LINE AND SCORE DISTRIBUTION FOR QUESTIONS.

The right most FR-DP pairs are related to the separation of production and support resources (FR-DP T5x), and to direct labor efficiency (FR-DP D1, D2, D3). UE has mostly very high scores in those areas. The company pays meticulous attention to efficient work design. Production and support resources are very well coordinated and do not interfere with each other (FR-DP T51, 52, 53). All material is fed from the outside to ensure that delivering new material and picking up empty kanban bins does not interfere with production operator. Assembly operators can easily reach the material bins.

UE continuously thrives at eliminating waiting times (FR-DP D1) and wasted motions (FR-DP D2). The shop floor is frequently rearranged to realize improvement suggestions and to shorten distances (the floor space for the assembly cell, pressure and temperature test has been reduced by more than 50% between 1997 and 1999). All tools have defined locations and the work area is clean and orderly (FR-DP D22). Tool locations and material supply locations facilitate easy reach for the operators.

The system layout exposes problems quickly (FR-DP R11x). The kitting operator delivers two new kits every two takt time intervals as discussed above. If the assembly cell falls behind, the chute for new kits fills up and the kitting operator cannot drop off the next kit. In the case that the chutes are full, she discusses with the assembly cell operators what to do and contacts the line supervisor if necessary (FR-DP R111 / R112).

Note that this type of problem recognition requires a leveled schedule as described above. If scheduling releases a sequence of units with long cycle times, the assembly cell would not be able to produce on average to takt time and a filled up kit rack would not necessarily indicate that the assembly cell falls behind. That is, leveling cycle time mix (DP-T223) can support fast problem recognition (FR R111). This dependency expresses coupling between the delay branch and the identifying and resolving problems branch. Chapter 7 further discusses the dependencies stated in the MSDD and provides suggestions how to determine dependencies among the FR-DP pairs.

The analysis of the questions, in which UE has no high score, reveals some interesting issues. Table 6-28 contains all questions in which UE has only achieved a medium to poor evaluation. The first group relates to equipment and the second groups relates to standardization aspects. The questions of the second group are bold in Table 6-28.

TABLE 6-28: QUESTIONS WITH MEDIUM TO POOR EVALUATION FOR UE. SHADED QUESTIONS RELATE TO STANDARDIZATION ASPECTS.

FR-DP	Question	Score
Q11	We have eliminated most machine assignable causes	medium
Q121	**We have standard training procedures for each operation.**	**medium**
Q121	**Operators are usually trained on the job.**	**poor**
Q121	**We continuously improve training procedures.**	**medium**
Q122	**Work methods have been defined for each operation and contain information about required quality standards.**	**medium**
Q122	**A written copy of operator's standardized work is available at each station.**	**medium**
Q13	**We have detailed process descriptions for all operations.**	**medium**
Q31	**We have procedures to distinguish between common and assignable causes of variation in process quality.**	**poor**
Q31	Disturbances from outside the process are detected before they can affect the process output.	medium
Q32	We have made our processes insensitive to disturbances from outside (e.g. material or environmental influences).	medium
R113	Breakdowns in equipment are easy to diagnose.	medium
R113	**We have standard procedures for determining the root cause of disruptions.**	**medium**
R123	**We document disruptions and create a knowledge base to understand recurring problems.**	**medium**
R123	We have information devices (e.g. a display at the machine panel), which show the cause of a disruption.	poor
P121	The ability to easily service equipment determines requirements for its design (e.g. accessibility, controllability, ability to monitor the process, exchangeability of components).	medium
P131	**We time each operating step in detail and include the information in the work instructions.**	**medium**
P131	**Variation in work completion time is being solved either by adjusting the work method or through operator training.**	**medium**
P132	Unplanned absenteeism often affects our ability to produce to schedule.	medium
T221	We design our manufacturing processes so that the cycle time closely matches the takt time.	medium
T221	When automatic cycles time are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two machines performing the same operation).	medium
T221	We usually try to minimize the number of machines by decreasing the cycle time per machine regardless of takt time.	medium
T32	We have low setup times for equipment in the evaluated value stream.	medium
T32	We have converted most of the setup time to external time while the machine is running.	medium

The equipment related questions have mostly a medium to low score. This reflects that UE has only recently started to improve the CNC area. Machine assignable causes are not completely eliminated yet (FR-DP Q11). The ability to service the machines was not well considered in previous years (FR-DP P121) and breakdowns are not always easy to diagnose (FR-DP R113). Setup times are not very short, but UE is aggressively working to reduce them (FR-DP T32). Questions related to FR-DP T221 "Ensure that automatic cycle time <= minimum takt time" – "Design of appropriate automatic work content at each station" are not very applicable. UE does not buy CNC machines for specific product lines. Therefore the automatic cycle time does not depend on the takt time for a given product. Furthermore, the CNC machines are often used for several generations of products.

The second group of questions relates to the lack of standardization. While the company continuously improves operational efficiency, it does not standardize work methods and does not document improvements very well. Operators are mostly training on-the-job without formal training procedures (FR-DP Q121), process descriptions are not very detailed and are not always updated (FR-DP Q13), work instructions contain only limited timing information (FR-DP P131). There are no man-machine charts available in the 120 cell. The company has no clear problem solving procedure and does not document how it solved previously occurreing problems (FR-DP R113, R123).

UE somewhat compensates for the lack of standardization with high worker motivation and very good teamwork. The supervisor of the 120 assembly cell pays very close attention to the operation of the cell. In addition, the operators train each other when they notice that somebody cannot perform a task correctly. All operators of the 120 line meet every morning for 15 minutes to discuss problems of the previous day and to do continuous improvement. The company is very good in realizing suggestions quickly and likes to improvise and experiment. However, changes are not always documented.

The high overall performance of UE suggests that the definition and enforcement of work standards is not a first step for the successful transformation of a manufacturing system design. It might become important to make achievements sustainable.

The former vice president pointed out that UE was not very capable in transferring knowledge. She said that the system was too dependent on tacit knowledge. She gave an example from the 120 cell where one assembly operator had very high skills and was very difficult to replace. When that operator was absent the company was not able to achieve the same output.

The determination of the two weak areas in UE's system somehow reflects the sequence in which UE has transformed its manufacturing system. UE started with rearranging all assembly work into work cells and has linked the assembly cells to CNC through a kanban system. This transformation lifted UE in all areas of the MSDD and is reflected in a good evaluation throughout the MSDD. UE has then focused on improvements in the work areas by paying very close attention to the elimination of wasted time and motion. Consequently, the evaluation of FR-DP pairs related to direct labor has mostly very good scores. The fact that UE has only recently started to improve the CNC area is reflected by medium to poor ratings in equipment related questions. The lack of standardization and sustainability could be seen as the final area in which UE must focus its efforts to achieve a very high score across the MSDD. Future research could confirm this sequence by analyzing the transformation of other companies. It may be possible to determine a sequence in which FR-DP pairs are considered by companies who have successfully redesigned their manufacturing system.

6.5.5 Summary

The case study evaluated a value stream at United Electric Controls, a medium sized company that manufactures automatic process controllers for pressure and temperature. The company is well known for having an efficient manufacturing system. The selected value stream consisted of a CNC machining area and an assembly area. The performance relative to the MSDD was good to very good as was expected at the outset of the evaluation.

The analysis of the questionnaire revealed two groups of questions in which UE did not show high performance. The first group dealt with equipment related aspects and reflected that UE has not reached the same level of efficiency in the CNC department as in the assembly area. The second group of questions related to standardization aspects. UE has not standardized work methods or documented improvements very well.

The following findings can be stated with respect to the MSDD:

(1) The MSDD evaluation reflected the efficient manufacturing system at United Electric. The case study therefore further verified the ability of the questionnaire and the MSDD to exemplify efficient manufacturing system designs.

(2) The case study showed that the MSDD is applicable in small to medium sized companies and in low production volume environments.

(3) The analysis of the questionnaire determined two weak areas of the company: lack of establishing standardized work procedures and the necessity to further improve the CNC equipment. The fact that UE has implemented a very efficient manufacturing system in spite of lacking standardization suggests that standardization is not a starting point in transforming a manufacturing system.

(4) UE uses a leveled schedule to increase the ability to quickly recognize problems, which suggests a coupling between the delay reduction branch and the identifying and resolving problems branch.

6.6 Chapter Summary

This chapter documented the case studies performed during the research of this thesis. Each case study was described in detail in four different sections. The first section compared three bumper production plants, the second section described how the MSDD has been applied in a manufacturing system design project, the third section used the MSDD to compare two distinctive system designs for the assembly of an electronic product and derived a schematic third design, and the fourth section analyzed a value stream in a company that is well known for having an efficient manufacturing system design.

The following paragraphs summarize the findings of the case studies and draw cross case conclusions:

(1) It was found that the MSDD was equally applicable across industry, manufacturing processes, production volume, and company size. The case studies applied the MSDD in the automotive industry, electronic goods industry, and industrial goods industry. The manufacturing covered machining (injection molding, paint, CNC machining) and assembly (bumpers, electronic goods, and process controllers). The production volume ranged from 120 to 7,800 parts per day. Company sizes varied from less than 100 to several thousand employees.

(2) The case studies analyzed plants with greatly different manufacturing system design. The evaluation of the systems relative to the MSDD reflected the differences. Two of the studies plants – plant T and United Electric – are well known for having an efficient manufacturing system design. Both plants showed good to very good performance relative to the MSDD. In contrast, two of bumper production plants showed medium to poor performance. The detailed analysis of the three bumper plants could explain the differences in the manufacturing system design.

(3) The questionnaire was a useful and reliable tool to evaluate manufacturing systems relative to the MSDD. The reliability of the questionnaire was discussed in Chapter 5.

(4) It was possible to determine strengths and weaknesses of the manufacturing system design with the help of the MSDD evaluation. In the case of the two electronic assembly value streams, the questions of the questionnaire were categorized into two groups that allowed relating the strengths and weaknesses to conceptual design differences. The grouping of the questions also supported the development of a third value stream design that can better satisfy the objectives and means stated in the MSDD.

(5) The application case study showed that the MSDD could be a useful tool during the design process of manufacturing systems. The MSDD was used to translate high-level system goals into design objectives and proved to be helpful in avoiding the use of ambiguous terminology such as "lean production." However, the integration of the MSDD into an application process for manufacturing system design requires further reserach.

(6) The case studies could neither prove nor disprove the dependencies stated in the MSDD. The limited number of case studies did not allow to firmly establish the dependencies. However, none of the case studies disproved the high-level dependencies between the branches of quality, identifying and resolving problems, predictable output, delay reduction, and direct labor efficiency. Dependencies among lower-level DPs and FRs were only briefly discussed and require further research as outlined in the next chapter.

(7) The dependencies stated in the MSDD did not provide precedence for system design decisions. The application case study showed that it was not possible to satisfy objectives in the sequence they are stated in the MSDD.

(8) The application of the MSDD and the questionnaire in the case studies revealed some inconsistencies in the decomposition or wording of the FR-DP pairs in the MSDD. Chapter 7 elaborates on those findings and develops suggestions for future modifications in the MSDD.

Chapter 7 MSDD Modifications

This chapter recommends modifications to the MSDD and the questionnaire based on their extensive use during the course of this research. The chapter also describes how the questionnaire can enhance one's understanding of manufacturing system design and discusses the dependencies that occur in the MSDD.

7.1 Modification Suggestions for the MSDD

Because this thesis concludes that the MSDD is a powerful tool for analyzing the strengths and weaknesses of manufacturing systems, it recommends no major modifications that would alter the nature of the MSDD. The changes that are suggested here are related to individual FR-DP pairs and low-level decomposition. Each branch is discussed separately.

7.1.1 Quality (FR-DP Qx)

DP-Q11 "Failure mode and effects analysis" is not sufficient to ensure that machine assignable causes are eliminated (FR-Q11 "Eliminate machine assignable causes"). The plant M case study showed that machine assignable causes were not eliminated even though failure mode and analysis tools were used. The paint system in plant M actually operated at its capability limits and a complete elimination of assignable causes was impossible to achieve – according to discussions in the plant.

The MSDD should be extended to explicitly include the selection of the processes to meet product specifications. If a process is not capable of producing according to product specification, it is impossible to eliminate machines assignable causes.

The ability of processes to meet product specification also affects FR-Q1 "Operate processes within control limits," but the FR only considers the operation of the system. Thus, FR-Q1 and the subsequent decomposition should be extended to include the selection *and* the operation of processes.

The dependencies between FR-DP Q11, Q12, and Q13 should be extended. DP-Q12 "Stable operator output" affects FR-Q13 "Eliminate method assignable causes." Plant M (bumper production) showed poor performance in operator output, a condition that operators and manufacturing engineers frequently referred to during the case study as a reason to adjust processes and methods. This example suggests an additional dependency from operator output to method assignable causes. The dependency expresses that the process plan should be finalized after the equipment and the operator skills have been determined.

General remarks

The quality branch focuses on single processes, reflecting the idea that there would be no need to provide quality feedback between operations if each individual process produces exactly to product specifications. This idea seems unreasonable. The MSDD should be extended to include quality feedback mechanisms. For example, if the inspector of the paint system in plant T detects a defect that is due to injection molding, he sends the defective part back to injection molding for further investigation. The MSDD does not cover the need to provide fast feedback to the upstream operation and to initialize problem resolution at the upstream operations Quality feedback could be integrated into the MSDD either by extending the quality branch or by covering the feedback in the identifying and resolving problems branch as discussed below.

7.1.2 Identifying and Resolving Problems (FR-DP Rx)

The decomposition of FR-DP R11 "Rapidly recognize production disruptions" – "Subsystem configuration to enable operator's detection of disruptions" distinguishes between when (FR-DP R111) and where (FR-DP R112) a disruption occurs and what the disruption is (FR-DP R113). This part of the decomposition does not seem to be useful for several reasons.

DP-R111 "Increased operator sampling rate of equipment status" cannot fully satisfy FR-R111 "Identify disruptions when they occur." The case studies revealed the importance of being able to identify disruptions quickly and discussed various different ways of achieving that goal. The bumper case study showed, for example, how the physical layout can contribute to quick recognition of disruptions. Figure 7-1 shows the injection molding areas of plant M and T and illustrates how the physical layout contributes to the ability to quickly recognize disruptions. In plant T, the injection molding team leader can get an overview of the system status by simply standing in the aisle. Operators are visible and Andon boards display the machine status. The physical layout of the injection molding area in plant M, by contrast, does not support the ability to recognize disruptions quickly.

