An Equipment Design Approach for Achieving Manufacturing System Design Requirements

by

Jorge Francisco Arinez

S.M., Mechanical Engineering
Massachusetts Institute of Technology, 1995

B.A.Sc., Mechanical Engineering
University of Toronto, 1993

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2000

Signature of Author: ____________________

Department of Mechanical Engineering
May 17 2000

Certified by: ____________________

David S. Cochran
Assistant Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: ____________________

Ain A. Sonin
Chairman, Committee on Graduate Students

An Equipment Design Approach for Achieving Manufacturing System Design Requirements

By

Jorge Francisco Arinez

Submitted to the Department of Mechanical Engineering
on May 17, 2000, in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Mechanical Engineering

Abstract

The use of a structured approach to manufacturing system design is an effective means to improve a firm's overall manufacturing capability. Design of a manufacturing system in addition to defining architecture also includes communicating high-level system requirements to designers of subsystems. An area where clear communication of requirements is particularly critical to system performance is in the specification, selection, and design of equipment. Companies that require new equipment can either buy it from suppliers or build it in-house. Companies that buy equipment must communicate and provide clear understanding of system requirements to outside suppliers to ensure that the equipment designed will perform well within the manufacturing system. Similarly, companies that build their own equipment also need to be able to communicate system requirements clearly to internal designers. These companies often use informal and experience-based methods to communicate and develop an understanding of their system requirements. However, such knowledge and capability is acquired over long periods of time and is difficult to replace or replicate.

Therefore, the objective of this work is to develop an approach that companies can use to obtain equipment that meets their manufacturing system requirements in a manner that is clear, understandable, and applicable whether equipment is sourced internally or externally. As a starting point, this work builds on a recently developed Manufacturing System Design Decomposition (MSDD) that includes high-level system objectives and lower-level equipment design requirements. An Equipment Design Approach (EDA) is then developed that uses the MSDD as a source of requirements. The EDA is comprised of four main steps: identification of the set of manufacturing system requirements that affect equipment design, transformation of the requirements into views for the various types of equipment designers, analysis of requirements, and decomposition of the requirements into equipment design parameters. Details of each step are explained and equipment design examples from compressor manufacturing and setup reduction are presented that illustrate the development and application of the equipment design approach.

Thesis Supervisor: David S. Cochran
Title: Assistant Professor of Mechanical Engineering

Acknowledgements

Since no dissertation is truly the result of a single person's work, I would like to thank the numerous people who have played an important role in contributing to the development of my work. First of all, I thank my advisor Professor David Cochran for the opportunity to conduct research in manufacturing system design. His guidance and support contributed much to both my thesis and learning experience at M.I.T. The members of my doctoral committee, Dr. Whitney and Professor Gutowski were also extremely helpful in clarifying and defining my thesis as well as always being generous with their time. My colleagues in the Production System Design Lab deserve special mention for their support and feedback from the many discussions that helped test my ideas. Also, the sponsorship of United Electric Controls and Visteon Automotive Systems is gratefully acknowledged. The support and access to resources at both of these companies provided me with the tools and test bed to carry out my research. Finally, I thank my family for their unwavering support during my time here at M.I.T. without which my work would not be possible.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

The main problem that this dissertation addresses is the difficulty in communicating requirements between manufacturing system designers and equipment designers. In finding a solution to this problem, this work examines how companies carry out equipment design. Also, equally important is how equipment designers understand manufacturing system requirements. Currently, there are no consistent methods for designing equipment. Companies tend to rely on previous design experience and therefore attempt to adapt equipment to prevailing market conditions. The result is the lack of a strategic and systematic approach to acquiring equipment that meets the needs of a company's manufacturing system. Furthermore, without such a systematic approach, equipment designers cannot acquire a good understanding of the wide diversity of manufacturing system requirements. In this type of design environment, equipment designers can only focus on a single operation instead of viewing the whole system. Thus, design of any piece of equipment without awareness of its effects on other areas of the manufacturing system leads to sub-optimal performance of the system.

The objective of this work is to develop an approach that companies can use to obtain equipment that meets their manufacturing system requirements. To meet this objective, this dissertation develops an equipment design approach that is linked to a recently developed source of manufacturing system requirements. The Manufacturing System Design Decomposition (MSDD) provides a source of requirements and can be also used to improve knowledge and understanding of the system and interactions with equipment (Arinez, 2000). This chapter gives an overview of the MSDD that is formally discussed in this dissertation. Following the MSDD is the introduction of an Equipment Design Approach (EDA) and how it uses equipment requirements that are contained in the MSDD. The approach consists of four steps that are initially presented in this chapter and later described in greater detail. Finally, this chapter presents the research structure used to develop the approach in design cases for compressor manufacturing equipment and setup reduction.

1.1 Industrial Motivation – Approaches to Equipment Design

Companies that seek to obtain equipment suitable for their manufacturing system requirements are faced with a variety of challenges:

- The dynamic nature of product designs with new products continually introduced creates many diverse expectations for the future performance of equipment.
- Since not every manufacturing configuration can be simulated equipment has to have the flexibility to be modified and improved to fit into system. Equipment in custom design situations is a one-of process, with little opportunity for prototyping other than limited run-offs.
- Companies face a sourcing decision in the design of equipment. The management of the equipment design process relies on how well manufacturing system requirements are communicated and understood.

The last point is particularly critical to the successful performance of equipment in the manufacturing system. Since companies are faced with a range of options between purchasing a standard machine and designing a machine in-house the sourcing decision made must correspond to the company's systems knowledge. Fine and Whitney (1996) and Parker (1998) have drawn a parallel between the generation of equipment design requirements and the necessary systems engineering skills to support varying levels of equipment sourcing, shown in Figure 1.1. Whatever sourcing decision the company makes, a systems perspective during the equipment design process is still required. The challenge is therefore to obtain the necessary systems engineering skills by means other than learning to build equipment in-house since not all companies have the luxury or time to develop internal machine tool divisions. An equipment design approach is one means to develop systems skills in the absence of significant internal equipment experience.

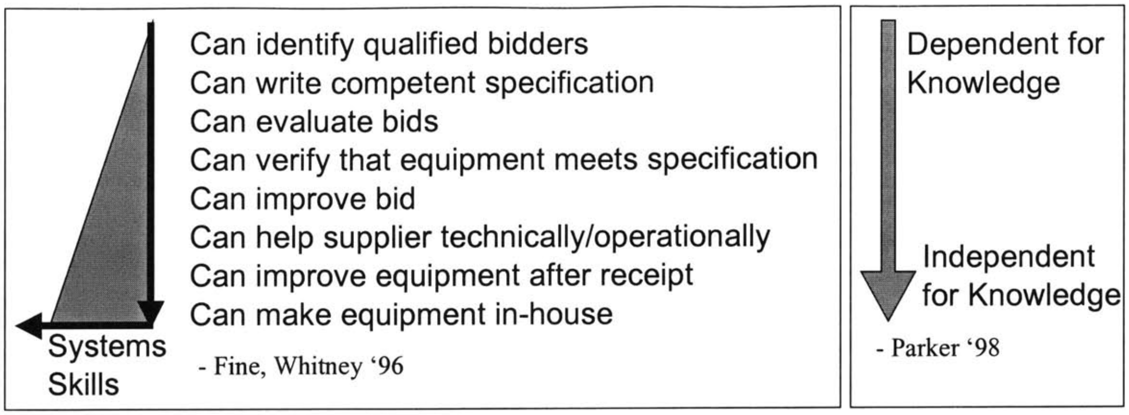


Figure 1.1 Systems skills in equipment design and knowledge dependency on suppliers.

1.2 Manufacturing System Design Requirements

This research builds on a recently developed Manufacturing System Design Decomposition (MSDD) (Suh et al., 1998) by applying it to the design of equipment. The MSDD (Figure 1.2) originated with the application by Cochran (1994) of Axiomatic Design to manufacturing systems. The MSDD incorporates the system level requirements of a manufacturing enterprise that affect decisions ranging from investment in manufacturing resources to the design and operation of these resources. In addition, the MSDD combines high level functional requirements (i.e. maximize return on investment) with lower level subsystem design parameters (i.e. cellular manufacturing, machine and station design). These design parameters represent specific engineering variables or design options that can be varied or selected. The design parameters chosen by product and manufacturing engineers ultimately determine how well the system can achieve product performance, profitability, and customer satisfaction requirements. Furthermore, as requirements are decomposed and refined, design solutions are simultaneously identified.

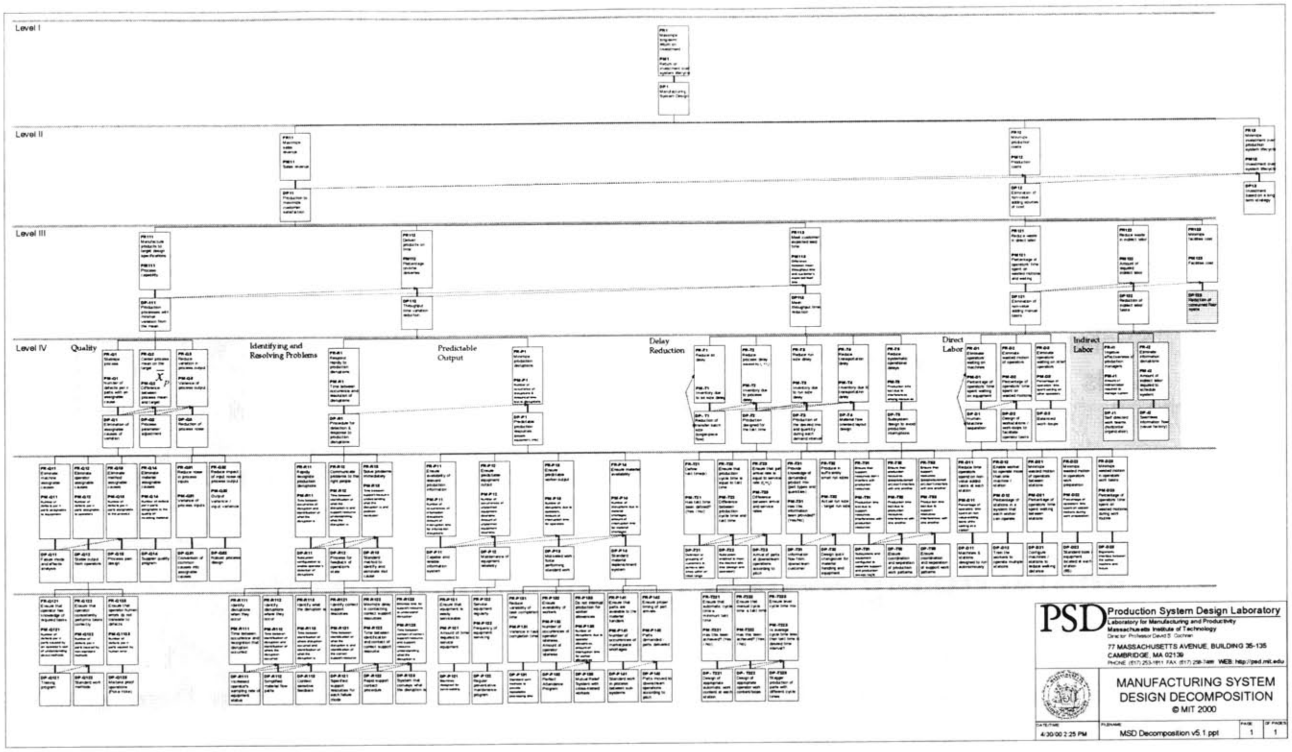


Figure 1.2 Manufacturing System Design Decomposition V5.1 (PSD Lab, 2000).

A further importance of the MSDD is that subsystem designers can check how their own design decisions impact high level goals by providing views of relevant requirements. Views of high level requirements are established in two different ways. The first way is by the use of a flowchart that establishes precedence and allows the design engineer to trace the flow down of requirements. The second way utilizes specific FR-DP pairs from the MSDD to generate sub-FRs for DPs in subsystem design.

1.3 Motivation for an Equipment Design Approach

Although researchers have recognized equipment design strategies that are different across companies and industries, the relation between the design of the manufacturing system and design of equipment has not been as well characterized. Thus, given a company's desire to design its manufacturing system in a structured way and to flow requirements to subsystems such as manufacturing cells, design and manufacturing engineers must then design and select appropriate equipment that will meet these requirements. The key task facing designers is therefore to follow an approach that will yield equipment that satisfies the requirements of the manufacturing system as well as those of the product or family of products. The motivation for this work is therefore to improve the equipment design process by providing better flow of systems requirements (from product and manufacturing engineering) to designers of equipment. One of the challenges in generating a good set of equipment requirements is to distinguish amongst the sources of manufacturing system and product engineering domain requirements. Equipment designers must understand these sources and how requirements potentially can interact with one another. Thus an important aspect of an equipment design approach is that it should permit traceability of requirements at various levels of abstraction. With traceability comes the need for a quantitative expression of the requirements so that performance measurement may be carried out once equipment and system are operational (or ideally as early in the design and modeling stages as possible). An equipment design approach therefore should also have the capability to translate engineering relationships in the form of models into specific parameters that can be used in detailed design.

Thus, a major focus of this work is how to use the MSDD in the context of equipment design. Therefore this work develops an approach consisting of four steps shown in Figure 1.3 to link manufacturing system decompositions to equipment decompositions. The first step deals with identifying the set of system requirements that influence equipment design. Secondly, this set must be transformed into views that permits requirements to be understood by the various parties involved in the design of equipment. The third step is to analyze the requirements according to whether they may be verified during detailed design. The fourth step of the approach is the generation of the equipment design decomposition itself by establishing the FR-DP links between decompositions.

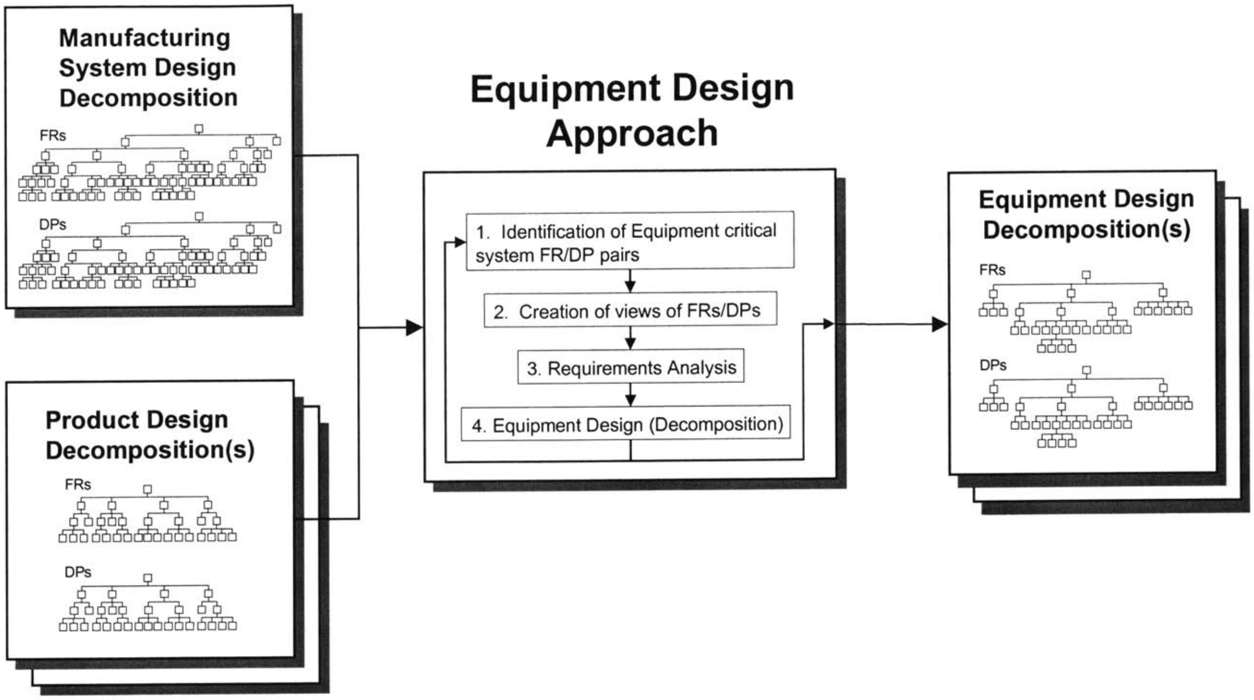


Figure 1.3 Equipment design approach to provide equipment designers with systems view of requirements.

1.4 Organization of Dissertation

The organization of the dissertation (Figure 1.4) reflects the development of the equipment design approach from a manufacturing systems requirements foundation. For this reason, the second chapter first reviews the design of manufacturing systems and different approaches that have been used. A classification scheme is introduced to aid in the characterization of the focus of each approach reviewed. The third chapter describes in detail the recent development of the MSDD and provides new analysis of the structure and the process by which it was developed. This analysis is conducted to better understand the relationship between the MSDD and equipment design. The findings are then incorporated into the development of the Equipment Design Approach presented in Chapter 4. The fourth chapter first reviews a conventional approach to equipment design and the four steps discussed in Section 1.3. Also, a hypothetical equipment decomposition of a CNC lathe is used to develop the approach. The fifth chapter and sixth chapters describe the application of specific steps of the EDA for cases in compressor manufacturing system design and setup reduction tooling design.

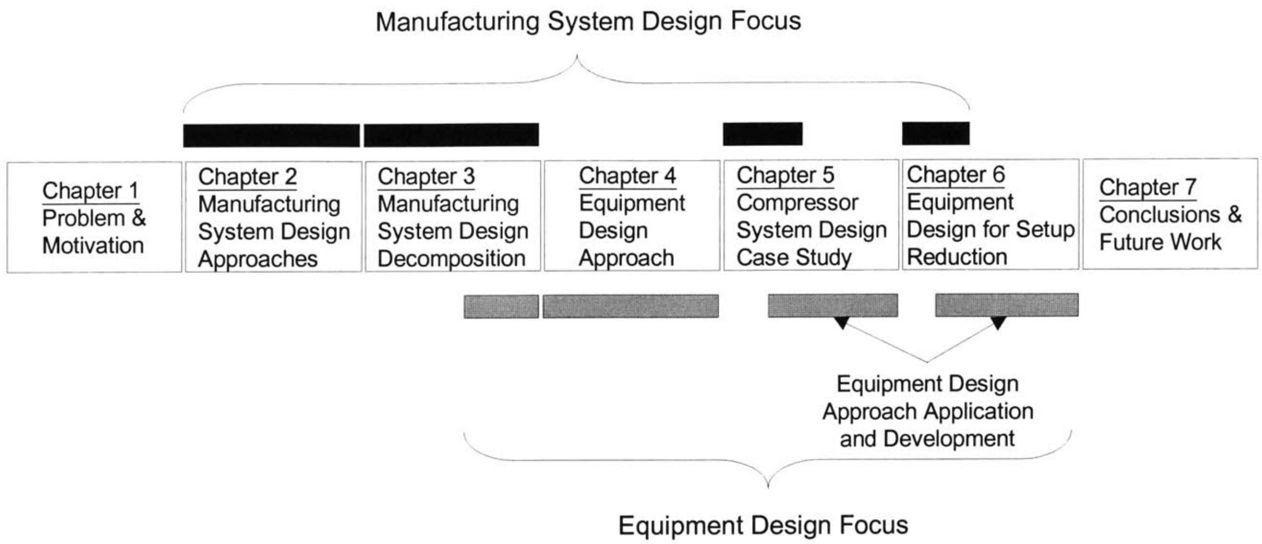


Figure 1.4 Organization of Chapters and Area of Focus.

Chapter 2 Literature Review of Approaches for Design of Manufacturing Systems

2.1 Introduction

The good design of a company's manufacturing system is an important contributor to competitiveness in the marketplace by its ability to deliver high quality products while effectively maintaining low operational costs. However, manufacturing systems continually face new and rapidly changing requirements as customer expectations of product performance, quality, cost, and delivery increase. For these reasons, the ability to design a manufacturing system in a way that carefully and systematically considers all requirements and the ability to continually improve is critical to ensuring a high level of customer satisfaction.

Traditionally, manufacturing systems have evolved as the design requirements evolved. In stable, and slowly varying industries, designers of manufacturing systems have the luxury to experiment and try different approaches until one is found that works. However, iterative design methods are not very successful at keeping pace in highly dynamic industries where product lifecycles are measured in months and production resources quickly become obsolete. Furthermore, manufacturing systems are complex organizations made up of many subsystems that interact with each other and with outside companies, thus there is a further need to design the system so that these interactions are well characterized and understood. Design of one subsystem without awareness of its effects on other areas of the manufacturing system leads to sub-optimal performance of the system as a whole.

To describe these challenges as well as others facing today's manufacturing systems, this chapter reviews basic definitions and concepts as well as approaches that have been developed by various researchers and practitioners to deal with design problems. Then this review establishes the context and the scope of the manufacturing system design approach presented in subsequent chapters.

2.2 Concepts and Definitions in Manufacturing

In defining the term "manufacturing system design," several questions immediately arise, namely: What is a manufacturing system? What does it mean to design a manufacturing system? How does system design relate to manufacturing? Unfortunately, there are many answers that people give to these questions and as a result multiple definitions can be a source of confusion requiring much clarification. For this reason, this section reviews definitions to establish the scope and context for working definitions used in this dissertation. Specifically, distinctions are made between definitions of a manufacturing system, manufacturing system design, and approaches to manufacturing system design.

2.2.1 Manufacturing System Definition

Table 2.1 lists a selection of manufacturing system and manufacturing system design definitions proposed by researchers. The list is by no means exhaustive, rather it gives a view of the many perspectives on manufacturing definitions that exist in the literature. The definitions of a manufacturing system share many similarities. In all cases, the definitions given by these authors share three basic concepts: resources, process, and organization. Resources may be thought of as the elements that make up the infrastructure of the manufacturing system and perform some operation on the product, or they support other resources (e.g. machines, people). For example, in Gershwin's definition (Gershwin, 1994) resources are "a set of machines, transportation elements, computers, storage buffers that are used together for manufacturing." In some cases, such as in Wu's definition (Wu, 1992), resources are implied to be a subset of processes and therefore he does not explicitly state any examples of resources.

The concept of process refers to the transformation of the incoming state of materials and products into a changed outgoing state. Also, process reflects the input/output view of a manufacturing system whose purpose it is to transform incoming raw materials into finished/semi-finished products having a greater value than before. Alting (1994) considers material, energy, and information as inputs and outputs in his generalized model of a manufacturing process (Figure 2.5).

Table 2.1 Definitions of Manufacturing Systems and Manufacturing System Design

Author(s)	Manufacturing System	Manufacturing System Design
G. Chryssolouris	A combination of humans, machinery and equipment that are bound by a common material and information flow.	Mapping of performance requirements (measurables) onto a system description (decision variables).
S.B. Gershwin	A set of machines, transportation elements, computers, storage buffers, and other items that are used together for manufacturing. People are also part of the system. Subsets of manufacturing systems are called cells, work centers or workstations.	The choice of machines, buffers, transport system, computer and communication system, operators, repair personnel, and so forth.
B. Wu	The organized activity devoted to the transformation of raw materials into marketable goods by employing a series of value adding processes.	Application of systems concepts/engineering at conceptual and detailed levels to manufacturing strategy, business systems interface.
D.S. Cochran, P. Lima, N.P. Suh.	The arrangement and operation of elements (machines, tools, material, people, and information) to produce a value-added physical, informational or service product whose success and cost is characterized by the measurable parameters of the system design.	Concerned with the use and provision of the right information to the right place, at the right time, with the right accessibility to control the complex arrangement of physical elements. It defines the information that is required to control the manufacturing system. (Cochran, 1994)
JT. Black	A collection or arrangement of operations and processes used to make a desired product(s) or component(s). The layout of all the processes, equipment, people.	Physical layout of the operations and material flow through the system.
J.L. Nevins, D.E. Whitney	Coordinated sets of machines, processes, products and people.	The series of steps beginning with transfer of product design requirements to fabrication and assembly. This is followed by process knowledge, alternatives, equipment design, and terminating with economic analysis.
J. Parnaby	A manufacturing system is one in which raw materials are processed from one form into another, known as a product, gaining a higher or added value in the process. It should be an integrated whole. It is composed of different subsystems each of which interacts with the whole system.	Consists of five interrelated stages: 1. Subsystem input-output analysis derived from product requirements, 2. Steady-state design using stage 1 specifications, 3. Dynamic design, 4. Specification of data-collection system, 5. Control system design.
K. Hitomi	The conversion process of the resources of production, particularly the raw materials, into the finished products, aiming at maximum productivity. This system is concerned with the flow of materials and constitutes the "production process system".	System design – to construct a new, useful system (static structure and operating procedure) under a specified evaluation criterion by the use of scientific disciplines and empirical laws concerning systems.

Hitomi (1996) refers to "the conversion process of the resources of production", and Wu similarly states "the organized activity devoted to the transformation of raw materials…"

Organization in manufacturing systems includes terms and concepts such as physical layout, arrangement, structure of the combination of resources and processes as well as specification of interactions (planning, control, etc.). The organizational aspect of the manufacturing system is emphasized by Suh (Suh et al., 1998) as the "arrangement and operation of elements", Black likewise calls it "A collection or arrangement of operations and processes…".

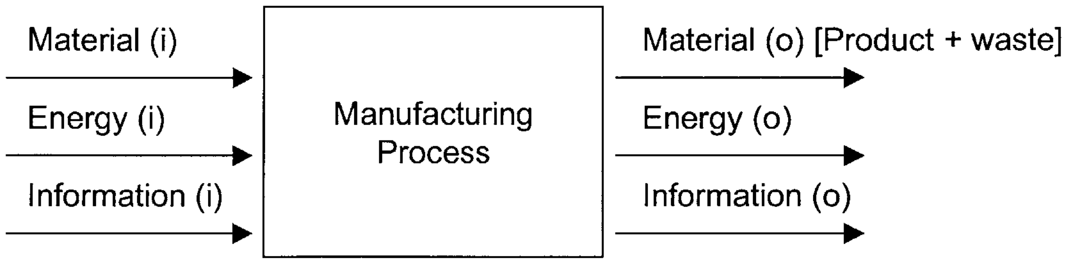


Figure 2.5 General input/output view of manufacturing processes (Alting, 1994).

2.2.2 Manufacturing System Design Definition

The various definitions for manufacturing system *design* listed in the far right column of Table 2.1 show greater variety than those given for a manufacturing system. These definitions can be classified into four broad types (some definitions share the characteristics of more than one type). The first type is concerned with the layout and structural organization of physical elements. Definitions from Black, Chryssolouris, Cochran, and Hitomi belong in this category. For example, Black's definition relates resources and processes by selection of physical layout.

The second type, are those that are procedural in nature, that is, they list a sequence of activities that constitute the manufacturing system design process. Parnaby's description of five interrelated design stages and Nevins and Whitney's flow of product design requirements to fabrication and assembly system design fall under this category (Figure 2.6).

The third type views manufacturing system design as a decision process whereby tradeoffs amongst the variables associated with resources, structure, and processes are made. Chryssolouris describes this as specifying the values of decision variables that comprise the manufacturing system. Gershwin's definition refers to the choice of elements such as machines, buffers, operators, etc.

The fourth type of manufacturing system design definition is one that emphasizes the "system" and aspects that affect the performance of the entire system such as control and information flow. Wu and Hitomi's definitions both make reference to systems engineering approaches to manufacturing system design. Wu considers strategy and other business goals that should be incorporated in system design. Hitomi's definition even goes beyond manufacturing and generically refers to design of a "system." Parnaby includes information and control system design in the fourth and fifth steps of design. The system organization is said to define the information and control requirements in Cochran's definition.

From these four types of definitions, a working definition that is used in this dissertation is that a manufacturing system **design** is the *specification of the attributes* of the manufacturing system, namely the resources, processes, and its organization. All of the definitions describe what constitutes a manufacturing system *design*, however, relatively little mention is given to the *steps* needed to realize a manufacturing system design. Parnaby, and Nevins and Whitney (Figure 2.6) are the only authors in the list that describe a design process by stating the steps involved in arriving at a manufacturing system design.

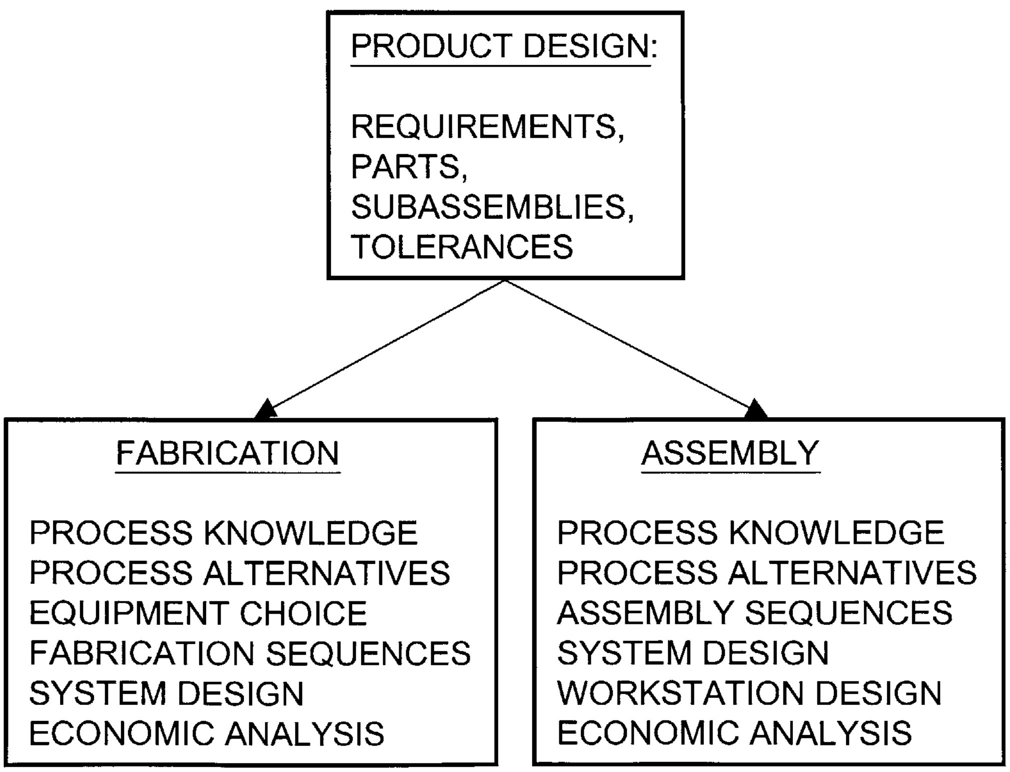


Figure 2.6 Steps involved in manufacturing system design. (Nevins et al., 1989).

The next section proposes a framework for classifying approaches or processes for generating manufacturing system designs. Such a description of the design process is important to guide designers and to help define the relationships between available design tools. The framework uses a basic classification model that describes the elements of a manufacturing system design process. In manufacturing system design there are no unique and universally accepted design approaches. There are only many possibilities and techniques that may be employed to arrive at a properly functioning manufacturing system. This classification model provides a reference for categorizing the various design processes that exist so as to make the selection amongst the available processes easier. The components of the model are subsequently used to review the manufacturing system design approaches in the literature.

2.3 Manufacturing System Design Approach Classification

The next sections will described manufacturing system design approaches, however, this section first gives a classification framework that can characterize each approach according to the activities that are undertaken during design. One way to classify approaches to manufacturing system design is according to the level of system focus and to the design focus of the approach. Doumeingts (1987) has noted the difficulty in categorizing manufacturing system design approaches attributing it to the "lack of formalism and research work". In this work, Doumeingts defines two dimensions in classifying approaches, that of abstraction level (conceptual, structural, and operational) and lifecycle. The difficulty with using these two dimensions is the wide range of levels and time horizons over which an approach may be used. Instead, The manufacturing system design approaches may consist of a combination of one or more of the following three activities: generating a structural representation of the manufacturing system (a model), analyzing the model, and following the steps required to build the model and/or the actual system. These three activities are more succinctly referred to in Figure 2.7 as model building, performing analysis, and method following.

A model here is broadly defined as a representation of the real world manufacturing system. The purpose of such a model is to provide insight and understanding about how the manufacturing system will operate and perform under required conditions (Buzacott, 1993). In the early conceptual stages of the manufacturing system design process, models are especially useful since they provide a view of the system when little concrete information is available. Models help clarify and simplify major issues that must be discussed at a high level of abstraction. In manufacturing system design, models can range from actual physical prototypes of manufacturing resources to mathematical equations representing processes (Askin, 1993).

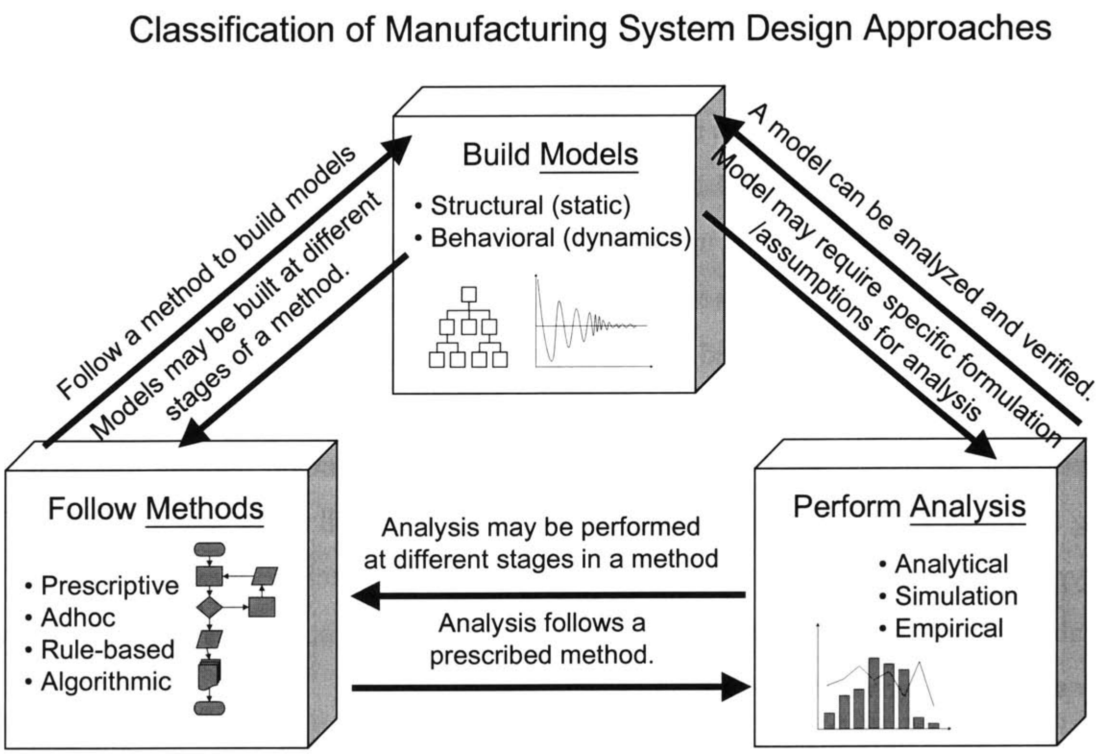


Figure 2.7 Classification framework for manufacturing system design approaches.

There are two basic types of manufacturing system models, structural and behavioral. Oliver (Oliver, 1997) defines this distinction clearly "Behavior is the *what it does* part of the system description, and structure is the *how it is built* part". Model building involves developing the structure to represent the resources and processes that will be used. Also, the model describes how resources and processes are organized and interconnected. A behavioral model contains the description of the manufacturing system's response to stimuli. A basic example of a behavioral model is one that predicts the variation in inventory for a given change in the repair frequency of equipment.

The second type of activity in developing a manufacturing system design is analysis. Analysis is used here to refer to the attainment of knowledge about the performance characteristics of the manufacturing system. This knowledge is obtained by using tools that permit the designer to better understand the structure and behavior of the model. Also, the effectiveness of following one method versus another can also be analyzed with a tool that can test methods. Tools may be thought of as mathematical functions that act on model data (whether structural or behavioral). Some examples of tool usage include the analysis of: facility layouts (structural analysis), part-machine assignments (resource allocation), scheduling and control policies (behavioral analysis), production flow analysis (process analysis), etc. Scheduling and part-machine assignment problems are applications that can be solved with optimization or heuristic algorithms (i.e. tools). Tools may be also based on empirical data obtained from current manufacturing systems or from simulation models.

The third activity that makes up a manufacturing system design process is the following of steps described by a method. A method describes general procedures, rules, or steps that are followed and that have clearly defined tasks that must be performed at each stage in the method. Such general procedures specify precedence and alternate sequences that are possible during the design approach. Methods may be global or local in scope. A method may be followed when designing the material flow through a single production area as well as through an entire factory. A local type of method may be thought of as the rules to design specific assembly cells with high manual labor content. A global method by contrast would be the set of rules to design all of the assembly systems in a given manufacturing system.

Finally, these three activities may be done concurrently in some cases and therefore may be inseparable from one another. For example, a model may be analyzed and thus modified while it is being constructed. Or, in the process of applying a method, different models of increasing detail have to be built at each successive step. Figure 2.7 shows how models, analysis, and methods interact with one another during manufacturing system design.

2.4 Review of Manufacturing System Design Approaches

A review of the field of research in manufacturing system design is difficult without a guide or means to identify the characteristics and contributions of the researcher or designer. Much of the practical and theoretical work that has been conducted in design processes often contains a mixture of modeling, analysis, and methods with varying scope and detail. As a means to organize the literature review, each approach is discussed with respect to its contribution and applicability in each of these three areas.

2.4.1 Manufacturing System Design in Industry

Long before anyone had conceived of the concepts of manufacturing systems and what entails their design, people during the first industrial revolution were dealing with the same basic challenges that face modern manufacturing today, namely, cost, quality, flexibility, and rate. In essence, the first manufacturing system designers were the engineers and tradespeople designing and building the factories that began to appear with the arrival of the first industrial revolution in the mid-18th century. Much has been written (Hounshell, 1984) about the operation and machinery in these early plants. The early designers of these manufacturing systems did not have sophisticated analysis tools nor much experience to draw upon and instead regional peculiarities and prevalence of resources often dictated the type of organization[1]. The system of interchangeable parts pioneered by Eli Whitney (Hounshell, 1984) was a manufacturing innovation that dealt away with the skilled craftsmen of the day with the Springfield Armory being the first modern plant to utilize this new system of manufacturing.