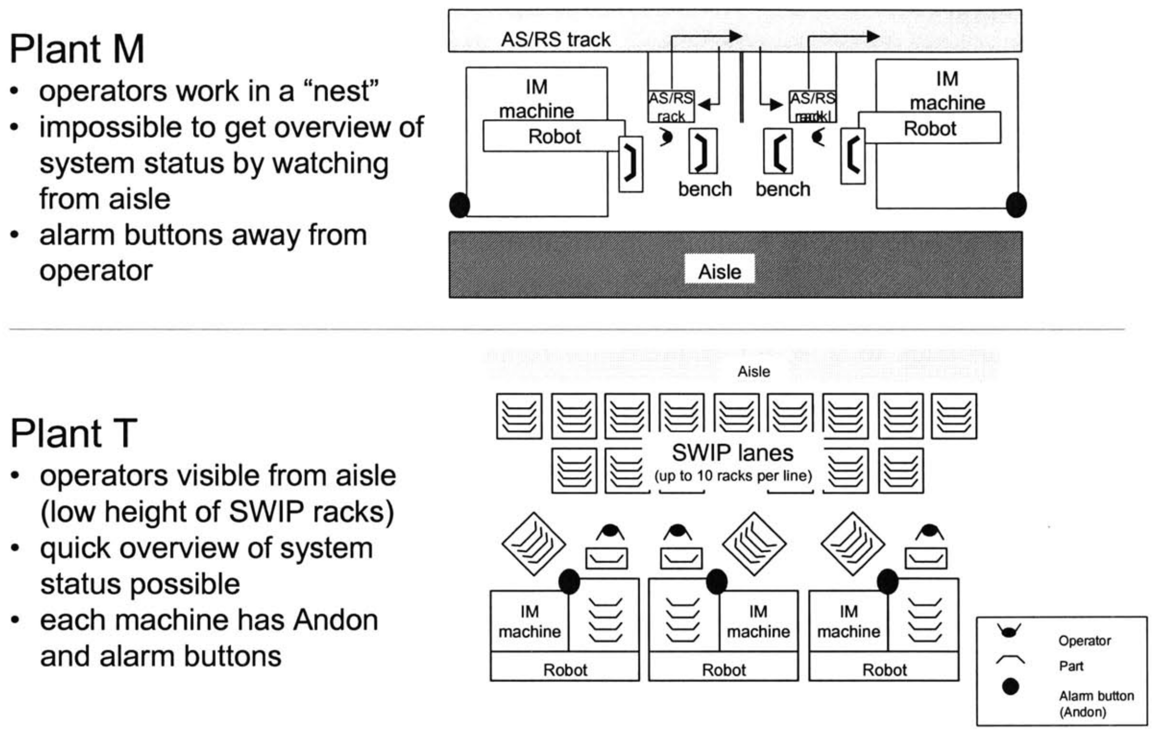


FIGURE 7-1: LAYOUT OF INJECTION MOLDING AREA IN PLANT M AND T.

Another aspect of identifying problems is the ability of operators to quickly recognize deviations in their work performance. For example, the bumper assembly operators in plant M did not know how long the assembly of a single bumper was supposed to take. Consequently, the operators and supervisors were not able to recognize problems that resulted in longer assembly cycle times. Plant T, in contrast, stressed the importance of following standardized work, which was used as internal benchmarks. Inability to meet the standards was considered to be an abnormal situation. Plant T was therefore able to recognize disruption almost on a per cycle basis.

The discussions in Chapter 6 showed that there are two dimensions in manufacturing system design that support the quick identification of disruptions: one relates to the physical layout, and the other relates to operational control. DP-R111 should therefore be restated to, for example, "Easy distinction of normal and abnormal situations" and then be further decomposed into layout and operational aspects. The questions in the questionnaire already cover both dimensions and proved to be very useful in analyzing the examined manufacturing systems.

FR-DP R112 "Identify disruptions where they occur" – "Simplified material flow paths" is more appropriate for quality related disruptions than for time. Flow paths can be very simple without exposing where a disruption occurs. Plant M, for example, had fairly simple flow paths: parts moved from – mostly – dedicated injection molding machines to one paint system to dedicated assembly cells. Nevertheless, it was not visible where disruptions occurred. Simplified material flow paths support the ability to trace back defects to the upstream operation that caused the defect. A reformulation and further decomposition of FR-DP R112 could also include quality related feedback as discussed above.

FR-DP R113 "Identify what the disruption is" – "Context sensitive feedback" should be eliminated, as it is redundant with other FR-DP pairs in the MSDD. The three questions associated with FR-DP R113 are reassigned to FR-DP R111, FR-DP R13, and FR-DP P121.

In summary: it is proposed to extend the scope of FR-DP R111 to better include layout and operational aspects that increase the ability to expose disruptions and make them easy to recognize. The decomposition should include all aspects of recognizing disruptions, not only related to when the disruption occurs. FR-DP R112 should be increased in scope to include quality feedback as well. FR-DP R113 should be integrated with the new FR-DP R111.

The decomposition of FR-DP R12 "Communicate problems to the right people" – "Process for feedback of operation's state" into three subcomponents is too detailed. The MSDD should only point out the importance of effective communication within the manufacturing system. To provide any further details would make the MSDD too application dependent. It is therefore recommended to rephrase DP-R12 into "Specified communication paths and procedures" with no subsequent decomposition. The questions associated with the decomposed FR-DP pairs should be assigned to FR-DP R12 with the exception of "We document disruptions and create a knowledge base to understand recurring problems" which is more appropriate for FR-DP R13 "Solve problems immediately" – "Standard method to identify and eliminate root cause."

7.1.3 Predictable Output (FR-DP Px)

The decomposition of FR-DP P12 "Ensure predictable equipment output" – "Maintenance of equipment reliability" was helpful in the analysis in that it provided insights into the way companies select equipment and maintain it. However, the formulation of DP-P12 should be made more consistent with the subsequent decomposition. The DP refers only to the maintenance of the equipment, while the decomposition includes requirements for the design of the equipment. DP-P12 should therefore be restated to "Selection and maintenance program for equipment reliability."

The decomposition of FR-DP P13 "Ensure predictable worker output" – "Motivated workforce performing standard work" should be changed. The existing three sub-FR-DP pairs (FR-DP P131 "Ensure predictable worker output" – "Standard work methods to provide repeatable processing time", FR-DP P132 "Ensure availability of workers" – "Perfect attendance program", and FR-DP P133 "Do not interrupt production for worker allowances" – "Mutual Relief System with cross-trained workers") are not sufficient to ensure motivated work force. FR-DP P133 should be eliminated, since FR-DP P132 includes mutual relief aspects and questions for FR-DP P133 should be assigned to FR-DP P132.

The importance of the operator for the success of manufacturing systems is widely accepted [Strohm, 1997]. Warnecke expresses the essential role of human being in manufacturing systems as he is "unbeaten in his ability to connect information with purposeful reaction" [Warnecke, 1992, p.44]. It is therefore recommended that the MSDD articulate more explicitly human resource development under the predictable operator output branch.

There should also be an additional dependency between predictable operator output (DP-P13) and predictable equipment output (FR-P12). The dependency would reflect that operators have to perform predictable work to ensure proper maintenance. It would also further underline the importance of operators in manufacturing systems.

The decomposition of FR-DP P14 "Ensure material availability" – "Standard material replenishment system" should be reviewed to better include inventory control policies. The present decomposition is too biased towards inventory control with a kanban system (see also discussion in the delay reduction branch below).

FR-DP P142 "Ensure proper timing of part arrivals " - "Parts moved to downstream operations according to pitch" assumes a fixed-time variable quantity material delivery approach. However, it seems unreasonable to make a general recommendation to use such an approach for the release of material. The intent of FR-DP P142 was to coordinate material delivery with downstream consumption. The discussion of the bumper assembly area in plant M and U pointed out that the assembly area was often blocked with pallets of parts that were not needed. The coordination of part deliveries with consumption, however, is better captured in FR-DP T23 "Produce in sufficiently small run sizes" – "Arrival of parts at downstream operations according to pitch." It is therefore recommended to eliminate FR-DP P142 and its associated questions.

7.1.4 Delay Reduction (FR-DP Tx)

The delay reduction branch covers those sources of delays that are predictable consequences of the design and operation of the system, in contrast to production disruptions that occur randomly. Overall, the delay reduction branch was very helpful in analyzing the design and operation of a manufacturing system.

However, it would be desirable to explicitly include planning and control aspects into the decomposition. The MSDD makes the general recommendation to use a pull control approach expressed by FR-DP T31 "Provide knowledge of demanded product mix (part types and quantities)" – "Information flow from downstream customer." While that type of control is considered to be very stable [Benton, Shin, 1998], it would be desirable to consider other planning and control policies as well and map those policies with the MSDD.

The MSDD offers a very good platform to relate planning and control with physical system design aspects. The development of the third value stream design in the electronic case study illustrated how physical and operational aspects were considered based on the MSDD. The application case study showed how the desire of implementing a control policy (pull control) affected the physical layout and operator work design. Further research is necessary to more explicitly state how operations and design influence each other.

DP-113 – "Mean throughput time reduction" should be changed to "Reduction of production delays" as the subsequent decomposition focuses only on delay reduction and not on other components that contribute to throughput time reduction.

7.1.5 Direct Labor (FR-DP Dx)

DP-D1"Human-Machine separation" is too broad for FR-D1 "Eliminate operators' waiting on machines" as discussed in Chapter 5.4. Human-machine separation, however, includes aspects such as human flexibility, decision authority, and process transparency [Grote et al, 2000]. The decomposition of DP-D1, however, does not consider those aspects which makes the DP inappropriate.

In addition, DP-D12 "Enable worker to operate more than one machine / station" – "Train the workers to operate multiple stations" is less related to the elimination of waiting time than to the skill level of operators. However, the skill level is covered by FR-DP Q121 "Ensure that operator has knowledge of required tasks" – "Training program." It is therefore recommended to delete FR-DP D12 and to replace DP-D1 with DP-D11 "Machines & stations designed to run autonomously." Questions for FR-DP D12 should be associated with FR-DP Q121.

The bumper case studies discussed several instances in which the operator cycle time was not balanced with the machine cycle time. For example the manual cycle time of the injection molding operator in plant M was shorter than the machine cycle time leading to idle time for the operator. It is also difficult to balance very short manual and automatic cycle times as illustrated at the paint system in plant M. However, the inbalance between manual and automatic cycle time is not covered by the MSDD. FR-DP D3 "Eliminate operators' waiting on other operators" – "Balanced work-loops" only considers unbalanced work loops among operators. It is therefore recommended to restate FR-D3 to "Eliminate operators' waiting on other production resources." The DP can remain the same.

7.2 Analysis and Modification of Questionnaire

This section summarizes how the questionnaire was used for the analysis of the case studies, it discusses future ways to enhance its usability and it makes recommendations for modifying the questionnaire.

7.2.1 Analysis of the Questionnaire

The following paragraphs describe two different approaches to analysis that were used during the case studies. The three approaches take advantage of the fact that Likert scales allow numerical analysis. The first approach aggregates the questions for each scale and provides a graphical overview of the value stream performance. The second approach uses grouping of questions in order to better understand value stream characteristics as done in the electronic case study.

7.2.1.1 General Overview

The filled-out questionnaire can be graphically illustrated on a computer screen as shown in Figure 7-2. Questions for each scale are aggregated to express a performance ranging from very poor to very good. The graphical illustration gives a quick overview how a value stream performs relative to the MSDD and is a starting point for further analysis.

Boxes indicating poor to very poor performance often triggered discussions among respondents of the questionnaire and provided a starting point for further analysis. The case study at United Electric, for example, showed a very high performance at the right most side to the MSDD, while indicating some weaknesses at the left side. It was then investigated in more detail why some questions had a low score.

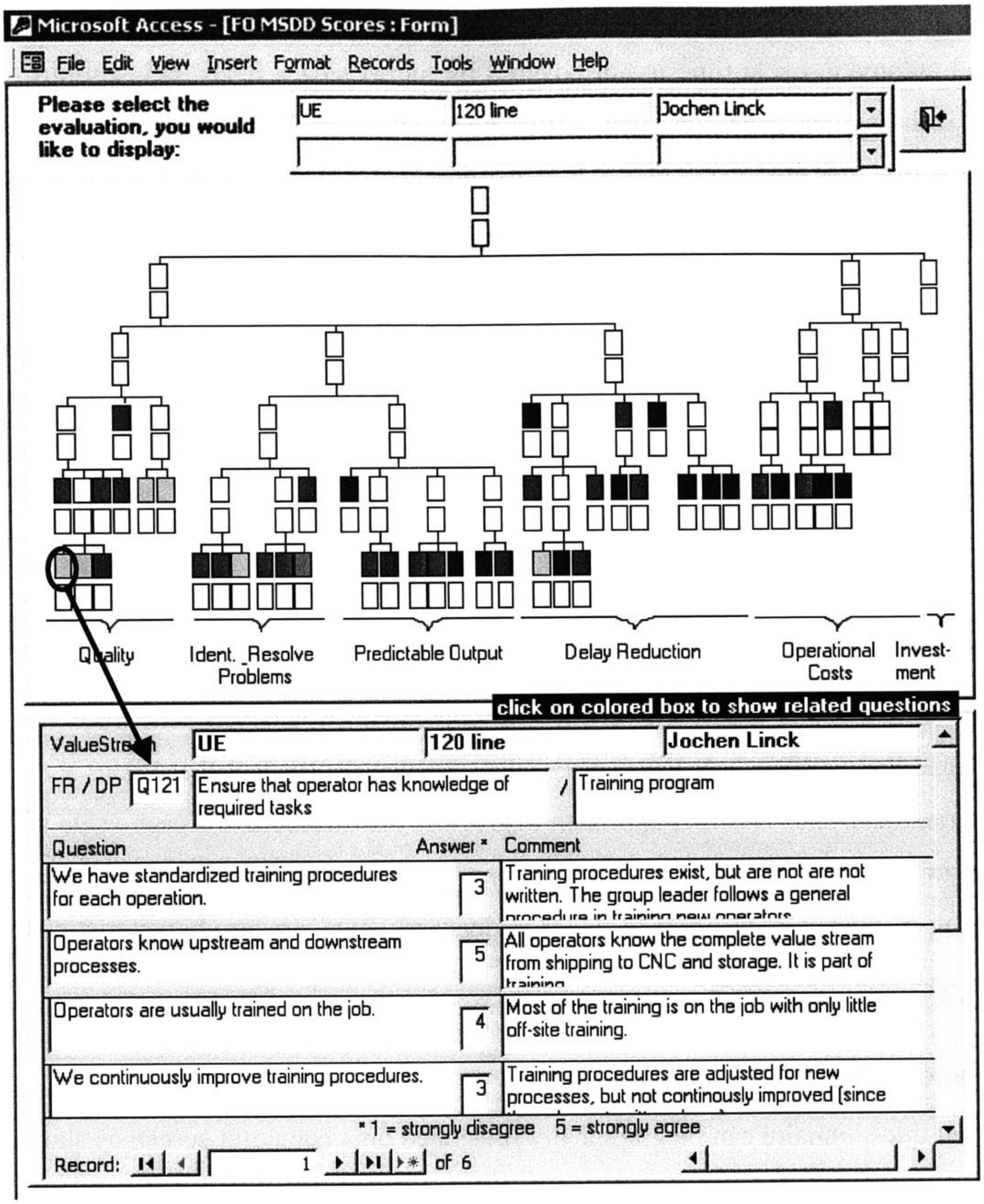


FIGURE 7-2: GRAPHICAL ILLUSTRATION OF QUESTIONNAIRE ANSWERS IN MSDD DATABASE.