From a scientific perspective it can be argued that early approaches for designing manufacturing systems were developed solely in the factory. This was natural since the best laboratory at the time to study manufacturing problems was the factory itself. Henry Ford made many rapid iterations and refinements as he and his managers implemented the Mass Production System. Further, though many had considered the organizational and management aspects of manufacturing Taylor (1911) was the first to publish and actively promote a science-based approach to manufacturing. In some sense this can be considered the first development of principles to design manufacturing systems not based on previous trial-and-error approaches used in factories.

Industrial and analytical approaches continue to exist as valid approaches to manufacturing system design. Industrial approaches are characterized by solving problems on the factory floor that are real and need to be solved in a timely manner. Analytical approaches though faster once they are developed are not always feasible and their implementation is subject to the firm's resource constraints and to simplifying assumptions. The next section describes the most recent development in modern industrial approaches to manufacturing system design, namely that of the Toyota Production System (TPS).

2.4.1.1 Lean Manufacturing

Lean manufacturing is a term given to a broad set of management and manufacturing methods first used by Toyota to achieve a system for low cost production of automobiles (Womack et al., 1990). There are many names given to the various elements of lean manufacturing ranging from JIT, kanban, poka-yoke, cellular manufacturing, single-piece flow, 5S to kaizen. Many firms, in an effort to emulate the success that Toyota has achieved in manufacturing, have attempted to apply these "Lean" elements to their own operations. However, relatively few firms have been able to reach the level of implementation and refinement that Toyota has demonstrated because the relationships between these elements and the design of manufacturing systems are not well understood.

Toyota uses these elements or in many cases methods to redesign or improve existing facilities. The main principle followed is that manufacturing should be conducted (hence designed) in a manner that minimizes "wasteful" activities. Waste is generally identified as originating from carrying excessive inventory, producing defects, waiting for parts to finish processing, transporting goods unnecessarily, and under utilizing people. An effective method that simultaneously reduces the above forms of waste is to organize physical processes to promote flow of parts from the raw material state to the finished good state with little delay between successive operations. With increased product flow there are less opportunities to be wasteful, moreover it becomes easier to continuously improve processes and relentlessly drive out waste (Kaizen) - a hallmark of the Toyota Production System (Ohno, 1988; Shingo, 1989; Monden, 1993).

Spear and Bowen (1999) write about the difficulty companies have in duplicating the performance of the Toyota Production System. They believe that the reason for this difficulty is that companies mistakenly copy the tools and methods without understanding Toyota's system. Further, they theorize that the system is difficult to understand for outsiders (and hence duplicate) because it is not recorded in any formal or explicit way since the system exists as "tacit" knowledge in the minds of workers and management.

[1] i.e. proximity and use of water power in New England textile factories forced a high degree of manufacturing process integration – a single shaft powered all equipment.

Table 2.2 Representation of tacit knowledge in the Toyota Production System according to four rules proposed by Spear and Bowen (1999).

Rule	Description
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.

Based on their observations from studying other companies that attempt to implement the Toyota production system and from participating in Toyota's Supplier Support Center (TSSC), they conclude that the "tacit" system knowledge can be reduced to four rules given in Table 2.2. They claim these four rules guide the design, operation, and improvement of all of Toyota's activities. Their description of manufacturing system design portrays TPS as a predominantly method (rule) driven design approach. A weaknesses of this "tacit" rule-based approach is that it is takes time to disseminate knowledge in a repeatable manner throughout large organizations.

Another design approach is the precedence of system objectives for implementing elements of the Toyota Production System (Monden, 1993) shown in Figure 2.8. Monden's depiction of many of the elements of TPS is as a bottom-up design approach. Beginning with machine and plant-floor level modifications, Monden's depiction shows how these detailed decisions lead to increased profitability at the company level. Monden's characterization of TPS is also a method-based approach to system design. Specific steps are taken in a predetermined order and integrate the necessary tools and analysis that have to be applied to ensure successful operation of the system.

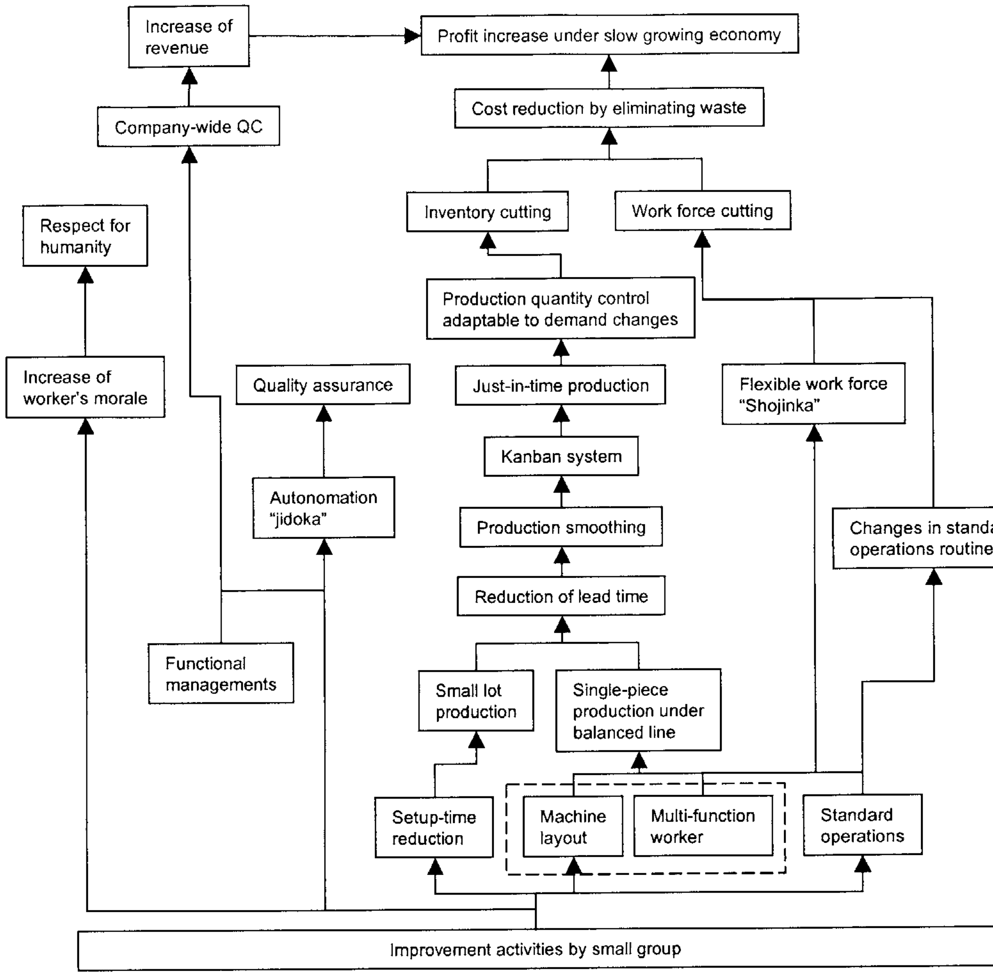


Figure 2.8 How costs, quantity, quality, and humanity are improved by the Toyota production system (Monden, 1993).

2.4.2 IDEF Method

IDEFx is a series of model building and methods developed for the ICAM (Integrated Computer Aided Manufacturing) program of the U.S. Air Force (ICAM, 1981) (IDEF is an acronym for ICAM Definition). Much of IDEF originated with work done by Ross (1977) to develop SADT a structured systems analysis method. The motivation for development of this suite of methods was the need to improve analysis and communication and thereby increase productivity in the aerospace manufacturing industry.

The initial IDEF specification consists of three methodologies: IDEF0, IDEF1, IDEF2 that respectively provide function, information, and dynamic modeling capability for the system design process. Presently, this initial specification extends to $IDEF_9$ and in addition there has been much research to explore enhancements and expansions to the base definition (Al-Ahmari, 1999; van Rensburg, 1995; Plaia, 1995). In particular, $IDEF_4$ is an Obect-Oriented (OO) modeling method (more on OO in Section 2.4.5) that has been developed to combine the existing IDEF system modeling effort with the benefits of OO techniques.

The IDEF0 technique has received a lot of attention because its functional decomposition[2] method is well suited to represent the hierarchical organization of functional departments commonly found in many manufacturing companies. Furthermore, as was discussed in Section 2.2.1, many activities in a manufacturing system may be characterized as having inputs and outputs, thus the basic function building block in IDEF0 modeling (Figure 2.9) is also well suited to describe manufacturing processes. An IDEF0 function block (or activity box) is used to describe manufacturing activities that consist of Inputs, Controls, Outputs, and Mechanisms (ICOMs). A function takes input quantities (which may be information or material) and subject to control conditions, a mechanism transforms these quantities into another form that is output. Also, since functions in IDEF0 are static, they do not imply any time dependence nor frequency of application. Functions at a given decomposition level are connected to each other through the appropriate routing of ICOMs. A by-product of connecting inputs to outputs is that function sequence is built into the decomposition and thus provides precedence modeling capability.

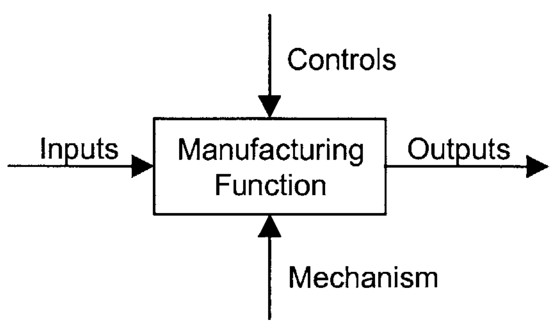


Figure 2.9 The basic building block for functional modeling IDEF0 (Wu, 1992).

Building a functional model of a manufacturing system using IDEF0 can be done in one of two ways depending on the situation. If the manufacturing system already exists, model building is said to be an "AS IS" task that consists of grouping like functions together (based on data gathered about the system) and establishing the correct connections between functions. This is essentially a bottom-up approach that begins with low level processes and continues upwards as functions are aggregated until the highest level process in the manufacturing system is defined.

Alternatively, if a new manufacturing system is to be designed, then it is a "TO BE" design task. Here, a top-down approach is followed that begins at the highest level manufacturing function and the model is continually refined (decomposed) to the required level of detail. An example of a three-level decomposition of a hypothetical three-stage manufacturing process is shown in Figure 2.10.

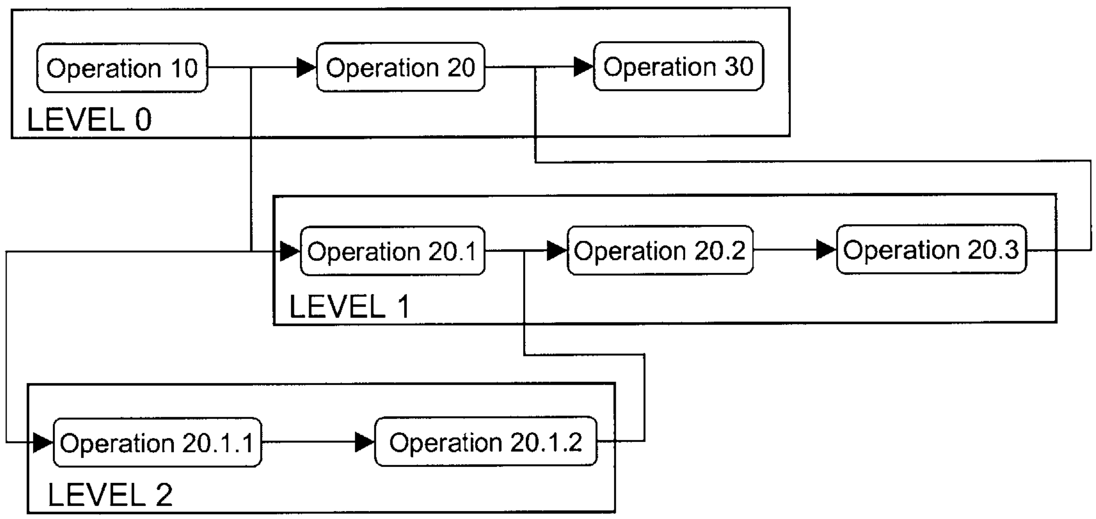


Figure 2.10 Functional decomposition using the IDEF approach.

2.4.2.1 Application of IDEF0 to Manufacturing System Design

Since the specification of IDEF, many researchers have applied it in different ways to design manufacturing systems (DeWitte, 1997; Sarkis, 1995). In particular, Wu (1992) used IDEF0 to generate a conceptual model of a manufacturing system (Figure 2.11) referred to as an Order-Material-Handling-System (OMHS). According to Wu, an OMHS is a make-to-order manufacturing system that depends on specific sales contracts. Wu primarily uses IDEF0 for its model building capability and makes limited reference to analysis that can be performed on each decomposed level of the system. Besides using the general IDEF0 decomposition guidelines, Wu includes methods to be followed as function blocks in the hierarchy. For example, the function

[2] IDEF0 is also reviewed here because it is an alternative decomposition method to that of Axiomatic Design which is employed to decompose the requirements of a manufacturing system design in Chapter 3.

"Prepare Advanced Drawings" represents a sequential procedure consisting of: analysis, synthesis, evaluation, and detailing. This is an example combining model building with method following.

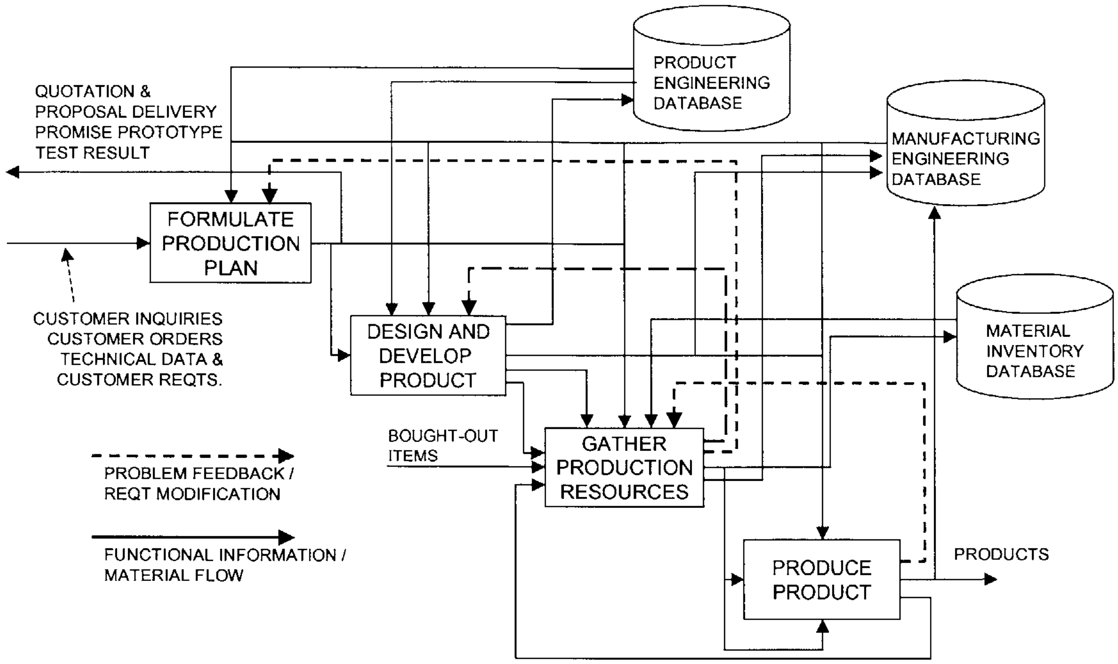


Figure 2.11 IDEF0 model for the highest level of an order-material handling system (OMHS), adapted from Wu (1992).

Bravoco et al. (1985a, 1985b, 1985c) review basic IDEF0 concepts by presenting an example that focuses on the IDEF0's capability to create views of a manufacturing organization. They define a "Functional Architecture" as the set of blueprints, drawings, and specifications that captures a formal definition of a system to produce a product. IDEF0 is defined as the "blueprint" methodology that produces this functional architecture, called a Factory View. These various factory views are reduced to a common representation of a factory that has a structure common to all factories in an organization. This view is referred to as a Composite View (Figure 2.12).

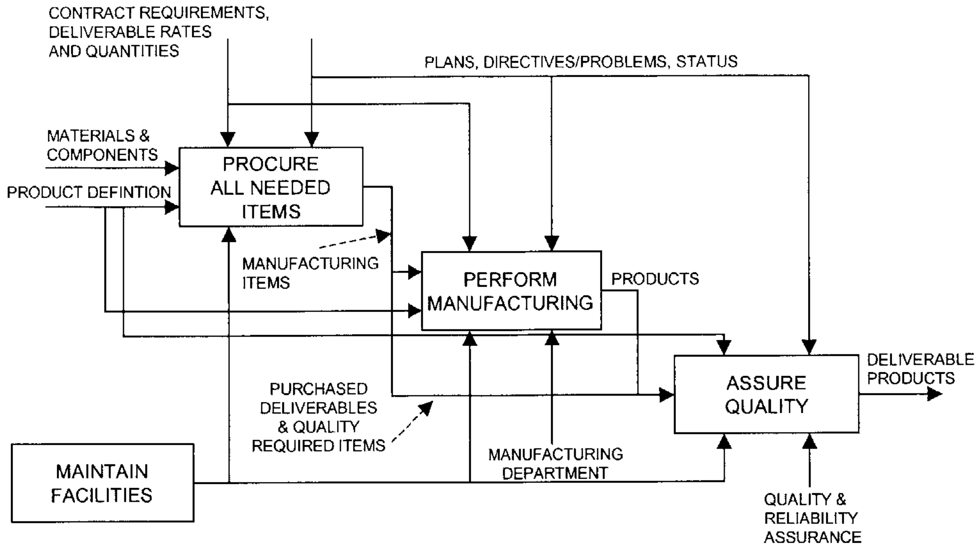


Figure 2.12 Conduct manufacturing operations factory view, adapted from Bravoco et al. (1985a).

2.4.3 GRAI Method

The Graphe a Resultats et Activites Interlies (GRAI) Method was developed for the design of production management with an emphasis on decision making and control activities (Doumeingts, 1987). The method as it is called, consists of a conceptual model for a manufacturing system, graphical tools, and a structured design approach. The GRAI manufacturing system model is subdivided into physical, information, and decision subsystems. The physical subsystem is the collection of physical processes that transform the product from its initial to its final state. The information subsystem links the other subsystems and provides them with their required data. Thirdly, the decision subsystem ensures production objectives are met subject to overall system constraints. The decision subsystem may also be regarded as the control mechanism for the entire physical subsystem.

Two types of tools have been developed for the GRAI Method. The first, GRAIgrid, is a top-down approach used to identify decision centers. Decision centers are functional areas that perform decision and control activities such as forecasting, production planning, purchasing, scheduling. The GRAIgrid graphically establishes a cross-reference between the planning horizons and various production management functions that perform decision and control. GRAIgrid thus gives the connection of information flows and indicates the time dependence between decision centers. The second tool, GRAInet provides a complementary view to GRAIgrid by describing the actual activities that take place in each decision center. However, it is a bottom-up approach (since it uses existing resource information) and also represents the sequence of activities performed by each decision center and its information requirements.

The third aspect of the GRAI Method is a structured approach used to design the manufacturing system. The approach is composed of an analysis phase followed by a design phase. In the first phase, the existing manufacturing system structure and behavior are analyzed for the capability to achieve system goals. During this phase, system requirements are also examined and the GRAIgrid hierarchy is constructed. After the initial analysis has been completed, the design phase takes this data and uses it to create an entirely new or modified conceptual model of the manufacturing system. The design specification phase also determines the behavior of the manufacturing system by using the GRAInet tool to specify the information and decisions for each decision center.

In characterizing the GRAI Method, the conceptual model it generates is at a high level of abstraction and is applicable from initial to detailed design stages of the system lifecycle. However, the actual procedures to obtain the structural and behavioral models are not formalized and not clear in their usage (Wu, 1992). The two GRAI tools are mainly used to support construction of the model rather than to perform quantitative analysis. The primary method is the GRAI structured approach as it integrates the conceptual model as well as the two GRAI tools. Its scope is confined to early modeling and detailed design. Proposals have been suggested that can extend the GRAI Method to include implementation and operation stages of the manufacturing system lifecycle. In summary, the GRAI Method contains aspects of modeling, method following, and analysis, though greater clarification of how these areas are integrated is still needed.

2.4.4 Rao and Gu Methodology for design of manufacturing systems

Rao and Gu (1997) propose a seven step procedure (Figure 2.13) for a manufacturing system design process. It is a serial design process that decomposes each step into sub-design tasks where analysis is performed to generate requirements for input to subsequent steps. The first requirements definition step includes market, product, and manufacturing operations analyses. They do not specify any specific tools that should be taken at each step of their design process, instead they leave these choices to the manufacturing system designer. In terms of the classification framework presented earlier, Rao and Gu focus in manufacturing system design is on method following and model building. The method (the seven steps) has a scope over the entire life cycle of a manufacturing system, but it is at a high level of abstraction.

To address the serial nature of their design process, Rao and Gu present a genetic algorithm (GA) model built to concurrently integrate the requirements generated in each step. They use the GA model of the manufacturing system to configure machines (assign operations and number of operations) and to configure the layout (material handling requirements). The GA uses a fitness function composed of machine utilization and queuing length to specifically determine how many operations are needed overall, as well as the number and types of operations to assign to each machine. A simulation is also built of the system to generate the utilization and queuing data. In this case, the simulation is an example of tool usage to aid in model building and analysis. Thus, this model has an operational level of detail with a scope ranging from machine design to layout design.

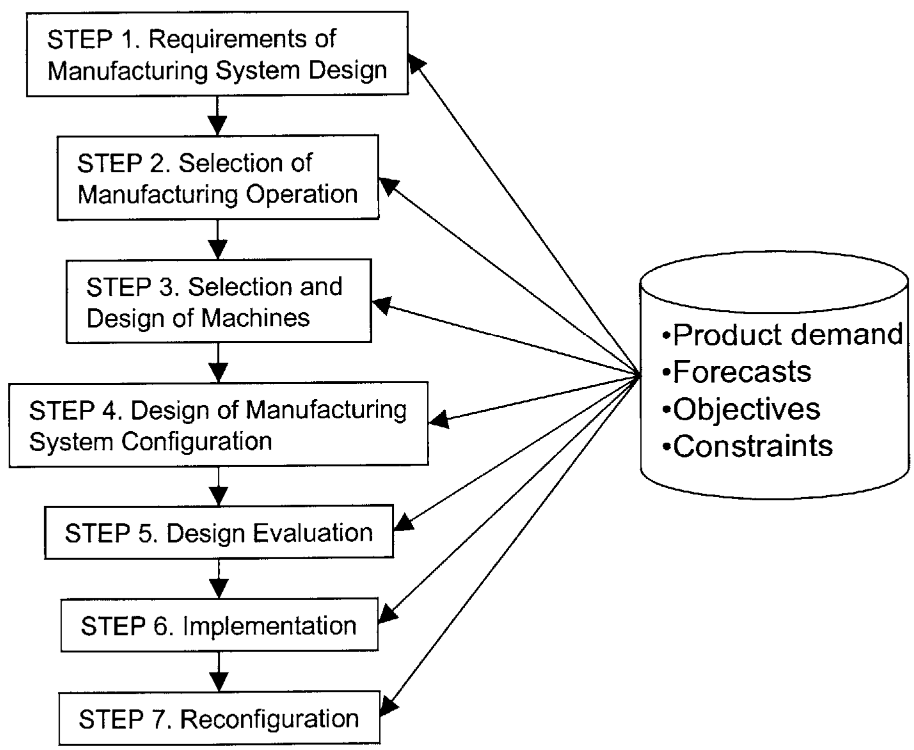


Figure 2.13 Manufacturing System Design Methodology (Rao and Gu, 1997).

2.4.5 Application of Object-Oriented Technology to Manufacturing System Design

The development and subsequent rapid adoption of Object-Oriented Technologies[3] (OOT) in the software design industry over the past thirty years has recently been a source of investigation for use in the design of manufacturing systems. Research in the application of OOT to manufacturing has been facilitated by earlier work in Computer Integrated Manufacturing (CIM) that now provides the information infrastructure required to test and develop models of manufacturing systems based on OOT. The interest by manufacturing system researchers in OOT applications can also be traced to similarities between the design lifecycles of software and manufacturing systems. Software engineers are faced with the same challenges in understanding system goals and analyzing requirements that arise in the initial stages of manufacturing system design.

The defining character of all OO technologies is the use of entities known as objects and groups of similar objects known as classes that combine data structure with that of behavior (Oliver-97). Object and classes of objects are said to possess defining attributes and are capable of performing operations or having operations performed. A direct result of this class structure for object data is the OO concept of *inheritance*. Inheritance is the sharing of attributes and operations in the object class hierarchy. A lower level class (subclass) in the tree is said to inherit the attributes and operations of the higher level class (superclass). Another important feature of OO programming is *encapsulation* (also known as information hiding) which means that objects cannot access another object's internal code. The ability to pass messages between objects in the form of specially defined operations supports the encapsulation of object data by allowing for objects to change state via such messages. It is concepts such as these, namely objects, operations, message passing in OO modeling that have made it attractive in representing the structure and behavior of manufacturing systems.

Unlike the IDEF0 structured approach to modeling manufacturing systems, OO-based models are "mainly" generated bottom-up (though the definition of class hierarchies may be viewed as top-down). This design approach reflects the view that objects are regarded to be more stable than requirements derived by functional decomposition. Coad (1991) has observed that systems design techniques are based on "functional decomposition" or "data". Data-based systems design approaches (such as OO methods) have a focus on the structure and organization of information as well as its flow between system elements. Top-down, functional decomposition approaches begin with an entire system level view that gets increasingly detailed as focus is transferred from high-level system structure to lower level subsystem or component structures. In data driven approaches, analysis and design of the system proceeds from the organization of components to the relationships between components. Thus, it is possible for such data-driven approaches to be combinations of both top-down and bottom-up design. When a known data structure is reused, it can be considered bottom-up design, however, if the system functions are decomposed and then "mapped" to data structures, it is top-down.

The implication of these two approaches is that when designing a manufacturing system, machines may be modeled as objects in a top-down fashion, however, Differences with functional decomposition approaches is that there is independence from and less sensitivity to changes in requirements. With traditional top-down approaches, each time higher level requirements change, the system must be decomposed again. This redesign effort can be quite costly depending on the size of the system. Thus the OO approach seeks to define objects that have greater stability thus enhancing reusability of objects in future modeling projects. The next three sub-sections review approaches that have in some way integrated OOT into a more general manufacturing system design process and have addressed the decomposition approach in different ways.

2.4.5.1 Hierarchical and Object-Oriented Manufacturing Analysis (HOOMA)

Wu (1995) has developed a design process called HOOMA that gives the procedure and tools for building an OO model of a manufacturing system. The procedure incorporates two existing OO design methods (HOOD and OOA; Coad, 1991) and also adds the capability to include dynamics into the description of objects. Also, the procedure attempts to address the inherent hierarchical nature of manufacturing systems with the bottom-up design approach of OO methods. A hybrid approach is used that first decomposes the overall structure of the manufacturing system and then refines it with the identification of detailed objects and classes that are embedded in the structure.

[3] The term "technologies" is used here to represent the many OO modeling methods, analysis, languages, and graphical tools.

Figure 2.14 shows the main steps in the HOOMA design procedure along with the graphical tools that are used at various stages. Once the initial system functions have been decomposed, the procedure is an iterative one that continues until all objects and classes have been identified and the model structural and behavioral models are completed. The functional decomposition of the manufacturing system is represented by a Function Block Diagram (FBD). The FBD is further refined by a Function Subject (FS) hierarchy that provides additional functional details not shown in the FBD.

Once these hierarchies have been generated, a Sub-system Relationship Diagram (SRD) is drawn which depicts the functions from the FBD along with the data flows between functions. The main purpose of the SRD is to identify data flows that correspond to objects and classes by checking which entities are responsible for specific functions in the FBD. Objects and classes after having been identified must be organized into two types of common OO structures. These are the type-of, and composed-of structures for objects and classes. The former as the term implies is a hierarchy of the various forms that instances of objects may assume, and the latter describes the composition of objects and how they are made up of sub-objects. This latter structure is similar to a bill-of-materials for product assemblies.

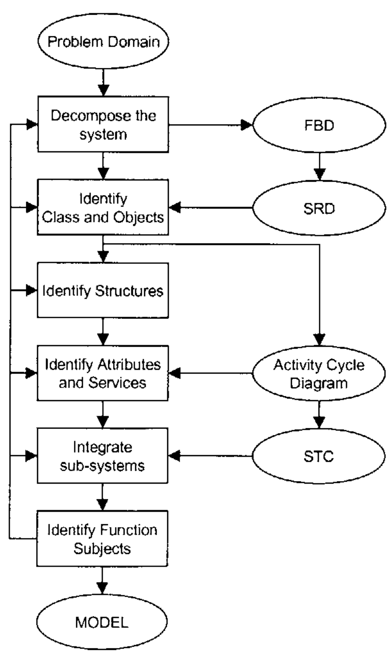


Figure 2.14 Procedure for Hierarchical and Object-Oriented Manufacturing Analysis (1995).

The behavioral (dynamic) model of the manufacturing system is constructed with the use of two more graphical tools called the Activity Cycle Diagram (ACD) and the State Transition

Chart (STC). Activity cycle diagrams are used to describe the interactions between objects and state transition charts. State transition charts illustrate the various states that a given object may be in and how it moves from one to another. Activity cycle diagrams are similar to STCs, however they are different in that they show the state space of multiple objects and their interactions as state transitions occur. The specification of object attributes and operations depicted in the ACD and STC diagrams completes the behavioral model of the system.

In summary, the HOOMA procedure is a method that when followed yields an OO model of a manufacturing system. Therefore, as a manufacturing system design process the major design activity is model building. The graphical tools (FBD, SRD, ACD, STC) are used in the procedure to help build the model. The procedure is applicable from initial concept development to detailed design and from the system to the component level of abstraction. Since it is in development it has not been applied beyond the design stage of the manufacturing system lifecycle.

2.4.5.2 Factory Design Software Environment (FDSE)

Harding et al. (1999) have developed a database driven manufacturing system model called the Factory Design Software Environment (FDSE). The stated objective is to provide designers with "an information-centered range of modeling and evaluation tools to permit progressive design of the manufacturing enterprise." A further motivation for the FDSE is to provide support for enterprise design at the conceptual stage where Enterprise Resource Planning (ERP) systems typically lack do not provide design guidance. The FDSE supports concept design by emphasizing the creation of views that management and designers can share by making use of a database driven manufacturing system model.

The FDSE also avoids use of prescriptive design tools (that are focused only a single aspect of model building) and instead follows a partial, progressive modeling and design approach. The approach has four goals meant to capture strategic intent, capability, organizational structure, and behavior. Also, the approach is an OO-based modeling tool with an interface to a simulation software package. An integration module links all the design tools which managers and designers can use during the factory design process.

Overall, the FDSE is a manufacturing system design process that emphasizes model building. The model of the factory that the FDSE builds is OO-based and is used to generate views for various system designers. Therefore, the structural and behavioral models of the manufacturing system reflect similar characteristics associated with OO models (described previously in Section 2.4.5). Also, the FDSE design process does not specify any formal methods in building the factory model other than those that would be borrowed from OO modeling approaches. In terms of tool usage, the FDSE is limited to an interface with a commercial simulation package. Requirements are an input to the FDSE model, however, no structured approaches are given for handling initial requirements. Finally, though the FDSE proposes a data architecture to represent a general manufacturing system (that is progressively populated), extensive simulation effort is still needed.

2.5 Review of Axiomatic Design in Context of Manufacturing System Design

Axiomatic Design (AD) is a design approach that is reviewed here for two reasons. The first is to review its application to manufacturing system design for the work presented in Chapters 3 and 4. Secondly, AD is reviewed from a pure design theoretic perspective to give the necessary background specifically for the design analysis presented in Chapter 3.

Axiomatic Design developed by Suh (1990) has received a great deal of attention in the academic design theory field with the publication of *Principles of Design*. Prior to this book there were earlier publications in which Suh and co-authors (Suh et al., 1978, 1987) had proposed the use of axioms in manufacturing and design to provide a scientific and therefore rigorous foundation for design activities[4]. In addition to Suh's work, Dimarogonas (1993) provides a historical summary of the development of design theory and methodology[5]. Dimarogonas traces the first statement of design theory to Redtenbacher in Germany who proposed a set of design principles, however, it was his student, Reuleaux who proposed two "ground" rules of mechanical design. Suh in his book not only published two axioms for general design, but in addition several corollaries and theorems to support the design theory. Thus, there is much interest in placing the design process that has long been attributed to craft, skill, and ingenuity on a mathematical foundation with the use of axioms.

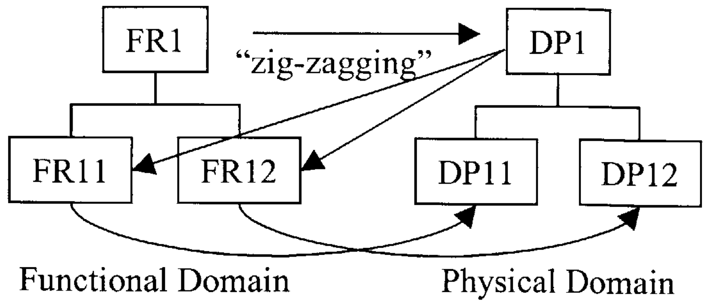
[4] ICAD 2000 is a recent conference dedicated entirely to Axiomatic Design (ICAD, 2000).

The Axiomatic Design literature can be grouped into three different categories with some work belonging to more than one category. The first category is that of work done to develop and address the fundamental statements and methods of axiomatic design theory itself. Since Axiomatic Design is a relatively recent development, it is still being discovered and reviewed by the academic community as well as industrial designers. The second category deals with applications of Axiomatic Design. These works represent case studies where the axioms have been used to solve actual design problems that are frequently taken from industrial situations. This category can be further subdivided into two types of applications, those that deal with classical mechanical design problems and those that attempt to apply axiomatic design in non-traditional design situations. Finally, the third category of literature is work that seeks to combine, augment axiomatic design with other existing engineering design tools and methods.

2.5.1 Review of Basic Concepts

Axiomatic Design (Suh, 1990) is based on two fundamental axioms. The first axiom is to maintain the independence of functional requirements and the second is to minimize the information content of the resulting design solution. The act of design consists of the mapping of functional requirements (FRs) to design parameters (DPs) to arrive at a solution that satisfies these two axioms. Development of a complete design solution proceeds by mapping FRs from the functional domain to DPs in the physical domain beginning from a high, general level to a lower, increasingly detailed level. This decomposition of high level FRs and DPs is a process termed "zig-zagging" where design of products is achieved by moving between the functional and physical domains (Figure 2.15).

[5] Dimarogonas also reviews developments in design beginning with ancient Greek philosophers, the Roman Empire, through to the Industrial Revolution in England.



$$\{FR\} = [DM]\{DP\}$$

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

Design Equation

Figure 2.15 "Zig-zagging" process between functional and physical domains.

In the design decomposition hierarchy, the relations between FRs and DPs are represented in the form of a design matrix *[DM]* with *{FR}* and *{DP}* being vectors. In this form, the design solution can be examined to see whether it satisfies the first design axiom by checking the elements of the design matrix. Depending on how the design matrix is populated, a design may be classified as uncoupled, decoupled, or coupled. An uncoupled design will have non-zero diagonal elements and zeroes for all other elements. A decoupled design has a triangular design matrix and a coupled design has non-zero elements above and below the principal diagonal. The uncoupled design satisfies the first axiom because each FR maps to one and only one DP to maintain functional independence. The decoupled design still satisfies the first axiom because with a triangular matrix, the independence of FRs may be maintained provided DPs are adjusted in an ordered manner such that previously set DPs do not change and thus one FR does not change while another is satisfied. A coupled design exists whenever the adjustment of one DP affects more than one FR regardless of how all the other DPs are adjusted.

2.5.2 Fundamental Research in Axiomatic Design

In the first category of Axiomatic Design literature that contains work to develop and address fundamental statements and methods, Tate (1999) has recently examined the decomposition process and has proposed guidelines to aid the designer. He defines activities in the decomposition process that include definition of sub-FRs, physical integration of DPs, inclusion of constraints at each level, maintaining consistency between levels, and rules for guiding the design process itself. Furthermore, he identifies inconsistencies that may arise in sub-FRs, sub-DPs and elements of the design matrix between levels. In particular, inconsistent sub-DPs are those that violate the independence axiom at higher levels by how they are physically integrated.

Tate's work also provides a thorough coverage of potential difficulties that can arise and the guidelines offer help to the designer following the decomposition process. However, Tate does not address issues in semantics that often give rise to these inconsistencies.

Clausing (1989) reviews the Axiomatic Design decomposition process and specifically examines the one-to-one correspondence between FRs and DPs. He observes that there are potential cases where functional decomposition may take place without a corresponding decomposition in the physical domain. Such possible decomposition patterns can create confusion for designers following strict decomposition methods (i.e. zig-zagging). Clausing also states that the verb-noun form for stating FRs can limit designers in expressing modifiers for more complex FRs. Another issue raised as being potentially disconcerting to Axiomatic Design practitioners is the existence of disparate entities on the same level, and similar entities on different levels. Clausing proposes functional requirement amplification sub-trees that can refine generally stated FRs by immediate decomposition without moving to the physical domain. Thus, Clausing's work represents important research that can advance fundamental Axiomatic Design theory.

Other researchers that also examine fundamental Axiomatic Design theory issues are Vallhagen (1994) and Sohlenius (1992). Specifically, Vallhagen applies process planning in Axiomatic Design to "complex" products and the subsequent design of the manufacturing system. Similar to Clausing's work, Vallhagen also observes that a one-to-one correspondence between DPs in the physical domain and PVs in the process domain is not consistent if DPs are not entirely made up of physical elements. Vallhagen suggests the use of an additional domain called the Process Requirement Domain (PRD). A PRD was first proposed by Sohlenius (1992) to go from product design (PD) to manufacturing system design (MSD) (Figure 2.16). Vallhagen uses the PRD but also partitions the MSD domain into five spaces: Parts manufacturing, Material handling, Integration/control, Assembly, Human factors. Despite the emphasis on the manufacturing world, Vallhagen's AD process planning applications do not give an integrated view of a manufacturing system. Therefore, there exists the potential for inconsistency in design matrices between domains in the absence of an integrating manufacturing systems hierarchy.