Figure 7-3 shows the percentage of points reached by each of the value streams examined in Chapter 6. The differences of the seven value streams suggest that a total aggregation of the questionnaire to one single number can be a starting point to categorize the performance of companies, while a ranking of companies is not appropriate. Plants T and UE are clearly superior to the other five value streams and could form a "high performance" category. The remaining 5 value streams are more difficult to separate into two more groups as the differences are less drastic. However, it seems justified to say that value stream C represents a better manufacturing system than plant M. The difference between value streams C and P, though, is too small to decide if one system performs better or worse than the other. Therefore, it is not recommended to rank manufacturing systems only based on the sum of scores achieved in the questionnaire.

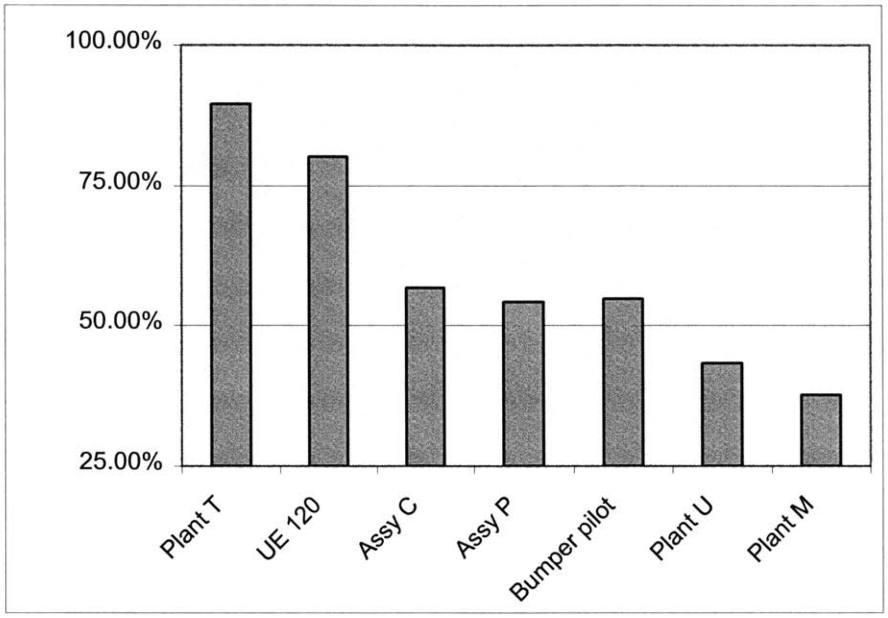


FIGURE 7-3: PERCENTAGE OF ACHIEVABLE POINTS FOR ALL VALUE STREAMS

The evaluations shown in Figure 7-3 were discussed in Chapter 6. They summarize observations made during plant visits, discussions with personnel, and answers of respondents of the questionnaire. The following paragraphs discuss the evaluations of the other respondents.

Figure 7-4 shows the distribution of responses to the questionnaire for the discussed value streams. The number in brackets behind the value stream name indicates how many questionnaires were filled out for each value stream. The figure shows the minimum and maximum percentage of all responses. The average does not consider the two extreme evaluations.

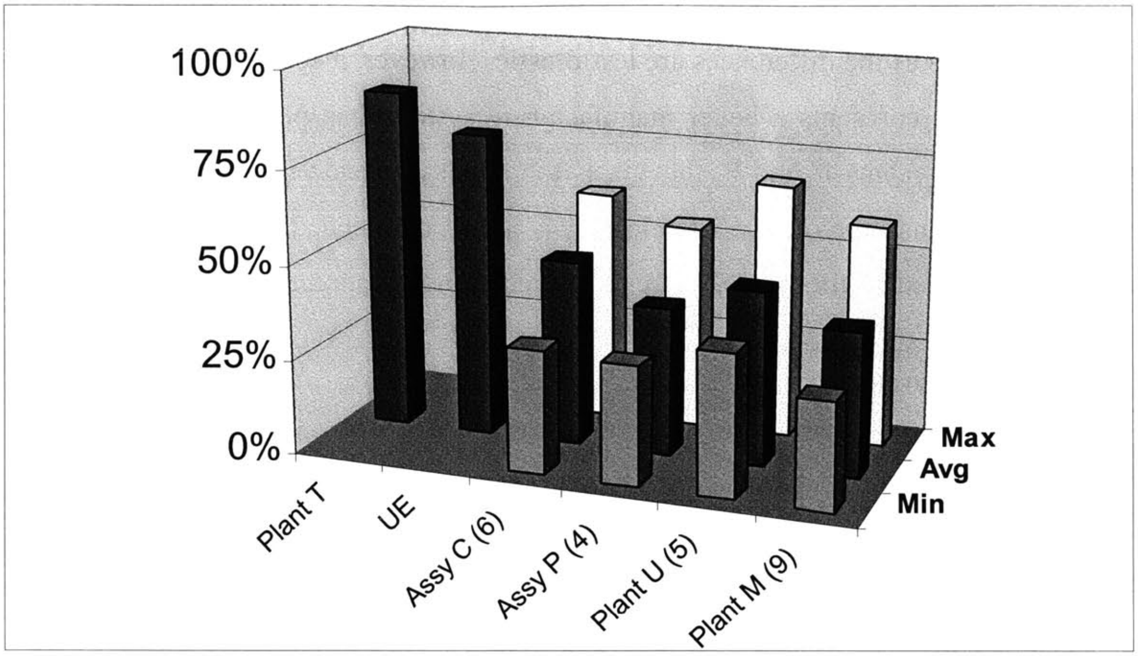


FIGURE 7-4: DISTRIBUTION OF QUESTIONNAIRE RESPONSES

Plant T and United Electric have only one evaluation. It was not possible that employees, who worked in the bumper production of plant T, filled out the questionnaire. The evaluation presented in section 6.2.2.2 was discussed with a team leader of the bumper production and an assistant manager of the quality department. The evaluation of United Electric was based on the intensive discussion with a former vice-president. It was not possible that current employees filled out the questionnaire.

Assembly line C was evaluated by four manufacturing engineers of the company and two researchers of the PSD laboratory. Two of the employees worked in the value stream, while the other two were only visiting the plant. The evaluations of the two engineers working in the value stream were 61% and 54%. The evaluation discussed in section 6.4.3 is between the two evaluations of those two engineers. The two visiting engineers had the lowest evaluation followed by the second researcher of the PSD lab. One of the visiting engineers worked for assembly line P. He also evaluated that assembly line with a similar low percentage (31%). In addition, two other manufacturing engineers evaluated assembly line P. The evaluation discussed in section 6.4.3 showed the highest percentage. That evaluation also took into account discussions made with a supervisor and an area manager during a plant tour in order to determine answers to a particular question. Furthermore, the evaluation related the performance of assembly line P to the other value streams examined during the course of the research for this thesis. An analysis of the responses of the manufacturing engineers working in assembly line P and subsequent discussions with those engineers pointed out a sometimes very critical perception of the employees. Overall it is believed that the evaluation presented in section 6.4.3 provides a fair representation of the system also in comparison with assembly line C.

Four employees of plant U evaluated the bumper production. Each employee considered only the department he was working in. Two employees worked in the paint system, one in the injection molding area and one in the assembly area. The best evaluation was given by the area supervisor of the assembly area, the worst by the area manager of the paint system. The remaining three evaluations of that value stream vary between 43% and 48%, which indicates a good reliability of the system evaluation. The evaluation discussed in section 6.2.3.2 considers the complete bumper production and reaches 43%. It is believed that the high evaluation of the assembly area manager was too positive compared with the observations and discussions made during the plant visit.

Plant M had the most responses. A total of 9 questionnaires were filled out by the assistant plant manger, the area manager of the bumper production, the superintendents of injection molding, paint, and assembly, the industrial engineer, a manufacturing engineer and two researchers of the PSD lab. The superintendents answered the questions only with respect to their area and not for the complete bumper production. The lowest evaluation was given by the injection molding superintendent and one PSD researcher (28% and 30% respectively). The assistant plant manager and the superintendent of assembly gave the highest scores (59% and 50% respectively). The assistant plant manager later said that his evaluation was probably too high considering the other assessments. The evaluation discussed in section 6.2.1.2 reached 38% and was two percentage points below the average.

In summary, it is believed that the evaluations discussed in Chapter 6 capture the strengths and weaknesses of the studied value streams and are supported by the evaluation of the personnel working in the those value streams. The evaluations in

Chapter 6 are very close to the average percentage, except for assembly line P for the reasons discussed above.

The spread of percentages in plants M and U can be partially explained by the fact that some respondents limited their evaluation to one area of the bumper production. That area may perform better or worse than the total value stream leading to extreme evaluations. The spread in percentages underscores the recommendation that several people per value stream - preferably from various levels of the organization - should fill out the questionnaire. Multiple responses provide a more complete understanding of the value stream and give a more thorough basis for a complete analysis.

7.2.1.2 Grouping of questions

Grouping of questions can greatly facilitate the analysis of the questionnaire as demonstrated in the electronic assembly case study in Chapter 6.4. Two groups of questions (group I and group D) were defined in order to better understand the differences between the two value stream designs. A third group of questions evolved during the analysis of UE and is related to standardized methods. The usability of the three groupings was tested by applying them to the other values streams discussed in Chapter 6.

It was examined how far the groupings of the electronic case study were applicable for the bumper comparison. It was found that the two groups of questions were suitable in most cases except for equipment-related questions. Since the manufacturing in the electronic assembly case study did not involve any machining, all questions associated with machining hardware fell into group I. However, bumper production included injection molding and paint processing so that equipment related questions had to be considered in the value stream design. The present grouping suggests that the applicability of some questions depends on the manufacturing circumstances, for example assembly or machining. Future applications of the questionnaire should aim at verifying the grouping in order to better facilitate the analysis and design of manufacturing systems.

Table 7-1 shows the questions related to standardized work and procedures. Table 7-2 shows the score of those questions for the value streams discussed in Chapter 6. The distribution shows three groups of value streams: plant T with the highest evaluation, the other two bumper plants with the lowest, and the electronic assembly value streams and UE with a medium evaluation.

TABLE 7-1: QUESTIONS RELATED TO STANDARIDZED WORK AND PROCEDURES.

FR / DP	Question
Q121	We continuously improve training procedures.
Q121	We have standardized training procedures for each operation.
Q122	Work methods have been defined for each operation and contain information about required quality standards.
Q32	We have standard procedures for eliminating root causes of quality variation.
R113	We have standard procedures for determining the root cause of disruptions.
R121	We have standard communication paths to contact support staff.
R13	We follow standard procedures for resolving problems.
P131	Variation in work completion time is being solved either by adjusting the work method or through operator training.
P131	We time each operating step in detail and include the information in the work instructions.
P133	We have standard procedures in place for mutual relief.
D12	We have a formal suggestion program for all employees.
D23	We use time studies to update standard work sheets.

TABLE 7-2: DISTRIBUTION OF ANSWERS FOR QUESTIONS RELATED TO STANDARDIZED METHODS AND PROCEDURES

Value Stream	Very Poor	Poor	Medium	Good	Very Good	Average*
Bumper plant T	0	0	0	1	11	4.9
Bumper plant U	2	6	2	2	0	2.3
Bumper plant M	3	5	2	2	0	2.3
Bumper Application	2	3	4	3	0	2.7
Value Stream C	0	2	6	4	0	3.2
Value Stream P	0	1	8	3	0	3.2
United Electric	0	0	6	4	2	3.7

* 1 = very poor, 5 = very good

Table 7-2 reflects the performance differences between the three bumper plants. The manufacturing system in the bumper application case study has only improved slightly as discussed in Chapter 6.2. The comparison of UE with assembly value streams raises an interesting point. UE has a much higher overall evaluation than the assembly value streams, but the score relative to standardization is very similar. The discussion in Chapter 5 speculated whether establishing standards might be a final step in designing a highly efficient manufacturing system (the bumper application case study would support this assumption. The project was still in an early phase of implementation and showed poor evaluations relative to standardized work methods). It might also be that the size of the company influences the necessity to standardize operations. UE might be able to compensate for the lack of standardization through a flat hierarchy and highly motivated workers. Future applications of the questionnaire and subsequent analyses may be able to establish a correlation between the company size, overall system performance, and level of standardization.

7.2.2 Modifications of Questionnaire

The following paragraphs suggest modifications to the questionnaire based on feedback from industry and from the analysis of the questionnaires. In order to ensure comparability between the case studies, it was necessary to freeze the status of the questionnaire at some point during the research. The following modifications were therefore not incorporated in the questionnaire used to perform the case studies. All changes are summarized in Table 7-3.