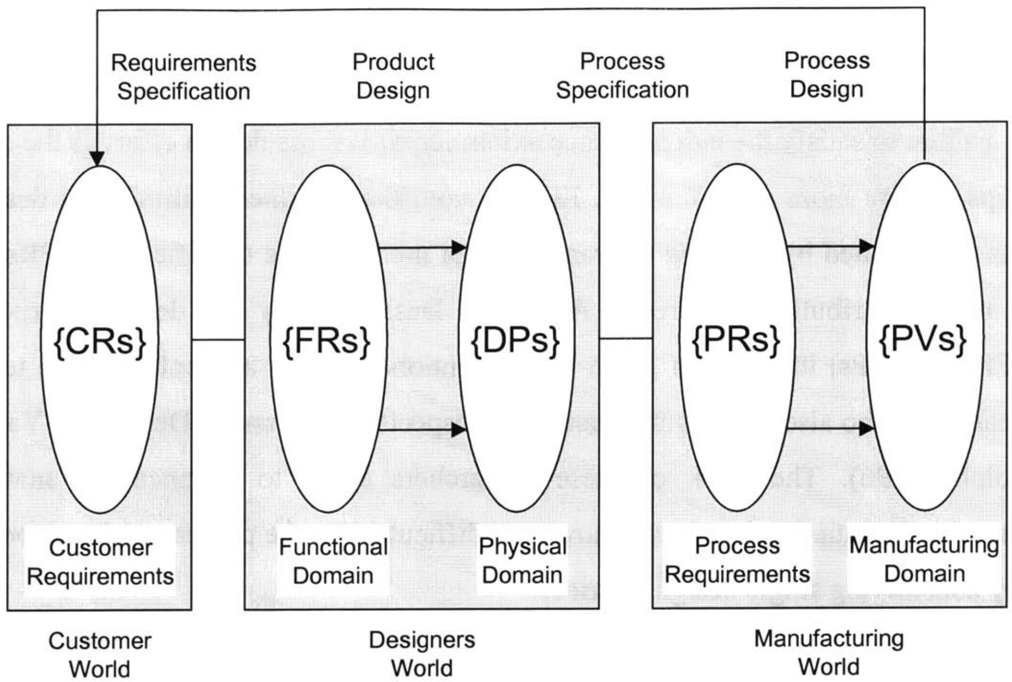


Figure 2.16 Addition of the Process Requirements Domain (PRD) to Suh's four Axiomatic Design domains by Sohlenius (1992).

2.5.3 Extensions to Axiomatic Design

In an approach to extend Axiomatic Design, Bascaran and Tellez (1994) propose enhancing Quality Function Deployment (QFD) by application of the independence axiom. The motivation for the enhancement is based on observations of inconsistent design views between QFD and Axiomatic Design. The main difference is that QFD gives tools for understanding coupling in designs, whereas Axiomatic Design seeks to eliminate coupling. Bascaran et al. suggest separating functional requirements from customer requirements and then applying the first axiom to derive corresponding design parameters. The design parameters may be then related to customer requirements by weighted interaction relationships according to standard QFD factors. In this way, the QFD relationship matrix is augmented by an axiomatic design matrix in the house of quality. This enhanced approach to QFD then offers the ability to highlight coupling via AD. However, FRs and DPs are only derived for the current level of interest that the house of quality considers and does not address decomposition of sub-FRs.

In contrast to the above approach to link QFD and AD, El-Haik (1999) examines the relationship between tolerance design and AD and the further relation to Robust Design methods.

El-Haik makes the link by using non-linear optimization methods to assign optimal tolerances to DPs and incorporates the first and second axioms in the formulation of constraints and cost functions. Failure to satisfy the independence axiom requires more design effort as the dependent relationships require more control effort. El-Haik considers "vulnerabilities" in a design when the axioms are violated by deriving tolerance design models for a specific set of FRs. Overall, El-Haik's main contribution is to recast Axiomatic Design theory (i.e. design matrix relations between FRs and DPs) into a form given by conventional quality and optimization techniques. Other researchers who also investigate quantitative aspects of Axiomatic Design are Yang (1998) and Rudolph (1996). The work of these researchers seeks to advance the mathematical foundation of Axiomatic Design theory, however, difficulties in the process of decomposition are avoided by considering single design matrices.

2.5.4 Applications of Axiomatic Design

Cochran (1994) applies AD to manufacturing system design and control and proposes an alternative formulation of the four AD design domains. Figure 2.17 shows that the replacement of the physical and process domains with Information and Manufacturing domains. Within each domain there are FRs, DPs and SVs (System Variables) corresponding to increasingly detailed levels of decomposition within each domain. In particular, the information domain proposes that DPs need not be strictly physical entities. Cochran applies this manufacturing system representation of AD in the context of three manufacturing systems, the armory system, the Ford production system, and the Toyota Production System and proposes FRs, DPs, and SVs for each system. Sohlenius (1992) had earlier proposed a similar view but with less detail of potential design parameters and process variables for the manufacturing system domain.

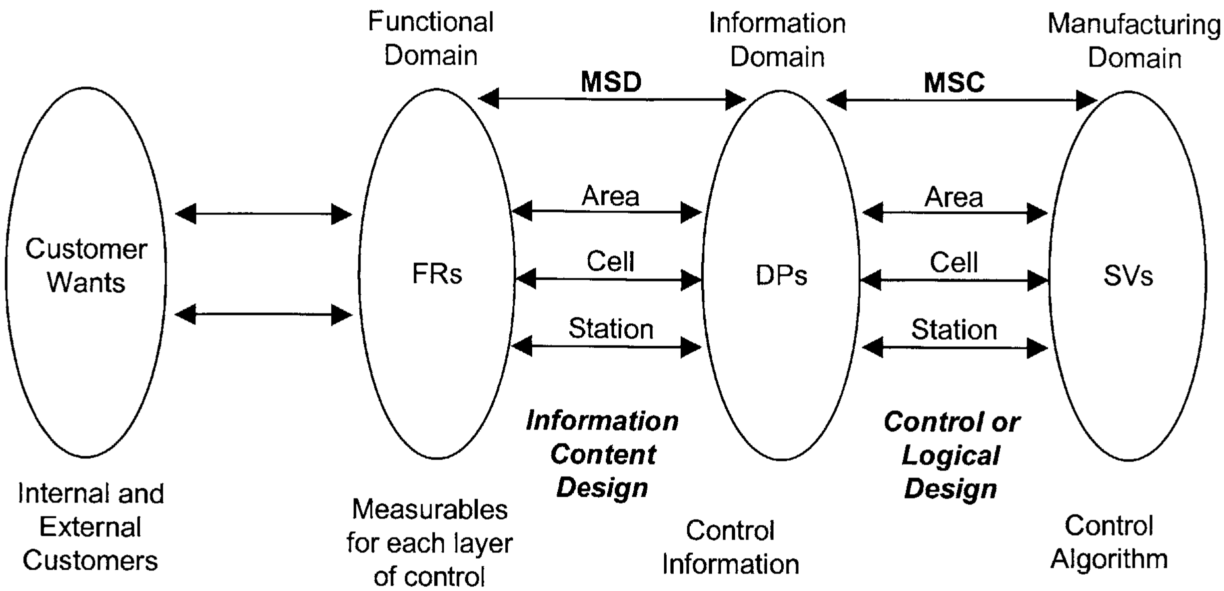


Figure 2.17 Process for Manufacturing System Design and Control (Cochran, 1994).

Babic (1999) proposes a FMS design methodology based on AD and applies it to analysis of a manufacturing process plan to be produced in an FMS system. The methodology proposed incorporates "intelligence" via a knowledge-based programming environment. The methodology uses a previously developed process plan as an input and various AD corollaries to the axioms as "rules" in the knowledge base. One of the corollaries is Corollary 3 – Integration of physical parts. However, the use of this corollary is unclear since the previously derived manufacturing process plan is used as the set of functional requirements. Babic uses FRs such as machine type, accuracy, roughness, removal volume and DPs machine name, number of machines, machine accuracy, max part volume, machine power, hourly machine cost. He calculates the information content for geometrical accuracy, surface quality, manufacturing capacity, manufacturing costs and uses the information axiom to compare alternative designs. The final result of solving the design equations is the selection of machines and production schedule. He comes up with a knowledge module that performs the mapping process and generates the resulting design matrix – "knowledge-based generation of the design matrix".

2.6 Chapter Summary

This chapter introduced basic manufacturing system and manufacturing system design definitions. The distinction was drawn between a design, and a process for obtaining a design.

Though there are many definitions and design approaches, there is little agreement on which approach to follow. To examine the different proposed design approaches, a classification framework was presented that classifies an approach based on its focus in the areas of method following, model building, and analysis. These three categories used to classify the different approaches were derived from studying the objectives that each approach seeks to achieve.

Use of the classification framework indicated that the industrial design approaches were largely methods-based. More theoretical and abstract approaches such as IDEF and GRAI were heavily focused on building structural models of the manufacturing system. In cases where there was analysis there was little relation to the methods used to perform the analysis or to build analytical models (i.e. Rao and Gu). Finally, few approaches fell under all three categories, indicating a lack of integration in manufacturing system design. The next chapter presents a manufacturing system design decomposition that offers an integrated view of a manufacturing system's requirements and specifies activities belonging to each one of the above classification categories.

Chapter 3 The Manufacturing System Design Decomposition

This chapter introduces the development of the Manufacturing System Design Decomposition (MSDD). The motivation for its development is to provide a tool and a method to guide the initial concept design phases for manufacturing systems from the statement of high-level business objectives to translation into detailed design requirements. In this chapter, the basic assumptions and the scope of the MSDD are stated. In addition, a classification technique based on the parts of speech is used to identify decomposition patterns and structural characteristics of the MSDD. Furthermore, the high-level objectives are described in detail to provide an overall view of the decomposition as it is used in subsequent chapters for subsystem design (i.e. equipment).

3.1 Objectives for the MSDD

The design of a new manufacturing system or redesign of an existing one begins with a statement of business objectives that should be fulfilled. These business objectives must be satisfied by any investment made into manufacturing resources. The challenge of designing a manufacturing system is to meet a diverse set of requirements that are rapidly changing and highly uncertain in the concept design phase (Oliver, 1997). The main purpose of the MSDD is to provide understanding of these requirements at the concept design phase when the relationship between structure and expected performance is both unclear and uncertain. Thus, the three main reasons motivating the development of the MSDD may be summarized as follows:

(i) To provide a ***structured*** approach for the design of manufacturing systems.

(ii) To provide ***understanding*** of the many interdependencies that arise between the elements of manufacturing systems.

(iii) To provide a means to ***relate*** high level requirements of the manufacturing system to the design parameters/attributes of its constituent elements.

First, a ***structured*** approach is one in which high-level goals are allocated and decomposed to the constituent elements of the design in an organized manner according to specific procedures (INCOSE, 1998). In the case of the MSDD, the approach is top-down and follows the design procedure specified by Axiomatic Design (see Section 2.5). A structured design approach supports generation of a clear representation of the manufacturing system requirements. The top-down approach decomposes high-level, general statements of requirements into more specific requirements that are more easily understood by system designers.

Second, manufacturing systems consist of many subsystems that interact with one another. In some cases, people must operate and manage these subsystems even though there may be many external interactions with other companies beyond a firm's own immediate manufacturing system. Nevertheless, during design of each of the subsystems, there must exist knowledge of how any given subsystem affects and is affected by other subsystems. To ***understand*** how the system as a whole will function, knowledge of these subsystem interdependencies is required. The decomposition specifies the dependent relations between subsystems via design matrices. Detailed design and engineering involves precisely determining these relations either analytically or empirically.

Third, for any manufacturing system design to successfully meet its business objectives, the objectives must be related to each lower level. With such decomposition relations between levels of objectives, designers at any given level of detail may see how design decisions influence attainment of high-level objectives. Therefore, the decomposition may be understood by anyone in the manufacturing organization from the vice-president of manufacturing operations down to the manufacturing engineer and manufacturing supervisor. Knowledge of decomposition relations is provided to designers in the form of inheritance relations (i.e. parent-child associations). Such parent-child relations give designers traceability of requirements through the properties of directed tree structures.

3.2 Prior MSDD Work

The manufacturing system design decomposition presented in this chapter was initially based on work by Cochran (1994). This earlier version of the MSDD was initially generated in an effort to organize (and thereby explain) the various operationally successful elements of the Toyota Production System (Ohno, 1988). This decomposition also built on the previous work of Reynal (1998) and Charles (1997). Reynal applied axiomatic design to a job-shop manufacturing system and Charles examined the role and steps for applying axiomatic design as part of an integrated design approach for manufacturing enterprises. Charles also developed a three level decomposition for design of a capacity planning process as well as decompositions for two types of broaching machine designs. The decomposition contained in Suh et al. (1998) first established the connection between a high-level business objective such as return-on-investment and detailed design of manufacturing system elements such as machines and people. The MSDD described in this chapter builds on this work.

3.3 Assumptions

The first basic assumption that the MSDD is based upon is that optimization of individual elements in a system does not lead to optimal performance of the overall system. Since there are no equations that capture all of the decision variables in a single objective function representing the entire system, an optimal system solution is not possible. Furthermore, at the concept design phase manufacturing data is uncertain and often incomplete and therefore limits the effectiveness of optimization approaches to design.

The second assumption is that a manufacturing organization may be considered a system and that its requirements can be decomposed. The definitions of a manufacturing system presented in Chapter 2 support this assumption. These definitions of manufacturing systems all included three basic elements: resources, process, organization. Each element is capable of being decomposed from an abstract representation into one containing increased levels of details. Therefore, a design decomposition approach may be adopted instead of design optimization of a manufacturing system.

The third assumption made is that the MSDD is valid throughout the lifecycle of the manufacturing system. All aspects of the decomposition are applicable in the design of a completely new manufacturing system and only some parts of the decomposition may need to be considered in redesign of existing manufacturing systems (or partial design). More information will become known as design progresses, but the decomposition's applicability will still hold.

The fourth assumption is that the MSDD applies to a general manufacturing company having the characteristics of discrete parts manufacturing. As the decomposition gets to lower levels, the generality decreases. However, insofar as the objectives are applicable to the company's processes, the physical hierarchy is still valid. Service industries, research and development, and other revenue-generating enterprises are not considered in the decomposition. Since, no specific types of factories or products were used in the development of the decomposition, it is therefore product independent.

3.4 Scope of Application of the MSDD

To explain the role of the decomposition in the overall manufacturing system design approach, it is first necessary to compare it with current system design processes. Furthermore, the classification scheme presented in Chapter 2 (Section 2.3) is used here to define related methods, modeling, or analysis activities that arise in the decomposition. Applying the classification scheme to the decomposition also helps to contrast it with the approaches reviewed in Chapter 2 thereby highlighting its strengths and weaknesses.

3.4.1 A design or design tool?

The MSDD is a decomposition of the requirements of a manufacturing system linked to design entities (parameters). The design parameters satisfy the FRs at each level in the hierarchy, however, the DPs can be developed and applied to achieve FRs in different ways. The MSDD may be first characterized on the basis of whether the decomposition is itself a design or a design tool. A design in its most fundamental form is a simply a description of the product that meets the needs of its intended customer (Shigley, 1983; Pahl, 1984). A description can exist in many different forms and with varying amounts of detail. In contrast, a design tool is an aid or means by which a designer generates a design. Therefore, by this general definition, the MSDD is a design because it contains descriptions for elements that make up a manufacturing system and the requirements that it must satisfy.

Also, since these elements do not appear in a problem-specific form, the manufacturing system design developed through decomposition may be more precisely regarded as a concept design. Furthermore, the FRs and DPs in the MSDD may be considered as placed-holders for all system design decisions that eventually are made. However, as a concept design the MSDD can provide guidance to designers by providing knowledge of interrelationships and dependencies between objectives. Therefore the MSDD may also be considered a design tool.

Blanchard and Fabrycky (1998) distinguish between physical and conceptual systems stating that physical systems are made up of components that occupy space whereas conceptual systems are comprised of components that exist in the form of ideas, plans, procedures, etc. Given this classification of systems, the MSDD is a combination of a physical and conceptual system. The MSDD is physical because it contains a description of component resources such as equipment, people, and facilities. It is simultaneously a conceptual system because plans, procedures, control policies, and operating principles govern the behavior of the physical components of the manufacturing system.

3.4.2 Comparison with a Systems Engineering Process

The purpose of this section is to define the stages in the manufacturing system lifecycle during which the decomposition may be applied. This section uses a more detailed lifecycle process description from the systems engineering field and adapts it to manufacturing system design. First, the definition given for a manufacturing system in Section 2.2.1 is a specific instance of a general system definition. The International Council on Systems Engineering (INCOSE, 1998) defines a system as:

> "An integrated set of elements to accomplish a defined objective. These include hardware, software, firmware, people, information, facilities, services and other support elements"

Furthermore, a system architecture is defined as:

> "The arrangement of elements and subsystems and the allocation of functions to them to meet system requirements."

The manufacturing system definition stated earlier in Chapter 2 is therefore consistent with these two general system definitions from INCOSE. By extension, the MSDD may be compared with a Systems Engineering Process (SEP) also developed by INCOSE. The SEP shown in Figure 3.18

consists of six general system design stages that begin with initial statement of objectives and end with the launch and operation of a system. The underlying activities are defined for each stage in the design process. The SEP is iterative in nature because as general, high-level goals and objectives are defined they are in turn refined as more knowledge becomes available. At each stage in the SEP, many concepts are developed that require analysis and evaluation of dependencies (i.e. coupling) between subsystems and of the capability for low-level components to meet high level goals. Tradeoff analysis is used to make design decisions between possible concepts and to accept requirements or request modifications to requirements.

First, the SEP begins with broad, general statements about the goals and objectives that the entire system must meet. These statements may be characteristics of the system that must be fulfilled such as its performance, efficiency or other specified behavior. In a manufacturing system, these "mission objectives" are performance measures such as return-on-investment, service level, quality metrics, manufacturing cycle time, etc. The next stage in the SEP is to translate these generally stated goals into more formally expressed requirements that can be used specifically in detailed design.

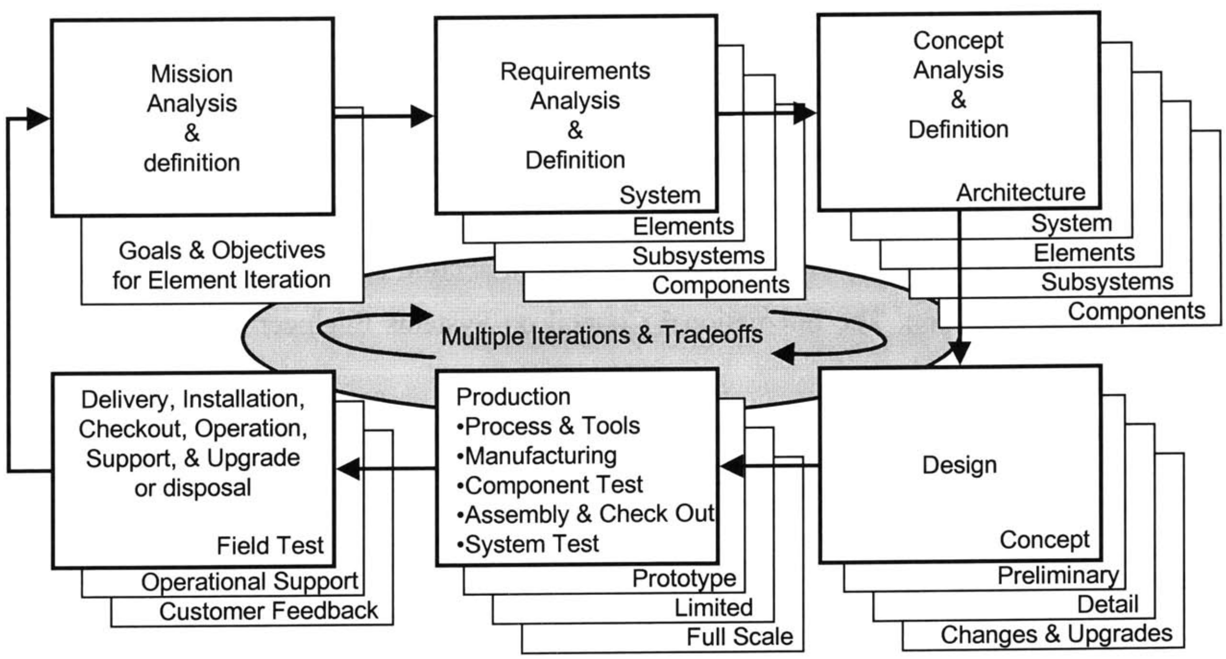


Figure 3.18 Systems Engineering Process (SEP) Overview (INCOSE, 1998).