TABLE 7-3: MODIFCATIONS TO QUESTIONNAIRE

FR-DP	Question	Explanation of Change
Q121	We have standardized training procedures for each operation.	Replaced "standard training" with "standardized training" to ensure consistency.
Q121	The operators are capable of performing more than one task.	Question was previously associated with D12
Q121	Plant employees are rewarded for learning new skills.	Question was previously associated with D12
Q121	We rotate operators to other jobs within their subsystem.	Question was previously associated with D12
Q121	Operators are only trained on the job.	Included the word "ONLY trained" instead of "trained" (eventually all operators are trained on the job as well)
Q122	A copy of operator's standardized work description is available at each station.	Replaced "written copy" to "copy" since the description could also be available on compuer screen.
Q123	We frequently use devices that prevent errors from occuring (e.g. using positioning holes, light curtains for picking material, poka-yokes).	Replaced Poka-Yoke with "devices that prevent errors from occurring"
Q31	We have procedures to distinguish between controllable and uncontrollable causes of variation in process quality.	Replaced "common and assignable" with "controllable and uncontrollable"
Q32	We apply standard procedures to eliminate root causes of quality variation.	Replaced "have standard.." with "apply standard.."
R111	Our system exposes disruptions and makes them easy to recognize (e.g. accumulating material shows that a production unit is falling behind).	Question was previously associated with R113
R12	Our communication devices allow rapid correspondence (e.g. walkie talkies, andon boards).	Question was previously associated with R122 now R12
R12	We have standard communication paths to contact support staff.	Question was previously associated with R121 now R12
R12	Disruptions are quickly conveyed (e.g. by starting an alarm, information technology).	Question was previously associated with R122 now R12
R123	We have information devices (e.g. a display at the machine panel), which show the cause of a disruption.	DELETED: R123 has been deleted.
R13	We have standard procedures for determining the root cause of disruptions.	Question was previously associated with R113
R13	We document disruptions and create a knowledge base to understand recurring problems.	Question was previously associated with R123
R13	We have a formal suggestion program for all employees.	Question was previously associated with D12
P121	Breakdowns in equipment are easy to diagnose.	Question was previously associated with R113
P131	If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other).	DELETED: It was originally thought that operators helping each other out would be desirable in achieving stable operator output. However, it is counterproductive to establishing standardized work. Thus, question is eliminated.
P132	We have standard procedures in place for mutual relief.	Question was previously associated with P133
P133	Operator allowances (e.g. for personal hygiene) usually lead to production disruptions.	DELETED: unnecessary question.
P142	Our part suppliers deliver on a just-in-time basis.	DELETED: P142 has been eliminated all together
P142	The frequency of material delivery is based on consumption as opposed to preset delivery times.	DELETED: P142 has been eliminated all together

FR-DP	Question	Explanation of Change
T1	We tend to have large transfer batch sizes between operations.	New questions formulation. Old question: "The internal transfer batch size is usually larger than 2 hours of production material."
T2x	... takt time ...	Replaced takt time with desired production pace of the manufacturing system
T21	We have clear customer - supplier relations throughout the value stream.	Eliminated second half of question "and production pace is based on takt time" to avoid double question.
T23	Part deliveries are independent of downstream consumption.	Previously under P142 (which has been eliminated)
T23	We communicate the pace of customer demand into the value stream (for example by using a Heijunka box or some other means)	Replaced old question: "We use a Heijunka box or some other means to communicate the pace of customer demand into the value stream"
T31	We schedule only one operation in the value stream.	Second half of question eliminated "Upstream operations are scheduled based on the consumption of the scheduled operation."
T31	Most operations are centrally scheduled.	DELETED: Reason: it cannot be said if strongly agree should be positive or negative. Toyota is centrally scheduled AND pull control.
T4	The shop floor layout has functional departments.	DELETED: Replaced by two other questions.
T4	We group machines of the same process together.	NEW QUESTION: Tries to better capture the idea of transportation requirements.
T4	We have eliminated the need for transportation by having processes necessary to manufacture a product adjacent to each other.	NEW QUESTION: Tries to better capture the idea of transportation requirements.
D11	Eliminating non-value added time spent at each station is a priority of station design.	DELETED: Too broad.
D11	Operators have to watch the machine cycle to ensure that the machine does not produce defective parts.	Clarified formulation of old question: "Operators usually wait at a machine until the machine cycle is finished."
D11	Our machines automatically detect when producing a defective part and shut down.	NEW QUESTION: Trying to capture the idea of autonomous machines.
D11	Our operators are able to perform other tasks while the machine is running.	NEW QUESTION: Trying to capture the idea of autonomous machines.
D3	We often design work loops for one operator independent from work loops of other operators on the same team.	DELETED: Poor reliability in Alpha test and difficult to understand.

Wording

Some questions have been reworded in order to clarify their meaning or to replace terminology that was not always known. The term "takt time" has been replaced with "desired production pace (or takt time)". The change affected several questions in the delay reduction branch (FR-DP T2x). "Poka-yoke" has been replaced with "devices that prevent errors from occurring" (FR-DP Q123).

The question "Operators are usually trained on the job" (FR-DP Q121) has been changed to "Operators are *only* trained on the job" to underscore the reverse character of the question.

Note that for filled out questionnaires, it is necessary to delete all answers to questions that were changed. Otherwise the responses could be misleading as the answer was given to a different question.

New questions

To improve the reliability, additional questions have been formulated for FR-DP T4 "Reduce transportation delay" – "Material flow oriented layout design" and FR-DP D1 "Eliminate operators' waiting on machines" – "Machines & stations designed to run autonomously."

Reassigning and eliminating questions

Section 7.1 suggested to eliminate several FR-DP pairs and discussed how the questions associated with those FR-DP pairs should be reassigned or deleted. The questions were reassigned to other FR-DP pairs if they were compatible with the meaning of the FR-DP pair. If it was not possible to use the question in the context of another FR-DP pair, the question was eliminated. Some more questions were deleted if they showed a poor reliability according to the Alpha test discussed in Chapter 5.

Two questions were eliminated based on discussions with manufacturing engineers in plant T. The question "If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other)" associated with FR-DP P131 was eliminated since it was misleading. It was originally thought that operators helping out each other would be desirable in achieving stable operator output. However, the discussions pointed out that doing so would be counterproductive in establishing standardized work. Therefore, the question was eliminated. The other eliminated question was "Most operations are centrally scheduled" (FR-DP T31) that was originally considered a reverse question, i.e. strongly agreeing to the question would represent a poor performance. The manufacturing engineer in plant T, however, pointed out that all operations were centrally scheduled in addition to using a pull control system. Thus, the question would only indicate an undesirable situation relative to the MSDD if the value stream was centrally scheduled *and* no pull control system was used. Since this type of combinational analysis is not desired, the question was deleted.

7.3 Discussion of Dependencies

The MSDD states dependencies between DPs and FRs according to the axiomatic design methodology. The dependencies express if the realization (or failure of realization) of a DP affects the system's ability to achieve an FR. The following paragraphs discuss the findings of the case studies relative to the dependencies and makes suggestions for future research.

The FR-DP pairs in the MSDD are arranged from left to right so that those DPs that affect the most FRs appear first. As a result, the MSDD shows path dependence when reading from left to right. The path dependence means that FR-DP pairs on the left side must be satisfied in order to effectively achieve the FRs on the right side.

The application case study showed that the dependencies stated in the MSDD do not dictate the order of steps in the design of manufacturing systems. It is not possible to first design all aspects related to quality, then predictable output etc. One of the earliest decisions made in the design project was to determine the production pace even though the corresponding FR-DP pair (T21) is in the middle of the MSDD under the delay reduction branch.

According to Suh [2001, Chapter 6, p.43], axiomatic design uses the dependencies to show the sequence of operation. This suggests that the dependencies stated in the MSDD represent a sequence in which the manufacturing system must be controlled or operated, but not a sequence in which the system must be designed. That is, the dependencies imply that it is operationally not possible to minimize delays in throughput time without ensuring high quality manufacturing. The limited amount of case studies is not sufficient to finally prove the dependencies (see discussion in Chapter 9.2.3) . However, none of the companies achieved high scores on the right side of the decomposition while having low scores on the left side. Thus, the case studies enhanced the credibility of the dependencies by not disproving them.

However, the reduction of the dependencies to the operational phase is not conclusive. The MSDD explicitly states requirements for the physical design of manufacturing systems, for example FR-DP T4 "Reduce transportation delay" – "Material flow oriented layout" or FR-DP P121 "Ensure that equipment is easily serviceable" – "Machines designed for serviceability." The electronic assembly case study showed that the schematic design of a third value stream incorporated several physical layout and operational aspects. The injection molding area of plant T supported the quick identification of problems with a visual factory layout. The dependencies of the discussed physical design aspects are not controlled during the operation, but must be considered during the design of the manufacturing system.

The clarification of the dependencies, both the meaning and the existence or non-existence, remains an open point for future research. The following paragraphs discuss three possible research paths in order to achieve the clarification.

One way to clarify and possibly quantify dependencies among FR-DP pairs is to collect a large number of questionnaires and perform statistical analyses. Filippini et al. [1998] used a sample size of 45 companies to statistically determine correlations between quality, delivery, and costs. Sakakibara et al. [1993] developed the JIT research framework using factor analysis techniques based on 41 different plants. These two examples suggest that a number larger than 50 companies allows the application of statistical analysis to determine correlations between single FR-DP pairs. These correlations can be used to express the dependencies between FR-DP pairs. Aggregating the questionnaire to the higher levels could establish relationships among the branches of the MSDD or other constructs. A construct could be, for example, aspects related to standardized work as discussed in the United Electric case study and in section 7.2.1.

Another research path to better understand the design sequence of manufacturing systems relative to the MSDD could be the long-term observation of manufacturing systems that are transformed from "mass" to "lean" manufacturing. In Chapter 6, it was tried to relate the current evaluation of UE's manufacturing system to the sequence in which United

Electric has transformed its manufacturing system. The application case study allowed evaluating the bumper production system at two different points in time. The current status of the redesign project exposed that the system has not achieved all design objectives yet. Continuous documentation of the project over a long period of time could eventually lead to an explanation why (or why not) the project was successful. The findings could then be incorporated into a procedure for manufacturing system design based on the MSDD.

A third way to explain the dependencies with respect to the design of manufacturing systems is to link the MSDD with a procedural design such as Kettner et al. [1984]. The linkage could refine which FR-DP pairs have to be considered in which phase of a system design project. The application case study (Section 6.3.3) showed that some FR-DP pairs of the delay branch have to be considered at a very early phase. The formal mapping of the MSDD with an established design procedure can further clarify the nature of the dependencies during the design of the system.

7.4 Summary

This chapter made recommendations for changes in the MSDD and the questionnaire. The modifications were limited to the refinement of single FR-DP pairs and changes in the lower-level decompositions. Some recommendations for further decomposition were made for the quality and identifying and resolving problems branches. The quality branch should include the selection of processes in order to ensure that the system is capable in producing according to specifications. It was further recommended to better include quality feedback in the identifying and resolving problems branch. The current version of the MSDD limits the focus of that branch to time disruptions. The decomposition of the predictable operator output should be extended to better consider motivational aspects of operators.

Some questions of the questionnaire were reworded to avoid ambiguous terminology. Other questions were removed either due to the change of the FR-DP pair or because the question showed poor reliability. Several questions have been added for FR-DP T4 and FR-DP D11 in order to improve the reliability.

The chapter reviewed how the questionnaire was used in the analysis of the case studies. Grouping of questions was a promising way to establish correlations between various system design aspects. It was recommended to apply the defined groups in multiple cases and industries to verify its general applicability.

Finally, the nature and use of the dependencies stated in the MSDD was discussed and reviewed. The case studies provided valuable insight for the understanding of the dependencies, but could not finally prove or disprove their existence. Future ways to determine the existence and use of the dependencies were discussed.

Chapter 8 MSDD Database

This chapter briefly introduces the MSDD database and its general functionality. It includes the linking of existing manufacturing system design methods to the MSDD using the database.

8.1 MSDD Database

The MSDD database was developed in order to provide a graphical user interface for the application of the MSDD, to administer and analyze the questionnaire, and to document observations made during the case studies. The database is programmed in Microsoft Access and is available at the Production System Design Laboratory.

The general functionality of the database is explained by referring to a database screen shown in Figure 8-1. The numbers are used to explain the functionalities. The user can select one or two questionnaires he would like to display (1). FR-DP pairs with associated questions are highlighted as colored boxes. Clicking on any colored box of the MSDD (2') shows the associated questions in the lower half of the screen (2"). The user can change the answer and edit the comment field.

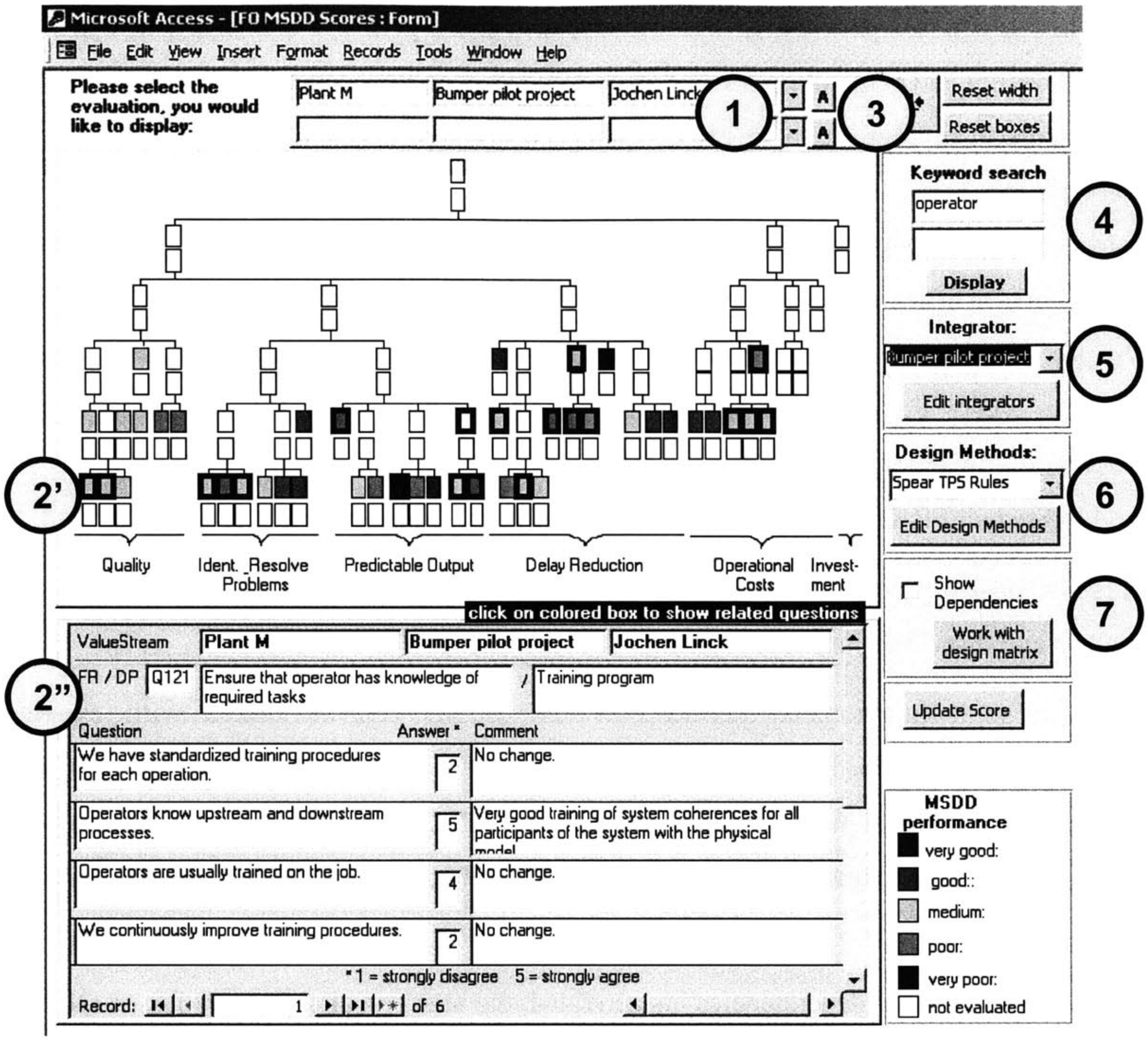


FIGURE 8-1: MSDD DATABASE WORKING WINDOW

(3) Clicking on the "A" button next to the questionnaire selection field opens a window with a numerical analysis of the questionnaire. It shows how many questions scored very poor to very good. It also allows filtering of questions by score to facilitate a first analysis of the questionnaire.

(4) The "keyword search" highlights all FR-DP pairs related to an entered word. This feature currently looks in the text of FRs, DPs and questions. The keyword search can greatly support the determination of design objectives and the understanding of the MSDD as discussed in Chapter 6.3.

(5) The "integrator" provides a platform to relate FR-DP pairs system design aspects such as cell design and scheduling, or to design projects. The user can select from an array of integrators to highlight related FR-DP pairs. For example, one integrator is the bumper pilot project and contains all determined design objectives. When the user selects the integrator, all design objectives are highlighted. It is then possible to overlay the questionnaire of the bumper pilot project with the objectives to determine to what degree the new design satisfies the determined objectives. The button "Edit integrators" opens a window where FR-DP pairs can be associated with the integrator. In addition, it is possible to document how a project succeeded in achieving stated objectives. Figure 8-1 highlighted all FR-DP pairs that were objectives in the bumper production pilot project.

It is also possible to define question groups (not shown in Figure 8-1) as used in the case studies and discussed in Chapter 7.2.1.

(6) The sixth functionality shows how the MSDD can be linked with existing manufacturing system design methodologies such as those described in Chapter 2. The linking procedure and purpose is described in section 8.2 below. The user can select from an array of design methods to highlight those FR-DP pairs (or questions) that are related to the design methods.

(7) If the box "Show dependencies" is activated, the user can click on any FR or DP box to highlight the dependencies. Clicking on a DP box highlights all FRs that are affected by the DP, clicking on an FR box shows all DPs that affect the FR. This feature can be helpful in determining dependent design objectives. The button "Work with design matrix" directs the user to the administration of the dependencies.

Summary

The MSDD database provides a powerful tool for the use of the MSDD, the questionnaire, and future applications build upon the MSDD. The structure of the relational database easily allows making cross-questionnaire analyses, analysis of project documentation, extracting common system design characteristics etc. The ability to record observations and design projects can lead to a knowledge database for manufacturing system design. Industry or company specific circumstances can be considered.

It is hoped that the MSDD database will continue to grow in functionality and use in the future days of the Production System Design Laboratory.

8.2 Linking Existing Design Methods to MSDD

The following paragraphs present possible ways to link existing manufacturing system design methods with the MSDD. The literature review pointed out that many existing methods provides a valuable tool for a particular task (for example the design of work systems within manufacturing), but it is often not known how the outcome of one method will affect the overall system design.

The MSDD covers a wide range of manufacturing system design aspects. It is believed that the MSDD provides a platform for linking various manufacturing system design methods. The purpose of the linkage is to combine the wide scope of the MSDD with more detailed design methods. The linkage can eventually lead to an integrative framework for manufacturing system design. The following paragraphs briefly describe a proposed linkage process.

The overall linkage process consists of three steps as shown in Figure 8-2. It is first necessary to translate methods into categories and phases. KOMPASS, for example, distinguishes three categories: work system design, human-machine interaction, and human work tasks. Each of the categories consists of several phases. The phases are then used to associate FR-DP pairs with them. The following paragraphs describe the process by means of the KOMPASS method.

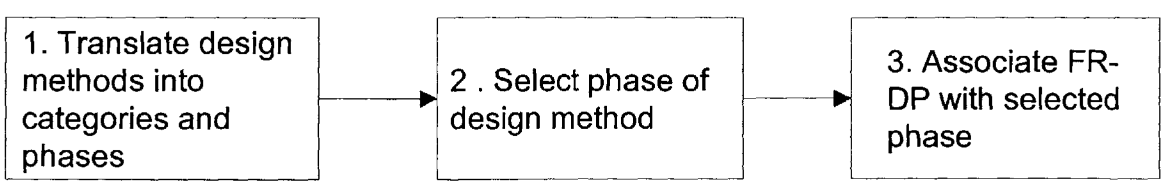
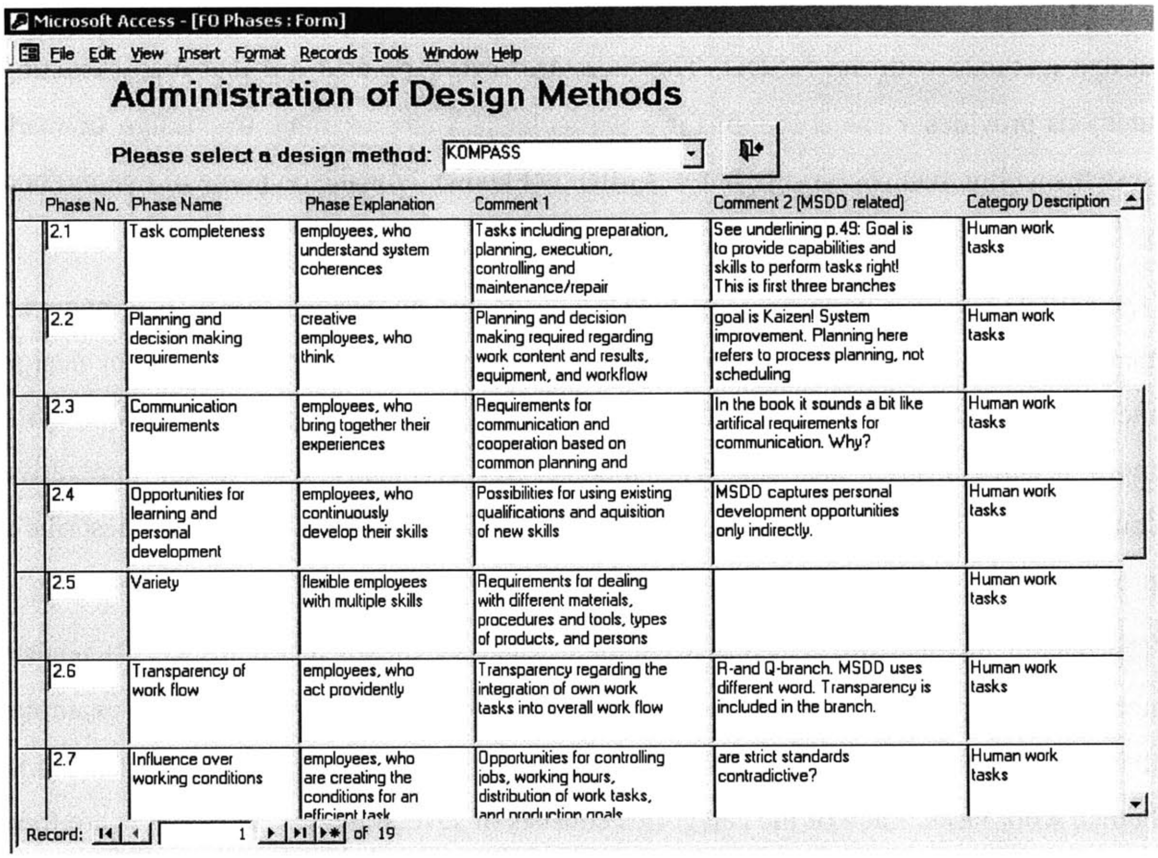


FIGURE 8-2: GENERAL PROCESS OF LINKING DESIGN METHODS WITH MSDD.

Figure 8-3 shows the screen for the administration of design methods. The KOMPASS is translated into categories and phases. Figure 8-3, for example, shows seven phases of the category "human work tasks." Each phase can be explained in detail using the comment fields.



Microsoft Access - [FO Phases : Form]

File Edit View Insert Format Records Tools Window Help

Administration of Design Methods

Please select a design method: KOMPASS

Phase No.	Phase Name	Phase Explanation	Comment 1	Comment 2 (MSDD related)	Category Description
2.1	Task completeness	employees, who understand system coherences	Tasks including preparation, planning, execution, controlling and maintenance/repair	See underlining p.49: Goal is to provide capabilities and skills to perform tasks right! This is first three branches	Human work tasks
2.2	Planning and decision making requirements	creative employees, who think	Planning and decision making required regarding work content and results, equipment, and workflow	goal is Kaizen! System improvement. Planning here refers to process planning, not scheduling	Human work tasks
2.3	Communication requirements	employees, who bring together their experiences	Requirements for communication and cooperation based on common planning and	In the book it sounds a bit like artifical requirements for communication. Why?	Human work tasks
2.4	Opportunities for learning and personal development	employees, who continuously develop their skills	Possibilities for using existing qualifications and aquisition of new skills	MSDD captures personal development opportunities only indirectly.	Human work tasks
2.5	Variety	flexible employees with multiple skills	Requirements for dealing with different materials, procedures and tools, types of products, and persons		Human work tasks
2.6	Transparency of work flow	employees, who act providently	Transparency regarding the integration of own work tasks into overall work flow	R-and Q-branch. MSDD uses different word. Transparency is included in the branch.	Human work tasks
2.7	Influence over working conditions	employees, who are creating the conditions for an efficient task	Opportunities for controlling jobs, working hours, distribution of work tasks, and production goals	are strict standards contradictive?	Human work tasks

Record: 1 of 19

FIGURE 8-3: ADMINISTRATION OF DESIGN METHODS

Figure 8-4 illustrates how FR-DP pairs area associated with the design phases. After selecting a design method (1) the screen shows all phases of the method on the left side of the screen (2). In Figure 8-4, the phase 2.1 "Task completeness" is selected and the right side of the screen shows all associated FR-DP pairs (FR-DP Q121, and FR-DP R1). Additional pairs can be selected to link them with the method phase (3). As a graphical help, the FR-DP pairs are highlighted in the MSDD in the upper right corner of the screen (4). The comment field of the associated FR-DP pairs can be used to explain why the pair relates to the design method.

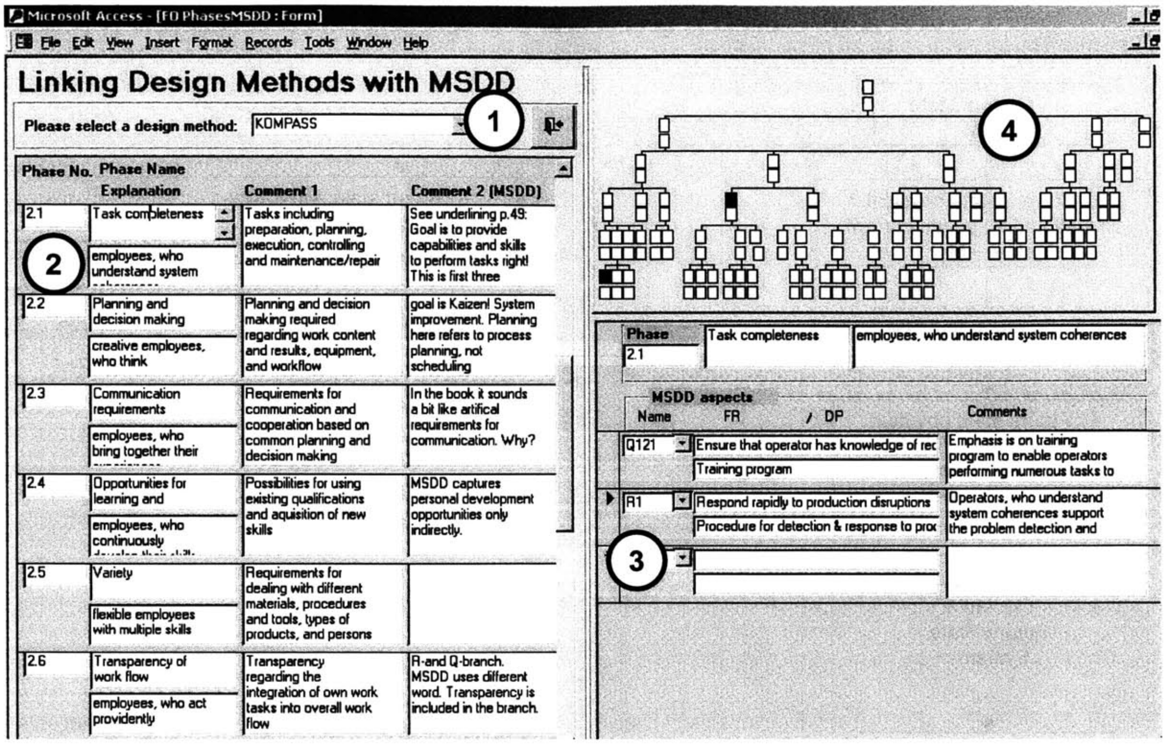


FIGURE 8-4: LINKAGE OF DESIGN METHODS WITH MSDD.