At the concept design stage, the overall system architecture is established thereby defining the subsystems and how they will be connected to one another. In manufacturing system design, the organization of resources such as equipment are defined as well as that of other subsystems. Architecture is selected based on the system objectives such as service level. Detailed requirements such as volumes, customers, product varieties play a major role in the generation of manufacturing layouts. Customer demand and future expected demand (forecast data) will guide the design of manufacturing planning and control subsystems.

After concept design and selection, the design stage formalizes the concept and adds detailed engineering specifications that are used to build the manufacturing system. Extensive testing, analysis, and simulation occurs concurrently at all levels of the system architecture by engineers. During the design stage, systems engineering is particularly important because interfaces between subsystems are finalized. Therefore, systems performance measures (i.e. reliability) that depend on good interfaces must be carefully monitored for system-wide consistency. In manufacturing systems the design stage corresponds to design/selection of equipment, process design, human factors engineering analysis, scheduling policies, and integration of information and control subsystems.

During the system launch phase the actual hardware and software components of the system are brought together and the system is operated for the first time in its entirety. The system may go through a ramp-up phase as it is being launched where prototypes, and limited production runs are made prior to full-scale production. There are varying degrees of verification and validation of the system operation that occur depending on the tolerances set for performance measures. Systems with tight tolerances on performance measures are subject to greater verification and validation. For example, capability studies of manufacturing processes based on prototype production are performed on subsystems (and equipment within the subsystem) prior to acceptance. Modeling and analysis conducted properly in the concept phase can mitigate the amount of problems that arise in the system launch phase.

The final phase, ongoing operation commences once full-scale operation at launch has been proven successful. Long term performance measures of the system are then verified to determine whether the mission objectives have been met. The manufacturing system may have aspects of the system redesigned after operation thus triggering the initiation of another SEP.

Given this overview of the SEP from a manufacturing perspective, the MSDD may be described with respect to its use at each of these phases (Figure 3.19). The first two phases of the SEP deal with determining the overall system objectives and goals that the system must meet.

Since the FR hierarchy of the MSDD is entirely a set of objectives and requirements, the FRs apply exclusively to the first two phases of the SEP.

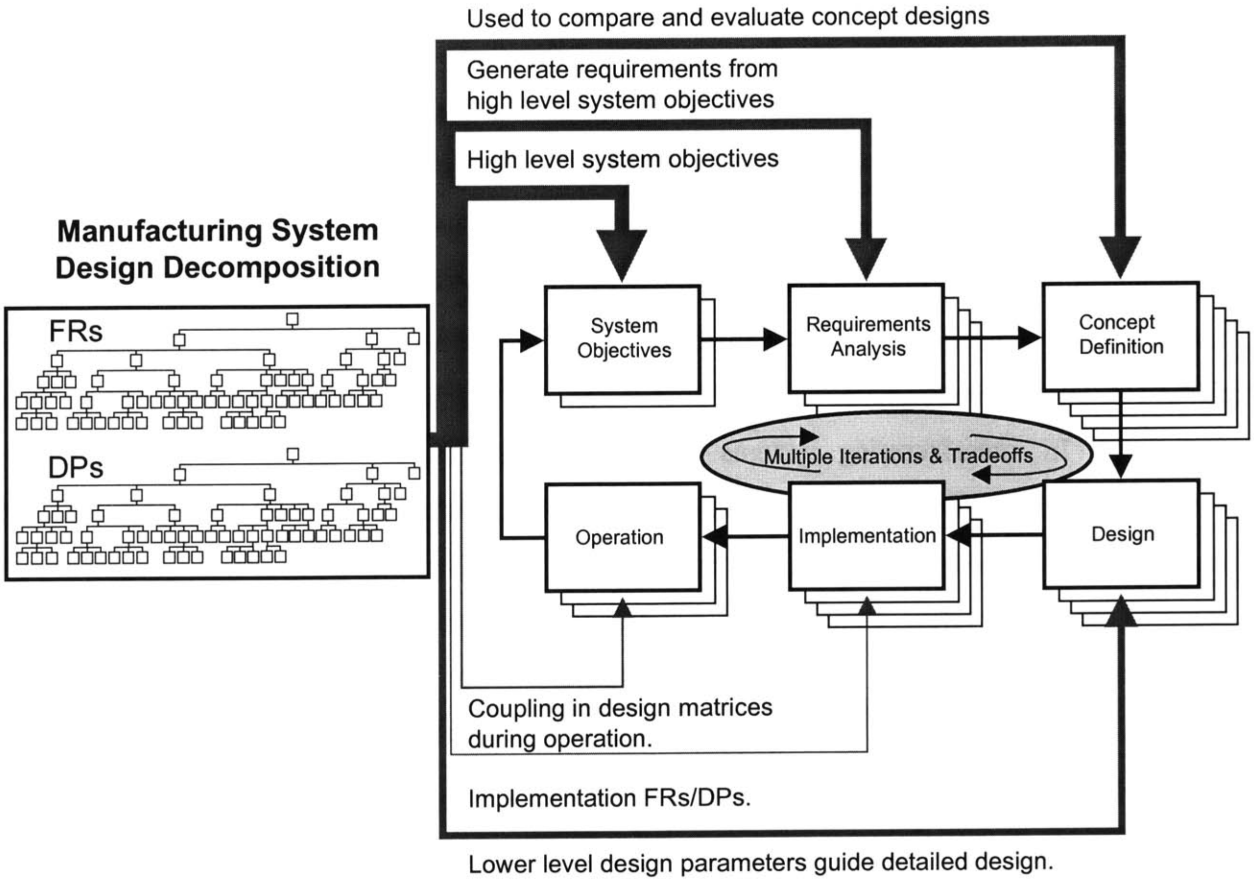


Figure 3.19 Applicability of MSD Decomposition to the INCOSE Systems Engineering Process (SEP).

Next, all of the FRs were further examined and classified according to whether they would be generated in either the first or second phases. The assignment of a FR to either of these phases is highly dependent on the system design problem. In some designs, objectives that arise in phase one will arise as more specific requirements in phase two in other designs. However, to make the distinction clear between the definitions of the two phases basic classification criterion were used. If the FR in question is stated as a desirable outcome (i.e. a goal) with no specific variable nor specific target value to verify its attainment, then the FR is considered to arise in phase 1 of the SEP. Alternatively, if the FR is stated with variables that could be assigned target values and could be subsequently measured to verify attainment, then the FR is assigned to phase two.

Phases three to six of the SEP are the design, launch and operational phases of the system design lifecycle. Since these phases deal with design solutions, it is therefore the DP hierarchy that should be examined to classify DPs into phases three to six. DPs are classified because phases 3 to 6 correspond to design activities. In classifying DPs, the following question is asked: at what phase in the SEP would the DP be realized? For example, DP-T221-Design of appropriate automatic work content at each station is realized during the detailed design phase of the SEP (phase 4). Detailed models of equipment design can be used to analyze the work performed at each station. As another example, material flow oriented layout, DP-T4 is defined during the concept design phase because the system architecture adopted leads to the selection of layout, and hence the material flow paths.

Figure 3.20 below shows a level-by-level classification of the fraction of FRs/DPs in the MSDD that apply to the six INCOSE systems engineering phases. This classification provides a systematic comparison between the MSDD and SEP. At high levels of the MSDD (Levels 1-3), FRs/DPs apply to the early SEP phases. In contrast, the latter phases map to lower levels of the MSDD. For example, Levels 1 to 3 of FRs in the MSDD belong to the initial systems objective definition phase. Also, Levels 1 to 3 of DPs are almost completely developed at the concept design phase. The increasing specificity that occurs in the MSDD with increasing depth of decomposition is further reflected in the correspondence with the latter phases of the SEP. For example, at Level 6, more than 60% of the DPs specified belong to the detailed design phase of the SEP.

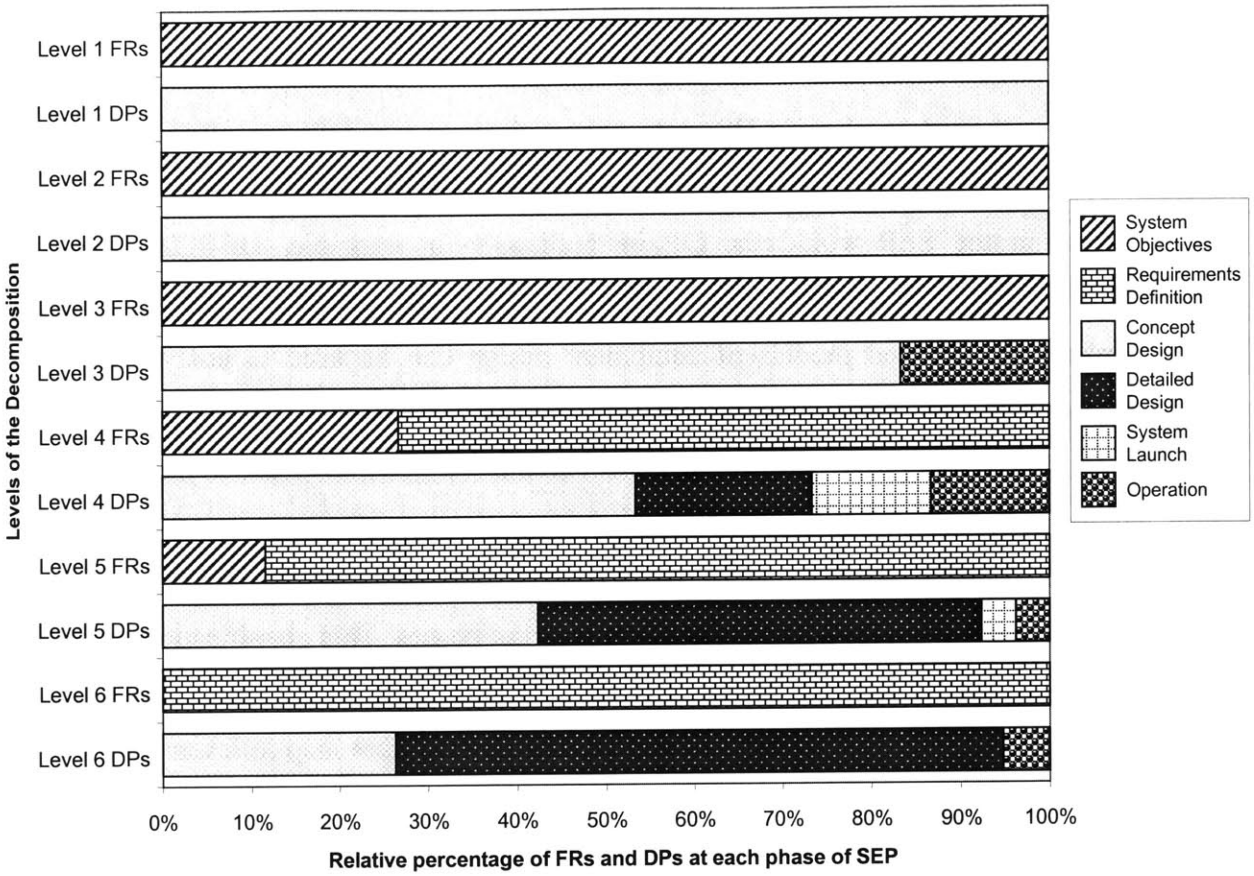


Figure 3.20 Comparison of the MSDD with INCOSE Systems Engineering Process.

3.5 High-level Structural Description of the MSDD

As with any product drawing, the designer must effectively communicate design intent and where possible, the reasoning behind generation of design requirements. Insofar as the decomposition represents objectives and means for a conceptual design of a manufacturing system, design intent and development logic must also be captured. Also, since design hierarchies quickly become complicated with increasing depth, abstraction of details is important to clearly represent intent and logic. In particular, the MSDD has a depth of six levels and abstraction on the first four levels is performed by grouping FR-DP pairs according to subject area and hiding the details of the text boxes. Figure 3.21 shows how abstraction serves to communicate the logic of the decomposition by establishing the relation between lower level areas and the high level objectives that they support.

The text boxes shown in Figure 3.21 abstract details of FR/DP pairs yielding the structural view of the decomposition. The decomposition begins at the highest level with the functional requirement being the desired return on investment. Return on investment as discussed in the next section decomposes into branches corresponding to customer satisfaction (revenue), production costs, and system investment. Customer satisfaction requirements are further divided into those related to manufacturing quality or delivery of the product. Similarly, production costs are subdivided into two categories: labor and facilities costs. While these first three levels of the decomposition are quite general, they organize the more detailed fourth level that includes key elements of manufacturing systems, namely: high quality processes, rapid problem resolution, predictable output, throughput time reduction, and effective use of labor resources. This structural view serves as the general guide for the detailed requirements in each branch of the decomposition. As such it helps the designer avoid the problem of not being able to "see the tree for the leaves."

However, it is not enough to simplify the decomposition by abstraction, this less detailed view must also be explained. The first four levels of the decomposition are described in a top-down manner and the design process is explained by describing how each high-level FR is in turn satisfied by its DP. This description also gives the logic behind the decomposition of a DP into sub-FRs. These descriptions explain the FRs and DPs while the corresponding design equations are also given to provide the relation between each FR and its DP.

In summary, these descriptions of the decomposition process and of the resulting FRs and DPs are needed for the following two reasons:

1. A high level of abstraction is needed to broadly summarize the logic and organization of the MSDD. The number of FR/DPs grows with lower levels and thus an abstract view that hides the FR/DPs is necessary to help understand the high-level system objectives.

2. The decomposition has general concepts that need further detailed explanation beyond the concise statements present in specific FRs and DPs.

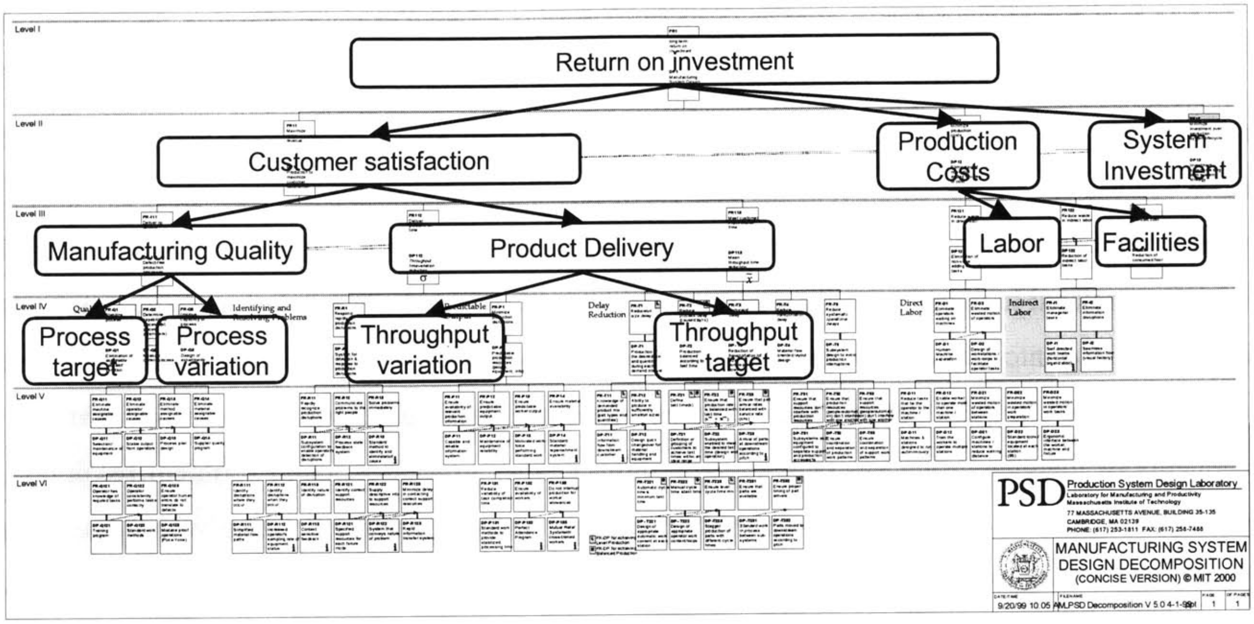


Figure 3.21 High level abstracted view of manufacturing system business objectives. (PSD Lab, 2000)

3.5.1 Financial Objectives

The highest level FR in the MSDD is to maximize return on investment (ROI) (Suh et al., 1998). As discussed above, Figure 3.21 gives the view of how the manufacturing system meets the ROI requirement by its decomposition into customer satisfaction, production costs, and system investment requirements. ROI in common financial terms is calculated from revenues, costs, and investments according to:

$$Return\ on\ investment\ (ROI) = \frac{Revenue - Cost}{Investment} \quad (3.1)$$

The use of ROI gives designers of the manufacturing system a means to gauge performance by comparison to other system design options as different system concepts imply different revenue, production costs and investments quantities. However, care must be taken in the use of ROI as a decision criterion when comparing manufacturing system design concepts. ROI performance measures have been criticized for encouraging less participatory upper management practices (Hayes, 1980, 1982) since such measures favor decision making solely on the basis of a single numerical quantity without consideration of other intangible aspects of a manufacturing system (or subsystem) design. Manufacturing investments that are cost reduction focused and short term in nature are favored over longer term strategic investments whose value and benefits are more difficult to quantify.

Also, investments that include benefits to manufacturing quality, innovation, process technology, and work force skills are more difficult to justify to managers who are intent on only having a single-valued summary in order to make a decision. A specific example of a risk associated with ROI measures can occur when making process technology decisions. A company may decide to improve ROI in the short term by buying inexpensive, readily available equipment from existing suppliers instead of making a long term investment to develop their own equipment and thereby gain a competitive advantage. The danger with the former decision is that the same equipment is also readily available to competitors who can just as quickly purchase it. Furthermore, if a competitor does invest in process technology, it is then even more difficult for the company to compete on manufacturing process capability.

Notwithstanding the short-term focus and bias towards easily quantified investments, ROI can still be a valid starting objective for conceptual design of a manufacturing system provided there is a means to consider the intangible aspects of a design. Hill (1994) discusses the need for a strategic view of investment and advocates evaluating investments based on how they support and contribute to the success of a company's corporate strategy. Kaplan (1984) proposes the valuation of a firm's intangible assets that do not immediately appear as dollar returns on standard financial accounting statements. The MSDD is in agreement with the views of these authors by addressing problems associated with ROI through the inclusion of manufacturing system requirements not typically used in ROI calculations. For example, these include requirements such as quality and product delivery (responsiveness as well as speed) that do not often have associated cost data.