The linkage between KOMPASS and the MSDD enables system designers to apply the steps of the KOMPASS method while still being able to relate those steps to the MSDD and the overall system design. The linkage can also be used the other way around: after determining system design objectives – as done in the application case study – the linkage with other system design methods refers the system designer to tools that can help him achieving the design objectives.

Cochran et al. [2001] have outlined a twelve steps process for redesigning existing manufacturing systems shown in Figure 8-5. The process enhances the approach described in section 6.3 and focuses on necessary steps prior to designing and implementing a manufacturing system. It starts with value stream maps and physical models for the current system and the future state. The process emphasizes the importance to align the performance measurement system with the system design (steps 2 and 11 in Figure 8-5) and the importance of establishing a mental model for all participants of the manufacturing system (steps 6 and 12).

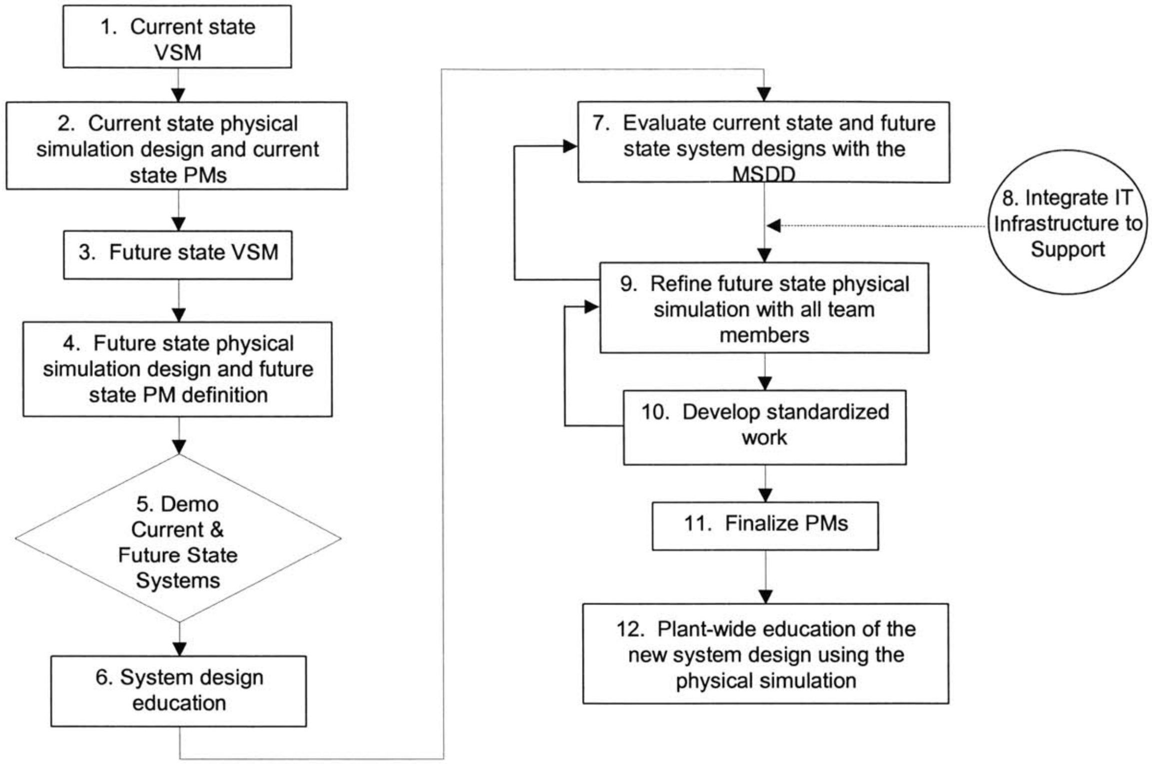


FIGURE 8-5: TWELVE STEPS FOR REDESIGNING EXISTING MANUFACTURING SYSTEMS [COCHRAN ET AL., 2001]

The process has been mapped with the MSDD as shown in Figure 8-6. Six of the twelve steps have associated FR-DP pairs. Steps 1 and 3 refer to Value Stream Mapping (VSM) discussed in section 2.3.3.2. Steps 2 and 4 include aspects of the physical model as described in section 6.3.3. The inclusion of the IT infrastructure in step 8 matches with two pairs: FR-DP P11 "Ensure availability of relevant production information" – "Capable and reliable information system" and FR-DP I2 "Eliminate information disruptions" – "Seamless information flow." However, it must be noted that the integration of the information infrastructure is not fully covered in MSDD and should be examined in more detail in future research. The development of standardized work (step 10) matches with the FR-DP pairs discussed in section 7.2.1.2.

The overall mapping of the twelve step process indicates a focus on quality and delivery aspects of the MSDD (quality, identifying and resolving problems, predictable output, and delay reduction). Direct labor cost aspects become more relevant when the system is implemented and operated. This line of thinking is expressed by the dependencies of the MSDD and is supported by the case studies as discussed in Section 6.6.

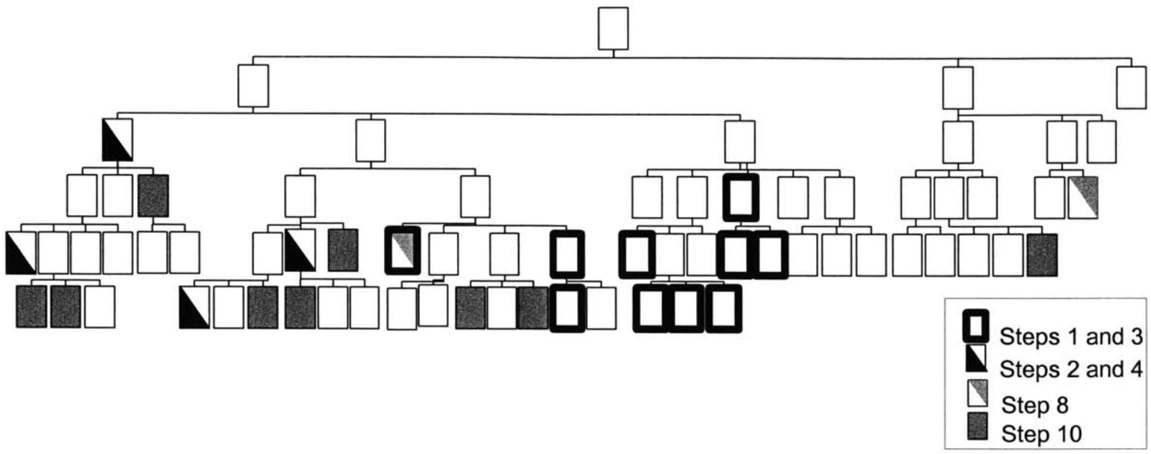


FIGURE 8-6: LINKAGE OF 12 STEPS PROCESS WITH MSDD.

The mapping illustrates that several aspects of the MSDD are not included in the twelve steps process as the process focuses on aspects prior to the actual design of the system. On the other hand, the MSDD does not explicitly include steps such as education (step 6) indicating that a combination of both approaches can be beneficial for system designers.

8.3 Summary

This chapter briefly introduced the MSDD database and its functionality. The database was used to administer and analyze the questionnaire. It was also discussed how the database can emerge into a knowledge database for manufacturing system design by using documentation and analysis functionalities. It was outlined how existing manufacturing system design methods can be linked to the MSDD. The integration of the MSDD with other design methods can greatly enhance the usefulness of the MSDD and offers a wide area for future research as outlined in the following, final chapter.

Chapter 9 Conclusions

9.1 Summary of Work

This thesis presented a decomposition-based approach as a basis for a manufacturing system design framework. The goal of the framework is to provide industry with a structured approach for designing manufacturing systems and to make use of existing methods that support the manufacturing system design task.

The research of this thesis consisted of two main steps: (1) development of the Manufacturing System Design Decomposition (MSDD), (2) validation of the MSDD.

The MSDD was developed in the Production System Design laboratory. The research of this thesis was part of the MSDD development. The MSDD was introduced and discussed. The central premise is that the MSDD expresses the relationships between objectives and means necessary to achieve a manufacturing system that is able to produce high quality products in a predictable and short time period at the lowest possible costs. The MSDD was designed to be applicable to a wide range of repetitive, discrete part manufacturing across industry, manufacturing processes, production volume, and company size.

The second research step validated the MSDD through a multiple-case study approach. Four case studies were performed to test whether or not the MSDD provides a useful framework for manufacturing system design. The research led to the creation of a questionnaire that guided the systematic investigation and analysis of the studies manufacturing systems. The reliability of the questionnaire has been tested successfully with Cronbach's Alpha factor.

The case studies proved the wide applicability of the MSDD. Companies of the case studies represented automotive industry, electronic goods, and industrial goods. The size of the companies varied from less than 100 employees to more than 7,000. Manufacturing processes included injection molding, paint, machining, and assembly. Daily production volume ranged from 100 to more than 7,800 parts per day. The MSDD was equally applicable in all cases.

The case studies supported logical and theoretical replication. It was found that the MSDD showed different results based on predictably different situations. Two companies participating in the case studies were well known for having an efficient manufacturing system design. The evaluation of the system design of those two companies showed high performance relative to the MSDD. On the other hand, two other plants were studied that were known for not having an efficient manufacturing system design. The evaluation of those plants showed a significantly lower performance than the first two plants.

The MSDD proved to be a powerful tool for analyzing the strengths and weaknesses of manufacturing systems. In addition, the MSDD was applied in a design project at a bumper production plant. The MSDD was used to determine project objectives and provided a communication platform for the design team. In another case study, the analysis of two electronic assembly value streams was used to derive an alternative manufacturing system design that could combine the strengths and avoid the weaknesses of the existing value streams. The integration of the MSDD into a cohesive application process, however, remained an open issue and is subject for future research.

Finally, a database was created to provide a graphical user interface for the use of the MSDD, document system design projects and to support the analysis of observations.

The research of this thesis enhanced the credibility of the MSDD as a valuable tool for manufacturing system design. The central premise was supported by the case studies. The questionnaire enabled consistent and reliable data gathering. The research provides the basis for several future research directions as outlined in the next section.

9.2 Recommendations for Future Research Directions

9.2.1 Long-Terms Studies

It is desirable to apply the MSDD in companies that are in the process of redesigning their manufacturing system. The goal is to determine the sequence in which a company improves relative to the MSDD. That knowledge can then be integrated in a design procedure. The United Electric case study discussed how the MSDD could be used to understand the transformation process of the manufacturing system.

It would also be desirable to apply the MSDD in companies that show a medium to good performance. The seven value streams discussed in Chapter 6 were either very good (plant T and UE) or medium to poor. The analysis of a company with a good performance would further enhance the knowledge where companies lack in achieving full conformance with the MSDD.

9.2.2 Performance Measurement

Chapter 6 discussed how defect rate and throughput time could be linked to the MSDD. A formalized linkage between traditionally performance measures (e.g., throughput time) could greatly enhance the use of the MSDD to guide the restructuring of manufacturing system designs. In section 5.3.1, it was argued that the exclusive use of numerical measures should not drive the design of manufacturing systems. Johnson and Bröms [2000] point out that companies are often driven by performance measures that do not improve overall system performance. However, it is a matter of fact that manufacturing are measured based on results. In order to convince those managers that the MSDD can provide a process to improve their performance, it is necessary to show the managers that activities derived from the MSDD will eventually improve their measured performance. If the connection between the performance measures and the MSDD cannot be established, it is unlikely that industry will fully adopt the MSDD.

9.2.3 Determination of Correlations and Dependencies

Chapter 7.3 outlined several ways to clarify and possibly quantify dependencies among FR-DP pairs. The questionnaire offers the opportunity to use statistical analyses for establishing correlations among DPs and FRs. The FR-DP pairs both within the same branch and across different branches. It is recommended to collect data from at least 50 value streams before determining statistical correlations [see e.g., Filippinin et al. [1998] or Sakakibara et al. [1993]).

The questionnaire also allows determining constructs or system design aspects. A construct could be, for example, aspects related to standardized work as discussed in the United Electric case study in section 6.5. Factor analysis could be used to determine such constructs and relate them to other constructs (see for example Sakakibara et al. [1993]).

The constructs could then be used to form groups of questions as used in the electronic case studies in Chapter 6.4 and discussed in Chapter 7.2.1.

Flynn et al. [1990, p. 267] discuss the determination of hypothetical linkages between constructs by establishing a "nomological network" or framework. Based on the nomological network, linkages can be empirically tested. The MSDD already provides such a nomological network which can expedite the establishment of linkages.

9.2.4 Empirical Research in Manufacturing System Design

The MSDD and the questionnaire provide a reliable and powerful basis to perform empirical research in manufacturing system design. Empirical research means "knowledge based on real work observations or experiment" [Flynn et al. 1990, p. 251]. The questionnaire allows relating studies of manufacturing systems in a structured way to the MSDD. The database supports the documentation and analysis of those observations. Most importantly, the MSDD provides a framework to explain the many relationships that exist in manufacturing systems. The analysis of the studies is not limited to forming correlations between questions, but can be put into context with a manufacturing system design framework.

9.2.5 MSDD as Part of Manufacturing System Design Framework

The MSDD has the potential to link existing methods that support the manufacturing system design task. Figure 9-1 illustrates how the MSDD can serve an integrative part of a comprehensive manufacturing system design framework.

The idea is to develop a framework with the MSDD as a centerpiece. Other methodologies are used to solve specific manufacturing system design problems by providing detailed support. The linkage to the MSDD allows relating the outcome of various design methods to each other in order to ensure that using specific design methods does not lead to local optimization of the manufacturing system. Chapter 8 introduced possible ways for the linkage of design methodologies with the MSDD. Further research is necessary to explicitly include the input / output relation of the linkage.

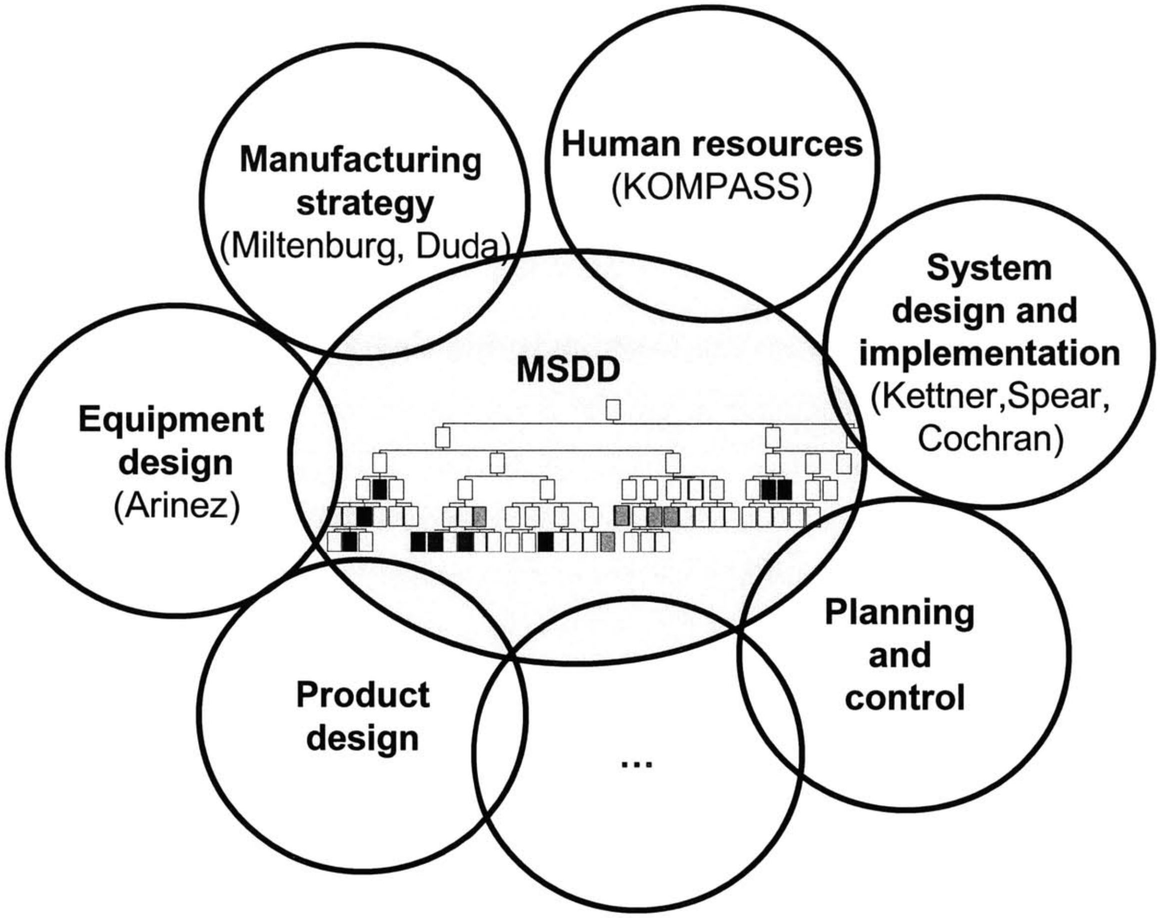


FIGURE 9-1: MSDD AS AN INTEGRATIVE PART OF A MANUFACTURING SYSTEM DESIGN FRAMEWORK.

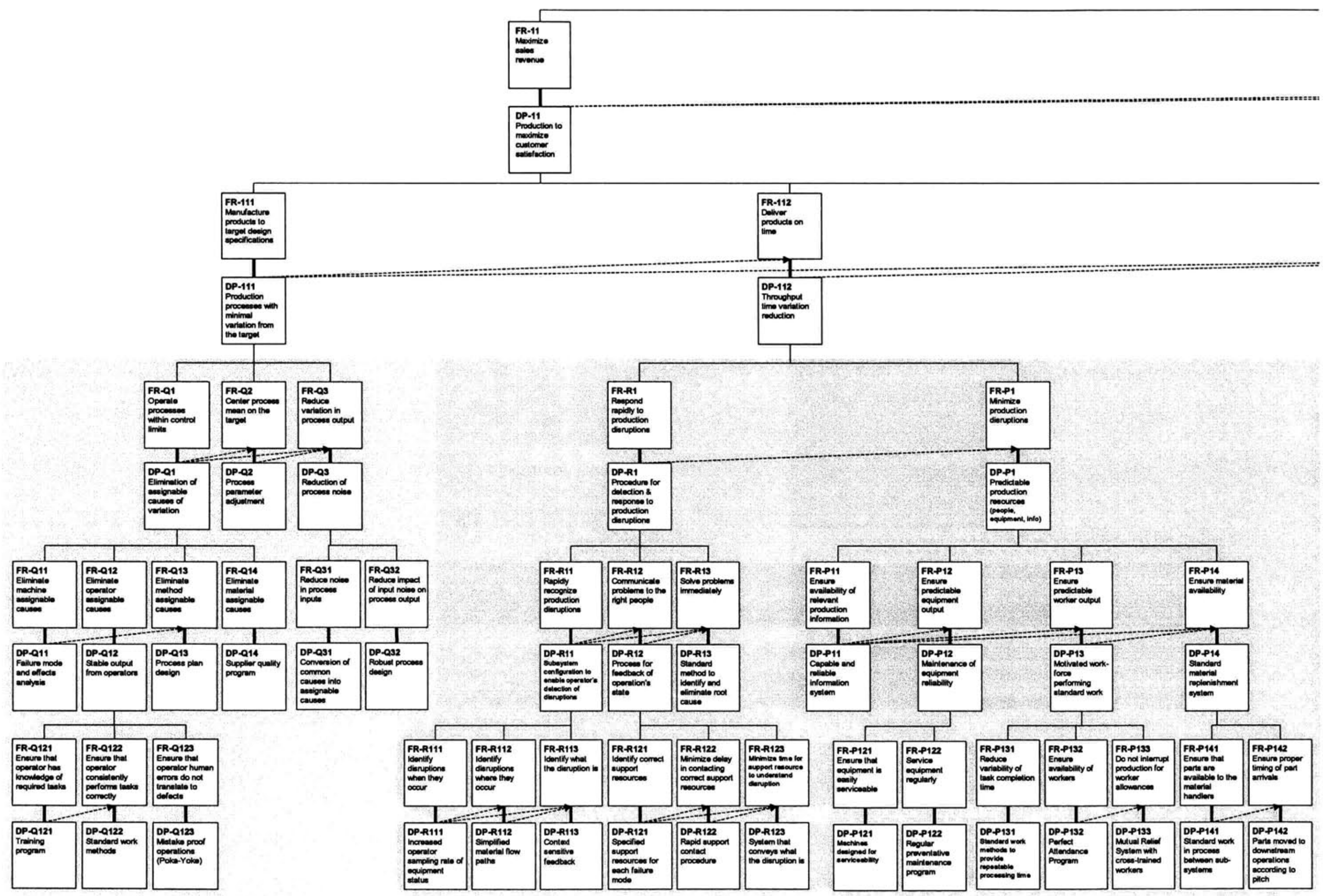
The linkage process has been applied to four design methods: KOMPASS, TPS Rule-based manufacturing by Spear and Bowen, value stream mapping, the Kettner approach for procedural system design, and Cochran's design steps. All design methods and the linkages are documented in the MSDD database. The database can be a helpful tool to integrate the linkages into a comprehensive manufacturing system design framework.

9.2.6 MSDD Database

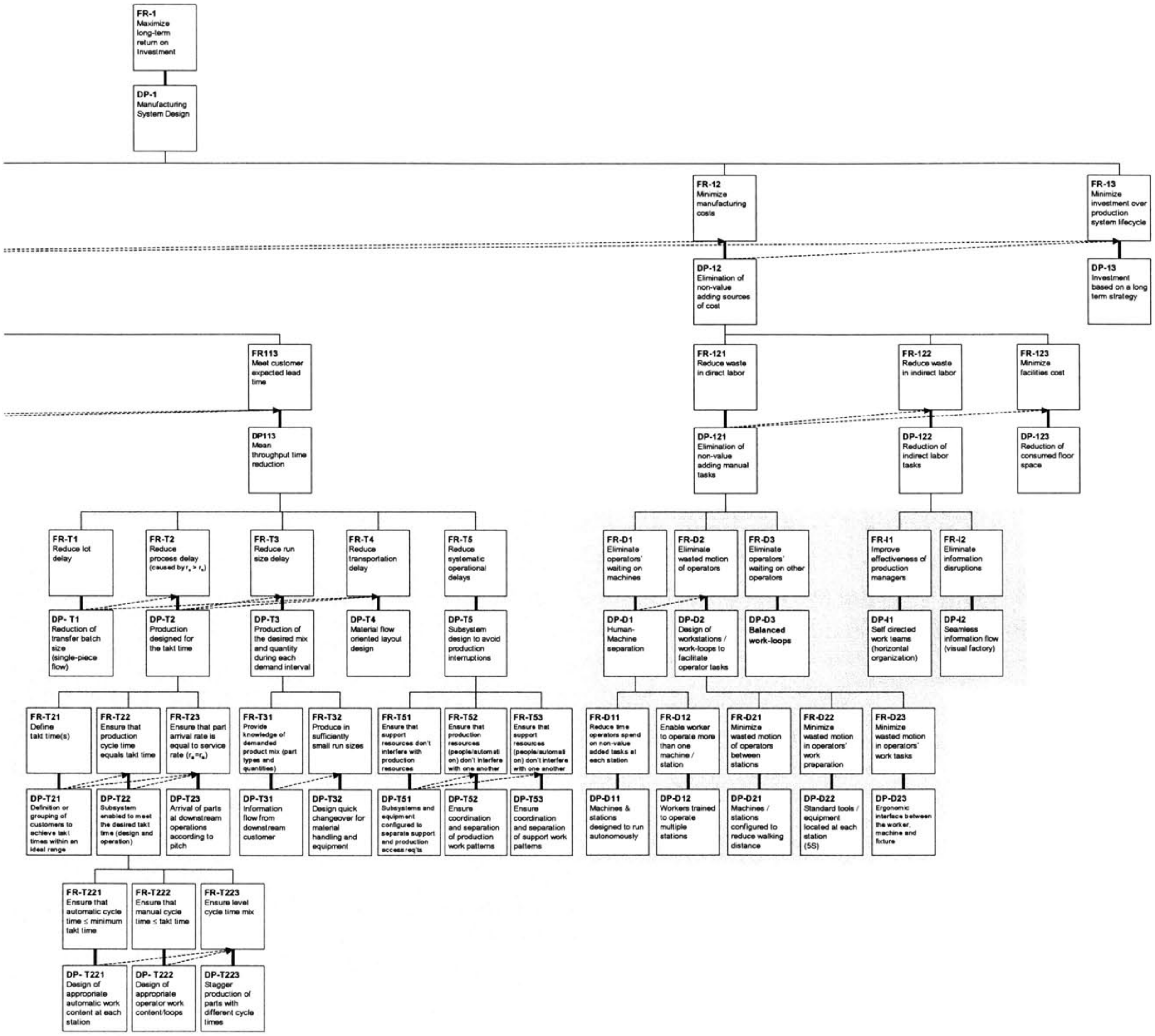
The MSDD database provides a powerful tool for the use of the MSDD and future applications build upon the MSDD. The structure of the relational database allows making cross-case analyses, project documentation, extracting common system design characteristics etc. The ability to record observations and design projects can lead to a knowledge database for manufacturing system design. Industry or company specific circumstances can be considered. It is hoped that the MSDD database will continue to grow in functionality and use in the future.

Appendix A (MSDD)

Manufacturing System Design Decomposition (MSDD) (page 1 of 2)



MANUFACTURING SYSTEM DESIGN DECOMPOSITION V5.1," PRODUCTION SYSTEM DESIGN LAB, DIRECTOR: PROFESSOR DAVID S. COCHRAN, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2000.


FR-1 Maximize long-term return on investment
DP-1 Manufacturing System Design
FR-12 Minimize manufacturing costs
DP-12 Elimination of non-value adding sources of cost
FR-13 Minimize investment over production system lifecycle
DP-13 Investment based on a long term strategy
FR113 Meet customer expected lead time
DP113 Mean throughput time reduction
FR-121 Reduce waste in direct labor
DP-121 Elimination of non-value adding manual tasks
FR-122 Reduce waste in indirect labor
DP-122 Reduction of indirect labor tasks
FR-123 Minimize facilities cost
DP-123 Reduction of consumed floor space
FR-T1 Reduce lot delay
DP- T1 Reduction of transfer batch size (single-piece flow)
FR-T2 Reduce process delay (caused by $r_a > r_s$)
DP-T2 Production designed for the takt time
FR-T3 Reduce run size delay
DP-T3 Production of the desired mix and quantity during each demand interval
FR-T4 Reduce transportation delay
DP-T4 Material flow oriented layout design
FR-T5 Reduce systematic operational delays
DP-T5 Subsystem design to avoid production interruptions
FR-D1 Eliminate operators' waiting on machines
DP-D1 Human-Machine separation
FR-D2 Eliminate wasted motion of operators
DP-D2 Design of workstations / work-loops to facilitate operator tasks
FR-D3 Eliminate operators' waiting on other operators
DP-D3 Balanced work-loops
FR-I1 Improve effectiveness of production managers
DP-I1 Self directed work teams (horizontal organization)
FR-I2 Eliminate information disruptions
DP-I2 Seamless information flow (visual factory)
FR-T21 Define takt time(s)
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
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 ($r_a = r_s$)
DP-T23 Arrival of parts at downstream operations according to pitch
FR-T31 Provide knowledge of demanded product mix (part types and quantities)
DP-T31 Information flow from downstream customer
FR-T32 Produce in sufficiently small run sizes
DP-T32 Design quick changeover for material handling and equipment
FR-T51 Ensure that support resources don't interfere 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
DP-T52 Ensure coordination and separation of production work patterns
FR-T53 Ensure that support resources (people/automation) don't interfere with one another
DP-T53 Ensure coordination and separation of support work patterns
FR-D11 Reduce time operators spend on non-value added tasks at each station
DP-D11 Machines & stations designed to run autonomously
FR-D12 Enable worker to operate more than one machine / station
DP-D12 Workers trained to operate multiple stations
FR-D21 Minimize wasted motion of operators between stations
DP-D21 Machines / stations configured to reduce walking distance
FR-D22 Minimize wasted motion in operators' work preparation
DP-D22 Standard tools / equipment located at each station (5S)
FR-D23 Minimize wasted motion in operators' work tasks
DP-D23 Ergonomic interface between the worker, machine and fixture
FR-T221 Ensure that automatic cycle time ≤ minimum takt time
DP- T221 Design of appropriate automatic work content at each station
FR-T222 Ensure that manual cycle time ≤ takt time
DP- T222 Design of appropriate operator work content/loops
FR-T223 Ensure level cycle time mix
DP-T223 Stagger production of parts with different cycle times

Appendix B (Questionnaire)

FR- Q11 Eliminate machine assignable causes
DP- Q11 Failure mode and effects analysis

- We use cause and effect analysis tools to determine the source of defects caused by machines.
- We keep records of manufacturing defects for every machine.
- We have eliminated most machine assignable causes.