3.5.1.1 ROI Decomposition

The decomposition of ROI is shown explicitly in Figure 3.22 where the FR1 – Maximize long-term return on investment is achieved by DP1 – Manufacturing System Design. To avoid the short time horizon bias of ROI measures described above, FR1 emphasizes the need for a longer term outlook when designing and investing in manufacturing systems. The functional requirements of the DP-Manufacturing System Design are decomposed into FR11-Maximize sales revenue, FR12-Minimize production costs, and FR13-Minimize investment over production system lifecycle.

Sales revenue in FR11 is a function of units sold and product pricing, however, the conventional approach for increasing these quantities is through marketing and product development activities. Through the forces of competition, the market sets the price for the product. Product development in combination with marketing identifies and then designs products that satisfy customer needs. The role that the manufacturing system design plays in contributing to maximized revenues is not as explicit as these two preceding activities, however, it is just as important in ensuring that customers will purchase the product. Product design creates the functionality desired by the customer and it is the responsibility of manufacturing to produce this product. Maximizing sales revenue from a manufacturing system perspective is then achieved when the customer is satisfied. The manufacturing system meets customer satisfaction by producing the product at the required level of quality and then delivering it to the customer within an expected period of time. Therefore it is through manufacturing quality and delivery that the manufacturing system satisfies the customer.

The second FR at this level is to minimize production costs. Though a firm has many sources of cost, the focus in the decomposition (as with sales revenue) is on cost incurred in operation of the manufacturing system. Costs are minimized by elimination of non-value added sources of cost (DP12). At this high level in the decomposition, non-value added sources of cost generally refer to those costs that do not contribute to increasing the value of the product as it is processed.

The third component of ROI is the investment in the elements that comprise the manufacturing system. FR13 states the objective to minimize investment over the manufacturing system lifecycle that is achieved by investments that are based on a long-term system strategy (DP13). The focus of investment is the purchase of resources required to deliver the product at the desired customer satisfaction level while meeting cost requirements. Resources are purchased both in the initial design of a new manufacturing system as well as during the ongoing operation as products are continually introduced. Furthermore, as with the statement of the ROI objective in FR1, FR13 also expresses the emphasis on giving system design projects with longer horizons sufficient consideration. Thus, investments should support (i.e. decompose into) the long term manufacturing strategy of the company. For example, investments must consider the capability for manufacturing system resources to produce the expected product varieties that will be introduced over the lifecycle of the system. Since such strategies are firm specific, DP13 is left as a leaf to be further decomposed in an actual manufacturing system design.

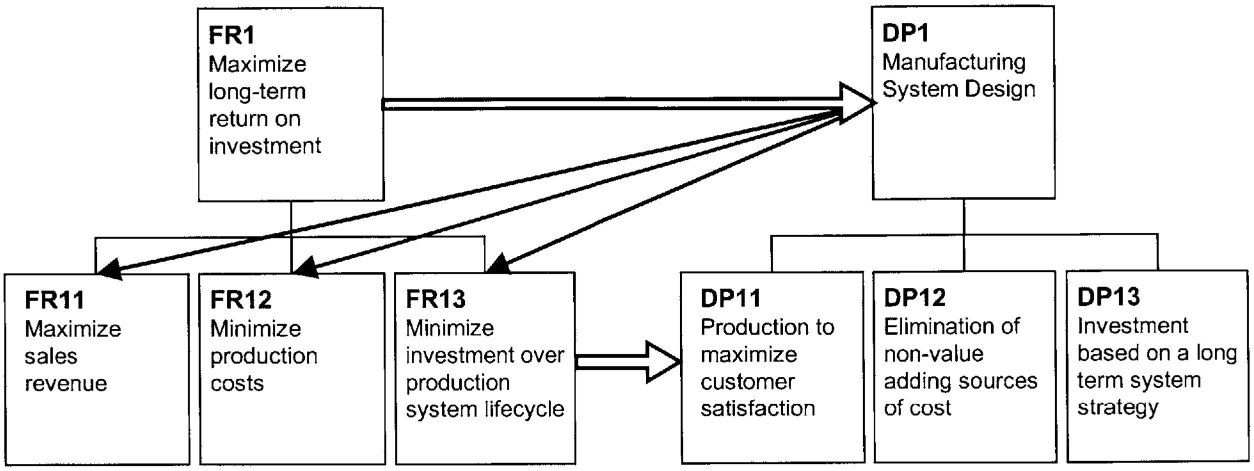


Figure 3.22 High-Level Decomposition of the financial objective: Return On Investment.

3.5.1.2 ROI Design Equation

The ROI design equation (Equation 3.2) resulting from the above decomposition is decoupled and therefore the meaning of the non-zero off diagonal elements needs to be described. Since the design matrix is decoupled it reflects that satisfaction of the customer influences all other aspects of the manufacturing system design. Another result from the diagonal design matrix is that it shows the limits to which cost minimization or investment strategies can increase ROI before customer satisfaction is jeopardized.

$$\begin{Bmatrix} FR11-\text{Maximize sales revenue} \\ FR12-\text{Minimize production costs} \\ FR13-\text{Minimize investment over production system lifecycle} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP11-\text{Production to maximize customer satisfaction} \\ DP12-\text{Elimination of non-value added sources of cost} \\ DP13-\text{Investment based on a long term system strategy} \end{Bmatrix} \quad (3.2)$$

DP11 influences FR12 since producing to maximize customer satisfaction consists of making design decisions regarding quality and product delivery that in turn affect production costs. Also, how well the manufacturing system satisfies the customer (i.e. service levels and/or fill rates), also indicates the ability to minimize production costs. DP11 also affects the achievement of minimizing investment over the lifecycle of the manufacturing system (FR13). For example, the type of methods needed to ensure that the customer will be satisfied by the manufacturing quality will directly determine the corresponding amount of investment required. Similar design decisions taken in the throughput mean and variation reduction decomposition branches (delivery responsiveness to the customer) will affect achievement of the investment objective.

The third off-diagonal element is the influence that DP12 has on FR13. The elimination of non-valued cost sources determines the amount of investment that must be made into the system. A poorly designed system with many wasteful activities present in direct and indirect labor tasks will require greater investment to offset inefficiencies. Clearly, if such sources of non-value added cost are reduced, then investment can also be reduced.

3.5.2 Customer Satisfaction

Decomposition of DP11-Production to maximize customer satisfaction in Figure 3.23 reflects "how" the manufacturing system should be operated to maximize sales revenue. The level of manufactured quality of the product and the timeliness of product delivery to the customer determine whether customer satisfaction is maximized and hence sales revenue maximized. DP11 is decomposed into three requirements that together define the manufacturing system's contribution to increased sales revenue. These three requirements form the top level FRs for branches of the decomposition referred to as the quality, throughput time variation reduction, and mean throughput time reduction shown earlier in Figure 3.21.

The first requirement to satisfy customers is achieved by providing a high level of *manufactured* quality of the product. The overall quality of a product is determined during product design, manufacturing process design, and during the act of manufacturing itself. In the decomposition, the assumption is made that product designers provide the correct nominal values[6] to assure that the product will function as required by the customer. Therefore, the emphasis of FR111 is for the output of manufacturing processes to yield products with characteristics that meet target design specifications (i.e. nominal dimensions). The frequently cited Sony television study (Phadke, 1989) illustrates the importance of producing to the target dimension rather than just meeting design tolerances. The study compares two factories in Japan and in the U.S. that were both producing the same television sets with little difference in defect rates. That is, both factories were producing approximately the same number of sets to the same design tolerance specification. However, customers in the U.S. preferred the televisions manufactured in Japan to those made in the U.S. The results of the study showed that the Japanese factory had a process that yielded a greater number of sets closer to the design target (nominal value) given by a smaller standard deviation. Thus the quality branch of the decomposition that begins with FR111 represents the manufacturing perspective that processes should be on the design target and not simply producing parts within tolerance. Designing manufacturing processes with minimal variation from the target (DP111) satisfies FR111 by decomposing quality methods that improve process variance and centering.

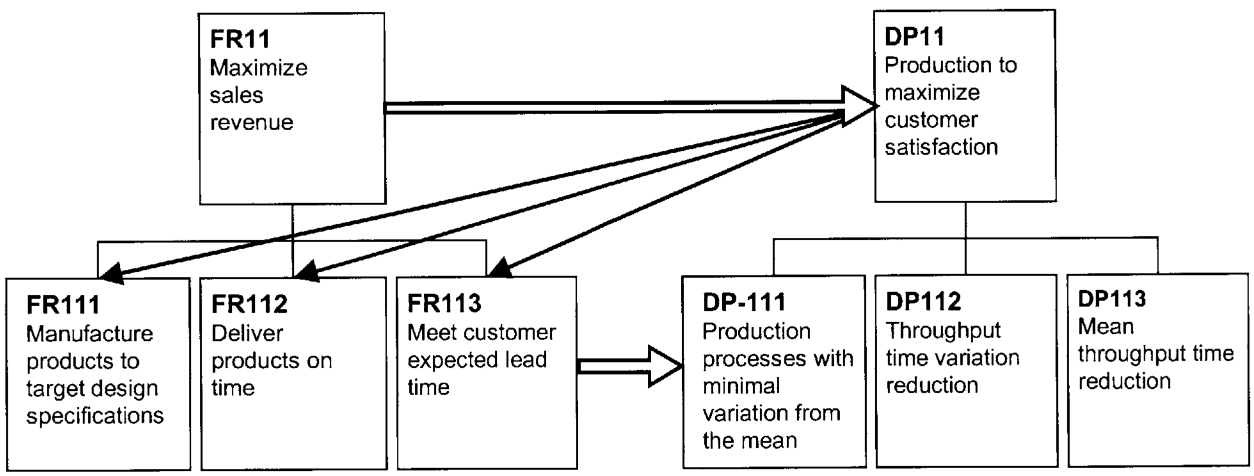


Figure 3.23 Decomposition of Customer Satisfaction.

The second and third requirements, FR112 and FR113 describe how customer satisfaction is attained through timely product delivery. Delivery in a make-to-order manufacturing system refers to the series of activities between the time the order is placed until the customer receives their requested product. The delivery activities that are considered in the decomposition are those related to the actual manufacture of the product. The sum of the time taken to carry out these "activities" is often called the throughput time or manufacturing cycle time of the product. Manufacturing cycle time is a random variable that may be characterized by an appropriate probability density function (i.e. normal, exponential, erlang). The requirements

[6] This statement does not preclude concurrent engineering activities, only that the nominal values are assumed to be correct as a result of the design process. The corollary to this statement is that no amount of manufacturing prowess

FR112 and FR113 respectively specify the standard deviation and mean for the chosen function (Figure 3.23).

Delivering products on time (FR112) indicates the requirement that the manufacturing system has to meet quoted lead times (in a make-to-order system) or to fulfill demand (in a make-to-stock system). Deliveries must be on time, that is they should be neither late (completely unacceptable to the customer), nor early (disruptive to the scheduling of resources in the system). Therefore, in the manufacturing system reducing the variation in the throughput time (DP112) decreases variability about the quoted lead time or on-time delivery. Methods for reducing the variation in throughput time are decomposed into two functional branches: problem identification and resolution, and predictable output of manufacturing resources (Section 3.5.4.1).

Though seemingly similar to FR112, the emphasis of FR113 is on being able to reliably and confidently (in a probabilistic sense) quote a lead time to the customer that will result in placement of an order. Customer satisfaction is maximized when this amount of time is equal to that expected by the customer. The customer expected lead time is the upper bound on the maximum time that the customer is willing to wait for delivery of the product. Thus, the manufacturing system should be designed so that the throughput time is less than or equal to that time which the customer could otherwise obtain with a competitor. For this reason, DP113-mean throughput time reduction further decomposes into methods for reducing the various components of manufacturing cycle time.

A system that satisfies the requirements of customer satisfaction will have a design matrix that is decoupled and will reflect the dependency of product delivery and customer lead time requirements on high quality manufacturing processes. If the design parameters are not well designed or vary excessively during the operation of the manufacturing system, then the matrix will become coupled. For example, poor process quality will result in lower yields and therefore increased variability in system throughput times. Coupling in Equation 3.3 can occur in this situation because improving quality becomes dependent on the ability to reduce variation in throughput time. Quality problems become more difficult to resolve when throughput times are lengthy (i.e. a large amount of work-in-progress makes problem detection more difficult).

---

can save a poorly designed product.

$$\begin{Bmatrix} FR111 \\ FR112 \\ FR113 \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP111 \\ DP112 \\ DP113 \end{Bmatrix} \quad (3.3)$$

3.5.3 Quality

Manufacturing quality today is assumed since customers no longer tolerate servicing or returning defective products. Products are expected to function as designed from their first use to the end of the lifecycle. Total Quality Management methods (Shiba, 1993) emphasize this expectation of quality as "fitness-to-use", where previous conformance measures of quality were based solely on meeting the minimum tolerance specification referred to as "fitness-to-standard." In decomposing customer satisfaction, quality begins with the requirement that manufacturing processes have output that is on the design target, and with minimal variation from the target. This requirement is in agreement with the quality loss function proposed by Taguchi (1989) that minimizes "loss to society" when performance (of the product or process) is at the nominal quantity (target) specified by the designer. FR111 and DP111 are superimposed on the quadratic loss function proposed by Taguchi. Further decomposition of DP111 is based on the necessary steps to attain high quality manufacturing processes via statistical process control methods, process design and optimization (robust design) shown in Figure 3.26. Thus, FR111 and DP111 together state that manufacturing contributes to a high quality product not just by simply being within the tolerance specifications but by having a process centered on the designer's target value with minimal variation.

The first requirement of manufacturing processes with minimal variation from the target is process stability (FR-Q1). A process is said to be in a state of control when there are no assignable causes of variation present and instead only common causes (Montgomery, 1985). Furthermore, assignable causes are non-random events, that when eliminated or corrected result in the process returning to a state of control (i.e. process is once again stable). Examples include tool wear and failure[7], improperly adjusted devices (torque guns, spindle speed), chips caught under fixtures, plugged coolant lines, etc. Therefore, the design parameter that achieves process stability is the elimination of assignable causes of variation, DP-Q1. This DP corresponds to the first major step in statistical process control techniques used to quickly detect the occurrence of assignable causes at the machine. Quick detection allows investigation of the process and permits corrective action to be taken before many non-conforming units are manufactured. However, a stable process alone is not a sufficient condition for high quality manufacturing processes. A process may be stable and yet the process variation may be such that a large amount of parts are produced beyond the specification limits. Conversely, a process which is producing an acceptable number of parts within the specification limits (defect rate) may not necessarily be stable. The next two functional requirements provide the necessary conditions for high quality given a stable process.

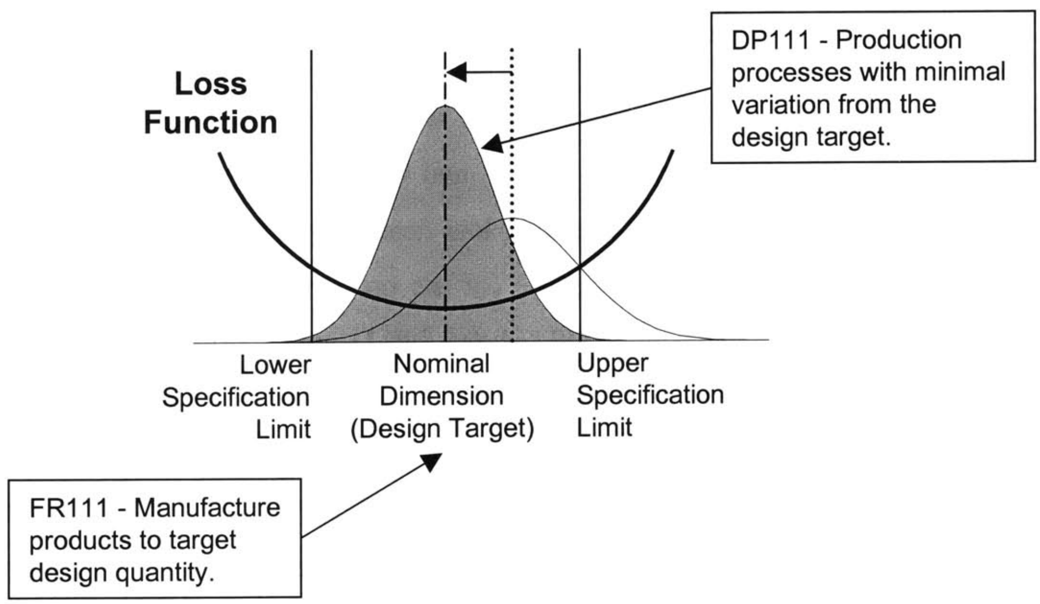


Figure 3.24 Decomposition of Quality branch by Loss Function Concept.

A process that is stable and has a sufficiently small standard deviation may still be producing an excessive number of out-of-tolerance parts. Figure 3.25 shows a process distribution with a mean that is too close to the upper specification limit and thus is producing defective parts despite an acceptable standard deviation. FR-Q2 gives the requirement to deal with ill-centered process means. To correctly place the process mean at the required design target involves adjusting process parameters DP-Q2. An indicator of process spread as well as centering is the process capability ratio C_{PK} given in Equation 3.4. C_{PK} is the dimensionless ratio obtained by calculating the minimum distance of the process mean from either the upper or

[7] Both are assignable causes, although one occurs more rapidly than the other triggering different patterns in the x-bar chart, both cause out-of-control alarms.

lower specification limits to the process standard deviation. The minimum is used because it is the worst case condition for equivalent process mean shifts. This is more clearly seen in Figure 3.25 where the initial process mean is closer to the USL. A shift to the right will result in more defective parts being produced than an equal shift of the process mean to the left.

$$C_{PK} = \frac{1}{3}\min\left(\frac{\mu - LSL}{\sigma}, \frac{USL - \mu}{\sigma}\right) \quad (3.4)$$

Thus, to achieve the process centering requirement FR-Q2 (which C_{PK} measures[8]) manufacturing system designers have only freedom to control μ and σ of the process (through operational process adjustment) since the specification limits LSL, and USL are dictated by product design.

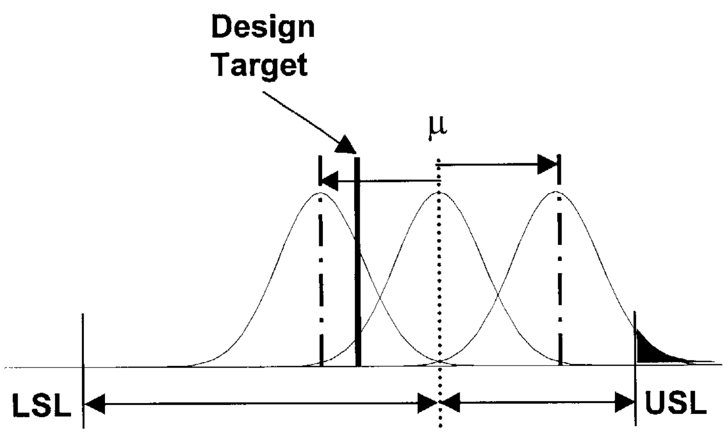


Figure 3.25 Centering process mean on the target, adapted from (Bothe, 1997).

The third high-level quality requirement is to reduce variation in process output – FR-Q3. Variation that is seen in the output of a stable process is the result of the existence of uncontrollable noise factors in the process. Noise factors as defined by Phadke are the parameters that cannot be controlled by the designer and lead to the variation causing quality loss. To reduce variation in process output requires the reduction of process noise, DP-Q3. Further decomposition of DP-Q3 leads to the requirements to reduce noise factors in process inputs and sensitivity to noise in the output.