FR- Q121 Ensure that operator has knowledge of required tasks
DP- Q121 Training program

- We have standardized training procedures for each operation.
- Operators know upstream and downstream processes.
- Operators are usually trained on the job. *(reverse)*
- We continuously improve training procedures.

- How many hours does each shop floor operator spend on training per year?
- Are these hours paid?

FR- Q122 Ensure that operator consistently performs tasks correctly
DP- Q122 Standard work methods

- Operators are involved in creating the work methods.
- Work methods have been defined for each operation and contain information about required quality standards.
- A written copy of operator's standardized work is available at each station.
- Variation in quality is reduced either by adjusting the work method or through operator training.
- We enforce that every operator performs the tasks according to the work method.

FR-Q123 Ensure that operator human errors do not translate to defects
DP-Q123 Mistake proof operations (Poka-Yoke)

- Poka-Yoke devices are frequently used to prevent errors.
- We immediately detect defects and do not send them downstream.
- Operators call for help or stop the line when they recognize a quality problem.

FR- Q13 Eliminate method assignable causes.
DP- Q13 Process plan design

- We encourage our operators to improve work methods.
- We have detailed process descriptions for all operations.

FR- Q14 Eliminate material assignable causes
DP- Q14 Supplier quality program

- Quality is our number one criterion in selecting suppliers.
- We cooperate with suppliers to ensure defect free deliveries of parts.
- Incoming material is defect free.

- If you cooperate with suppliers, please describe briefly how you do it?

FR- Q2 Center process mean on the target
DP- Q2 Process parameter adjustment

- Process mean is only set within tolerances, but not necessarily on target. *(reverse)*
- We operate processes on target.
- We continuously monitor processes to check whether they are staying within tolerance specifications (e.g. through SPC).

FR- Q31 Reduce noise in process inputs
DP- Q31 Conversion of common causes into assignable causes

- We have procedures to distinguish between common and assignable causes of variation in process quality.
- Disturbances from outside the process are detected before they can affect the process output.
- We have procedures that enable operators to detect a change in the process inputs rapidly.

FR- Q32 Reduce impact of input noise on process output
DP- Q32 Robust process design

- We have made our processes insensitive to disturbances from outside (e.g. material or environmental influences).
- We have standard procedures to eliminate root causes of quality variation.

FR- R111 Identify disruptions when they occur
DP- R111 Increased operator sampling rate of equipment status

- Machine downtimes are immediately noticed (e.g. through information technology or process design)
- We use devices such as Andon boards or radio communications to signal the occurrence of disruptions.
- Operators can easily see whether they are ahead or behind schedule.
- Variation in work completion time is easily identified.

FR- R112 Identify disruptions where they occur
DP- R112 Simplified material flow paths

- We can always determine which upstream machine is responsible for a defect.

- Process lay out allows immediate detection of disruptions (e.g. downstream operations are quickly starved).
- Machine downtimes can be unnoticed by downstream processes because processes are separated from each other either physically or through large buffers. *(reverse)*

FR- R113 Identify what the disruption is
DP- R113 Context sensitive feedback

- We have standard procedures for determining the root cause of disruptions.
- Our system exposes disruptions and makes them easy to recognize (e.g. accumulating material shows that a production unit is falling behind).
- Breakdowns in equipment are easy to diagnose.

FR- R121 Identify correct support resources
DP- R121 Specified support resources for each failure mode

- We have standard communication paths to contact support staff.

FR- R122 Minimize delay in contacting correct support resources
DP- R122 Rapid support contact procedure

- Our communication devices allow rapid correspondence (e.g. walkie talkies, andon boards).
- Disruptions are quickly conveyed (e.g. by starting an alarm, information technology)

FR- R123 Minimize time for support resource to understand disruption
DP- R123 System that conveys what the disruption is

- We have information devices (e.g. a display at the machine panel), which show the cause of a disruption.
- We document disruptions and create a knowledge base to understand recurring problems.

FR- R13 Solve problems immediately
DP- R13 Standard method to identify and eliminate root cause

- We follow standard procedures for resolving problems.
- We have frequent group sessions where we discuss problems and develop solutions to prevent reoccurrence.
- To keep production moving, we usually solve problems only temporarily. Reoccurrence of the disruption is likely, since the root cause is not eliminated. *(reverse)*
- Operators on the shop floor have the authority to take necessary steps for resolving disruptions.

- How would you characterize your problem solving process? (team based, Kaizen sessions, management driven etc.)

FR- P11 Ensure availability of relevant production information

DP- P11 Capable and reliable information system

- Our operators have access to all information regarding their tasks.
- The operators always understand what to produce, when to produce, and how to produce.
- Operators have easy access to process information.
- We often have production disruptions due to missing information. *(reverse)*

- What information regarding production is most important to you? How do you communicate the information and make it accessible?
- How do operators know what, when, and how much they are supposed to convey, maintain, produce, repair? Please list the main ways to transfer this information.

FR- P121 Ensure that equipment is easily serviceable

DP- P121 Machines designed for serviceability

- We are able to perform standard service checks without interrupting production (e.g. from the back of a machine).
- The ability to easily service equipment determines requirements for its design (e.g. accessibility, controllability, ability to monitor the process, exchangeability of components).
- Repair: equipment is usually repaired by outside contractors or the equipment. *(reverse)*
- Maintenance: our own employees maintain our equipment.

FR- P122 Service equipment regularly

DP- P122 Regular preventative maintenance program

- We dedicate a portion of every day solely to preventive maintenance and follow the preventive maintenance schedule.
- We are usually behind production schedule and have no time for preventive maintenance. Repair is our maintenance. *(reverse)*
- We emphasize proper maintenance as a strategy for achieving schedule.
- Our equipment and tools are in a high state of readiness at all times.

- What percentage of time do you dedicate for preventive maintenance? (time for preventive maintenance / available production time)
- What percentage of time is lost due to unscheduled maintenance? (unscheduled maintenance / available production time)

FR- P131 Reduce variability of task completion time

DP- P131 Standard work methods to provide repeatable processing time

- We time each operating step in detail and include the information in the work instructions.

- Variation in work completion time is being solved either by adjusting the work method or through operator training.
- If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other).
- Work completion time of the same task often varies between operators. *(reverse)*
- There is high variation of work completion time between cycles of the same operator. *(reverse)*

FR- P132 Ensure availability of workers
DP- P132 Perfect attendance program

- Our operators are at their work station, when they are supposed to be there.
- Operators can work ahead of schedule and take an unplanned break. *(reverse)*
- Unplanned absenteeism often affects our ability to produce to schedule. *(reverse)*

- What is your average percentage of absenteeism per year? (only unplanned absenteeism such as sickness, not showing up at work place)

FR- P133 Do not interrupt production for worker allowances
DP- P133 Mutual Relief System with cross-trained workers

- We have standard procedures in place for mutual relief.
- Operator allowances (e.g. for personal hygiene) usually lead to production disruptions. *(reverse)*

- What do you think is important to the operators in helping them produce high quality products? (please circle) Being on a team - being well trained - taking part in designing their workplace - having suggestions accepted - monetary incentives - other
- What of those circled in the previous question is in place? (please circle) Being on a team - being well trained - taking part in designing their workplace - having suggestions accepted - monetary incentives

FR- P141 Ensure that parts are available to the material handlers
DP- P141 Standard work in process between sub-systems

- We have standard levels of inventory between sub-systems for each part.
- Operations are frequently starved due to unavailability of incoming parts. *(reverse)*
- There is unpredictable fluctuation in our inventory levels. *(reverse)*

FR- P142 Ensure proper timing of part arrivals

DP- P142 Parts moved to downstream operations according to pitch

- Our part suppliers deliver on a just-in-time basis.
- The frequency of material delivery is based on consumption as opposed to preset delivery times.
- Part deliveries are independent of downstream consumption. *(reverse)*

FR- T1 Reduce lot delay

DP- T1 Reduction of transfer batch size (single-piece flow)

- The internal transfer batch size is usually larger than 2 hours of production. *(reverse)*
- We usually transport small parts in large containers or large bins. *(reverse)*
- We are transporting standard quantities between operations - i.e. each trip transports the same number or parts).

FR- T21 Define takt time(s)

DP- T21 Definition or grouping of customers to achieve takt times within an ideal range

- We determine takt time at an early stage of a manufacturing system design project.
- We have clear customer - supplier relations throughout the value stream and production pace is based on takt time.

- How do you determine the number of machines for a value stream?
- How do you determine the cycle times for each operation in the value stream?

FR- T221 Ensure that automatic cycle time <= minimum takt time

DP- T221 Design of appropriate automatic work content at each station

- We design our manufacturing processes so that the cycle time closely matches the takt time.
- When automatic cycles time are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two machines performing the same operation).
- We usually try to minimize the number of machines by decreasing the cycle time per machine regardless of takt time. *(reverse)*

FR- T222 Ensure that manual cycle time <= takt time

DP- T222 Design of appropriate operator work content/loops

- We design each operator's work loop to run as close to takt time as possible.
- When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each

operation (rather than having two operators performing the same operation in parallel).

FR- T223 Ensure level cycle time mix
DP- T223 Stagger production of parts with different cycle times

- If a manufacturing unit produces several parts and the parts have different cycle times, we stagger the parts to produce on average to takt time.
- Our run sizes depend on consumption rate not only on the optimal run lot size per machine.
- The team leader or line supervisor is capable of creating a leveled schedule.

FR- T23 Ensure that part arrival rate is equal to service rate
DP- T23 Arrival of parts at downstream operations according to pitch

- We are well balanced across the process flow.
- We use a Heijunka box or some other means to communicate the pace of customer demand into the value stream.

FR- T3 Reduce run size delay
DP- T3 Production of the desired mix and quantity during each demand interval

- We usually meet the production schedule every day.
- We frequently produce more (or less) than scheduled. *(reverse)*
- We frequently produce more (or less) of a particular part type per day than the downstream customer consumes per day. *(reverse)*

- What is your policy in determining run sizes for the different operations?

FR- T31 Provide knowledge of demanded product mix (part types and quantities)
DP- T31 Information flow from downstream customer.

- We schedule only one operation in the value stream. Upstream operations are scheduled based on the consumption of the scheduled operation.
- Most operations are centrally scheduled. *(reverse)*
- We use a pull system for production control.
- Our operators have easy access to the production schedule.

FR- T32 Produce in sufficiently small run sizes
DP- T32 Design quick changeover for material handling and equipment

- We are working aggressively to reduce setup times.
- We have converted most of the setup time to external time while the machine is running.
- We have low setup times for equipment in the evaluated value stream.
- We tend to have large run sizes in our master schedule. *(reverse)*

FR- T4 Reduce transportation delay
DP- T4 Material flow oriented layout design

- We have laid out the shop floor so that our machines and processes are in close proximity to each other.
- The shop floor layout has functional departments.

FR- T51 Ensure that support activities do not interfere with production activities
DP- T51 Subsystems and equipment configured to separate support and production access requirements

- Delivery of material does not interrupt production.
- Picking up outgoing material interrupts production (e.g. due to the need for fork lifts to move large bins). *(reverse)*
- Material handling and transportation equipment does not limit the pace of the production.
- Operators have to leave their work station to pick up new material. *(reverse)*
- Operators frequently perform activities, which disrupt the standardized work. *(reverse)*

FR- T52 Ensure that production activities don't interfere with one another
DP- T52 Ensure coordination and separation of production work patterns

- Operators work loops are laid out so that one operator does not interfere with another.
- The coordination and separation of production work patterns is considered during the design phase - it does not just evolve during operation.

FR- T53 Ensure that support activities (people/automation) don't interfere with one another
DP- T53 Ensure coordination and separation of support work patterns

- The process design ensures that support resources do not interfere with each other.
- The coordination and separation of support work patterns is considered during the design phase - it does not just evolve during operation.

FR- D11 Reduce time operators spend on non-value added tasks at each station.
DP- D11 Machines & stations designed to run autonomously.

- Eliminating non-value added time spent at each station is a priority of station.
- Operators usually wait at a machine until the machine cycle is finished. *(reverse)*
- Machines are designed to eliminate the need for operators to watch the machine.

FR- D12 Enable worker to operate more than one machine / station
DP- D12 Train the workers to operate multiple stations

- The operators are capable of performing more than one task.

- Plant employees are rewarded for learning new skills.
- We rotate operators to other jobs within their subsystem.
- We have a formal suggestion program for all employees.

FR- D21 Minimize wasted motion of operators between stations
DP- D21 Configure machines / stations to reduce walking distance

- When the shop floor layout is designed, equipment and material are placed so as to minimize walking distances.
- We usually arrange equipment first and then consider the work loop of the operator. *(reverse)*
- We design equipment to minimize walking of the operator.
- Most of our operators are bound to one station and do not have to walk at all. *(reverse)*

FR- D22 Minimize wasted motion in operators' work preparation
DP- D22 Standard tools / equipment located at each station (5S)

- We have defined locations for all tools.
- Tools to perform a task are frequently missing. *(reverse)*
- We enforce keeping work stations in clean and orderly condition.

FR- D23 Minimize wasted motion in operators' work tasks
DP- D23 Ergonomic interface between the worker, machine and fixture

- We continuously improve workplace ergonomics by rearranging equipment, tools, material presentation etc.
- We use time studies to update standard work sheets.
- Ergonomic interfaces among worker, machine, and fixture are an important consideration during initial layout design.

FR- D3 Eliminate operators' waiting on other operators
DP- D3 Balanced work-loops

- Balancing work loops of operators is an important system design objective.
- It is often the case that within a team of operators some are idle for part of the cycle, while others are busy for the entire cycle. *(reverse)*
- We often design work loops for one operator independent from work loops of other operators on the same team. *(reverse)*

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