These reductions are achieved by first converting previously assumed common causes to assignable causes that can be dealt with by the DPs under FR-Q1. SPC methods do not indicate how to convert common causes into assignable causes, only that the conversion is a necessary

[8] An estimate of the process capability ratio is calculated in practice by replacing the mean and standard deviation of the population with the sample mean $\bar{x}$ and standard deviation, S (estimators of the population).

step to improving process capability. Secondly, robust design methods[9] can be used to minimize variance of the quality characteristic of interest while keeping the mean on target. Or in other words, to achieve the design target value for the quality characteristic under all noise conditions (minimize process sensitivity to noise in the production environment).

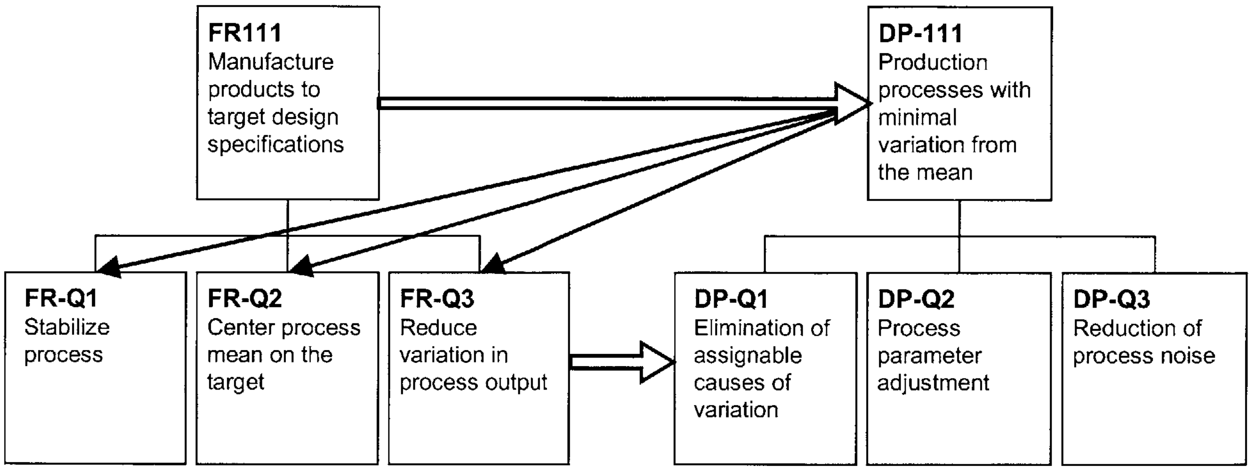


Figure 3.26 High level decomposition of quality.

The resulting design matrix shown in Equation 3.5 is decoupled and shows the dependence of process capability and improvement on stable manufacturing processes. However, in some processes the mean is not always easily adjusted and therefore can lead to coupling between FR-Q2 and FR-Q3. In these cases, alternative process design approaches are needed to find parameter values that will simultaneously reduce variation and center the mean.

$$\begin{Bmatrix} FR-Q1\ \textit{Stabilize process} \\ FR-Q2\ \textit{Center process on the mean} \\ FR-Q3\ \textit{Reduce variation in the process mean} \end{Bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP-Q1\ \textit{Elimination of assignable causes of variation} \\ DP-Q2\ \textit{Process parameter adjustment} \\ DP-Q3\ \textit{Reduction of process noise} \end{Bmatrix} \tag{3.5}$$

3.5.4 Delivery

The time taken to transform raw materials into a final product along with intermediate transportation and storage together comprise the throughput time, also known as the cycle time

[9] However, the robust design method is contingent upon the existence of a scaling factor that changes the quality characteristic proportionately at all points. Thus it is a two step process, maximize the S/N ratio (where the quality characteristic is the signal) and then secondly adjust the mean. This requires use of orthogonal arrays so that generate and test methods are avoided. It also requires knowledge of interaction between factors.

or manufacturing throughput time. Throughput time is a function of the path that the product must traverse from the raw material state to the finished product state and into the hands of the customer. The throughput time therefore depends on the manufacturing system design elements along which the product moves. Customer satisfaction is maximized when this amount of time is less than that in which the customer expects to receive the product. The customer lead time is then the upper bound on the maximum time that the customer is willing to wait for delivery of the product. Thus, the manufacturing system design should be designed so that the throughput time is less than the customer lead time otherwise, the potential exists that the customer will become dissatisfied with late delivery and move to another competitor.

In real manufacturing systems, the throughput time of any given product is a random variable with a corresponding probability density function for which the mean and variance may be determined. The concept of service level[10] (Hopp and Spearman, 1996) is used to combine the mean and variance of throughput time (TPT) with the required customer lead time (CLT). Service level (Equation 3.6) is defined by Hopp and Spearman as the probability that the throughput time for a make-to-order product will be less than the customer lead time. Thus delivery may be decomposed into two further requirements, meeting the target time and in less time than that required by the customer. Management uses Figure 3.27 to determine the lead time to quote to customers for a desired service level (i.e. to ensure a desired level of customer satisfaction).

$$service = \Pr\{TPT \leq CLT\} \quad (3.6)$$

[10] The concept of a fill-rate is a similar performance measure used in make-to-stock manufacturing systems that is calculated as the fraction of demands that are met from stock (Hopp and Spearman, 1996).

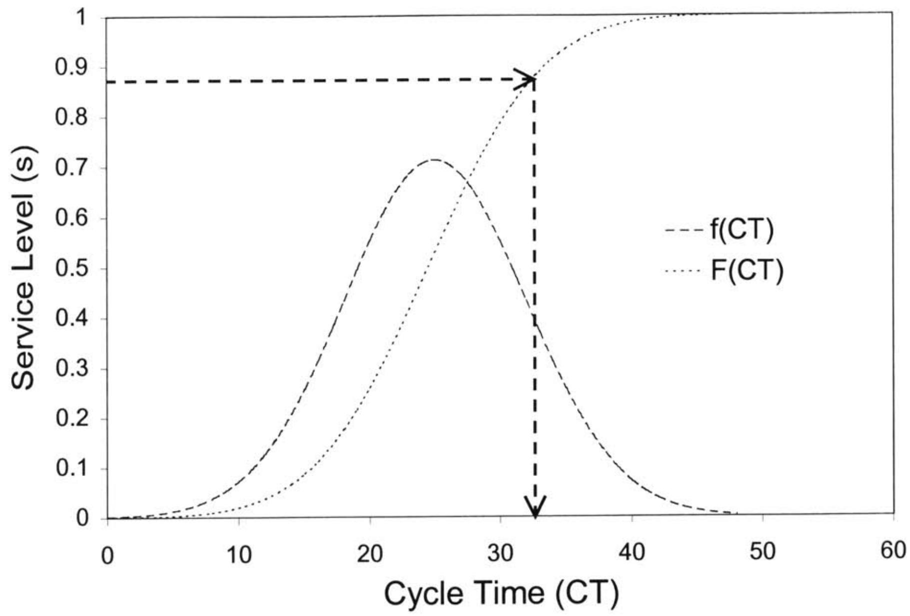


Figure 3.27 Service level versus cycle time[11] in a make-to-order manufacturing system (Hopp and Spearman, 1996).

In addition to decreasing the mean delivery time for a production system, it is also important to decrease the variation of the delivery time. Together, reduced mean and variation ensure consistent and on-time delivery of parts or finished goods. Meeting both of these FRs produces goods in a manner that satisfies the customer. Reducing variation in cycle time is often overlooked with so much focus on reduction of the mean cycle time, however, firms facing technological constraints in equipment or processes can often still reduce cycle times by examining the variability in their manufacturing system.

3.5.4.1 Throughput time variation reduction

On-time delivery of products (FR112) is dependent on the reduction of variation in throughput time. Throughput time variation is largely a consequence of the amount of disruptions in the manufacturing system as well as how they are resolved. Disruptions in the MSDD are problems that lead to a loss in system availability. Quality problems though disruptive to the system are treated separately under the FR111 branch, and therefore the decomposition of DP112

[11] (Hopp and Spearman, 1996) uses the term cycle time, in this work throughput time is used in an equivalent manner.

(Throughput time variation reduction) considers only disruptions that do not result in a quality problem (Figure 3.28).

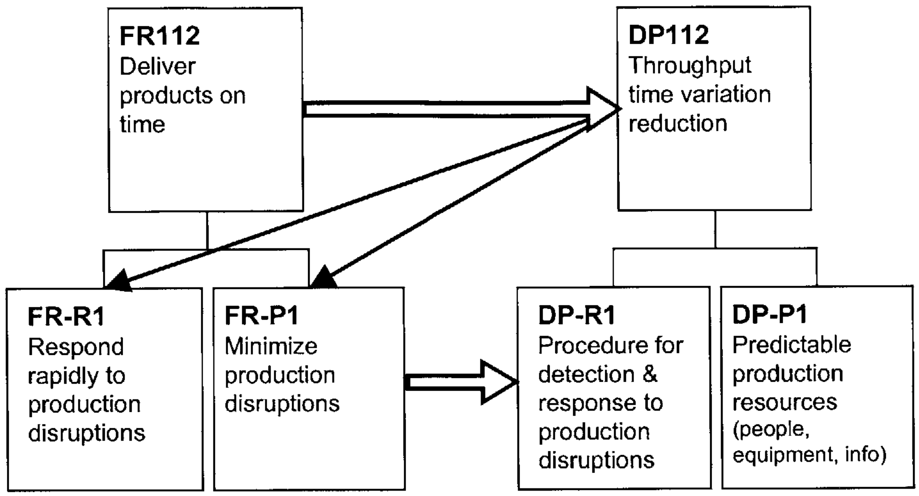


Figure 3.28 Decomposition of throughput time variation reduction.

Decreasing the variation of delivery time (moving from a standard deviation of 2 to 1 in Figure 3.29) to the customer relies on a manufacturing system that has predictable output. With greater predictability a company can make promises to its customers with the confidence and assurance that it can meet promised delivery times. Customer satisfaction is therefore increased because the customer has to wait less time for receipt of products that they order. Furthermore, if the customer receives their products consistently in the same amount of time from one order to the next, then they are likely to gain confidence in the ability of the manufacturer to satisfy their orders.

The requirement to produce with a predictable time output reflects a system's ability to decrease variation in delivery time. Producing in a consistent and timely manner can be done when production resources are reliable and in themselves predictable. The resources that affect timely production are having sufficient material supply, adequate machine availability, and consistent labor productivity.

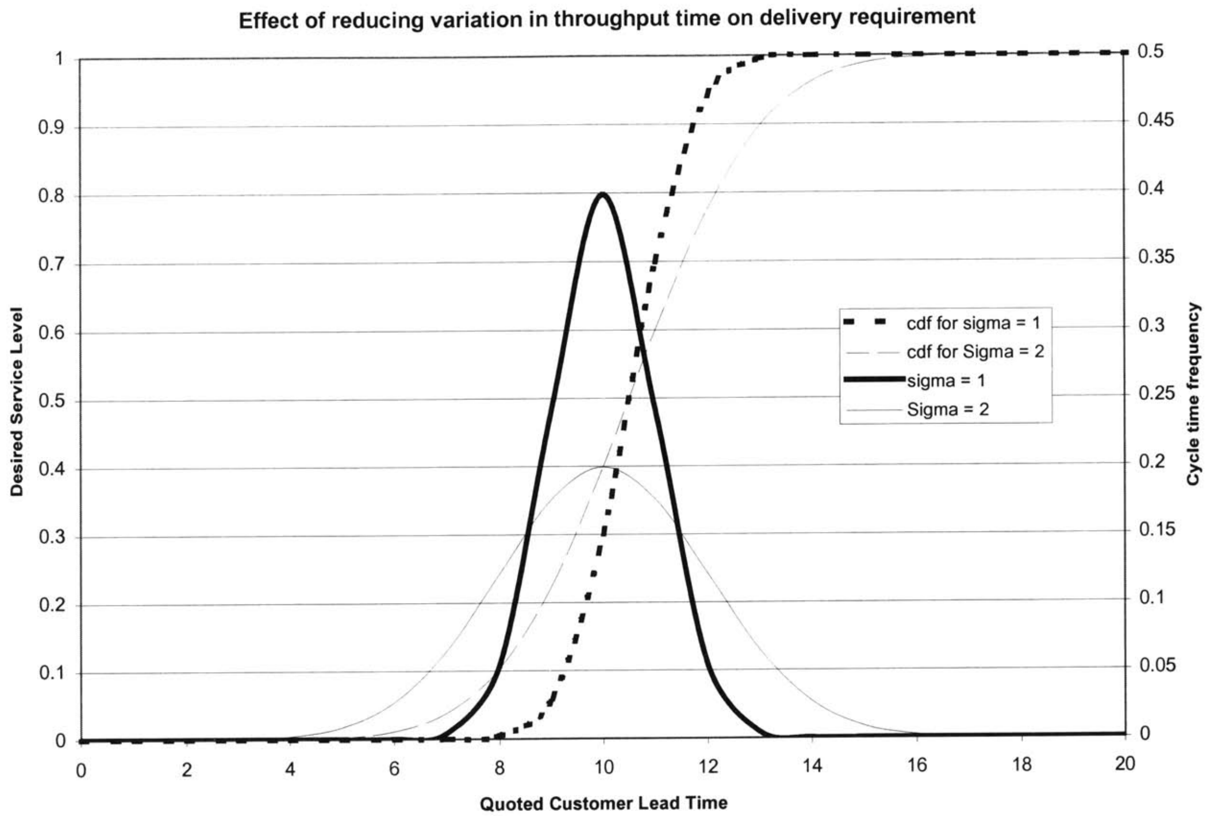


Figure 3.29 Reduction in variation in throughput time, modified from (Hopp and Spearman, 1996).

Requirement FR-R1-Respond rapidly to production disruptions means that there must exist a procedure for detection and a mechanism for resolution of disruptions. Rapid response includes recognition of a problem, communication of the problem to the corresponding people that can deal with it, and resolution of the problem as soon as is possible. At a more detailed level, Figure 3.30 describes the decomposition of response requirements as a sequence of events beginning with the recognition of a disruption and ending with its resolution. The first three requirements correspond to recognition of the nature of disruptions (when, where, and what). Subsequent requirements establish the connection between information about the disruption and the resources that can resolve it.

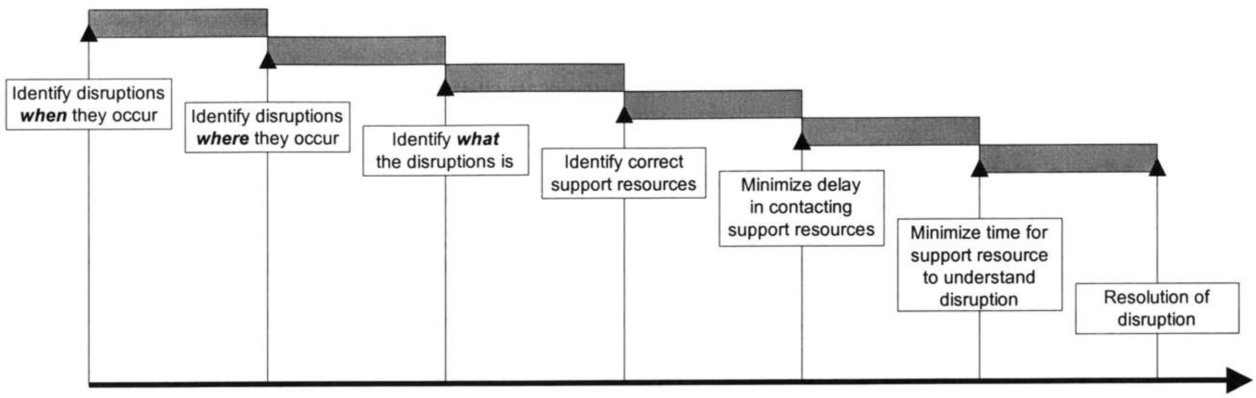


Figure 3.30 Decomposition of requirements to reduce variability in throughput time.

The second FR-R2 is to reduce the frequency of occurrence of such disruptions and depends on having reliable (i.e. predictable) manufacturing resources, namely DP-R2. Manufacturing resources whose availability contributes to fewer production disruptions includes that of equipment, people, material, and information. These four FRs represent the elements of availability needed for a predictable resource. Lower level decomposition of the FRs are based on the detailed methods required to attain necessary levels of availability. For example, equipment maintenance programs require easily serviceable machines along with a schedule for regular monitoring of machine condition.

The rapid response to production problems helps achieve predictable production output. Each time a problem occurs, the root cause must be identified quickly and resolved so that it will not occur again. Root cause identification techniques are effective means to improve the reliability of machines whenever the variation in output of any given machine is observed to rise. Practices associated with total preventative maintenance are effective in reducing potential failures that can decrease machine output.

Operations performed by humans are inherently variable. Ensuring predictable time output of workers is just as important as that of machines because both contribute to variation in delivery time. The standard work developed for operators to produce predictably may be regarded as the analog to the programming of a machine. Standard work is the means by which tasks that operators perform can be improved. Without a predictable sequence of steps for operators follow, it becomes difficult to identify wasteful motions that are unique to each operator. With standard work, a motivated work force can improve their motions and their own work environment, and hence help to reduce variability in human tasks.

3.5.4.2 Mean throughput time reduction

The decomposition of FR/DP-112 provides system designers with the two main requirements for variation reduction. Meanwhile, decomposition of FR/DP-113 (shown in Figure 3.31) gives the requirements for reduction of the mean throughput time that together represent delays in meeting the expected customer lead time. Conceptually reducing the mean throughput time is shown in Figure 3.33 where the cumulative distribution function shifts to the left but the probability distribution variance remains constant. There are five types of delays that can occur to production flow: lot, process, run, transport, and operational delay. See Duda (2000) for a development of equations to describe these delays.

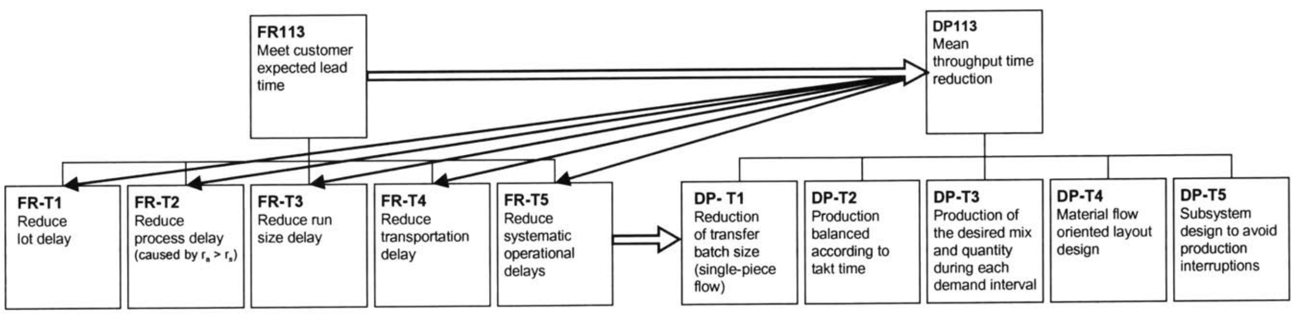


Figure 3.31 Components of delays for throughput time reduction.

To illustrate the first four delay requirements, Figure 3.32 shows a basic serial manufacturing line capable of producing two different types of parts (shown in the figure as cylinders and rectangles).

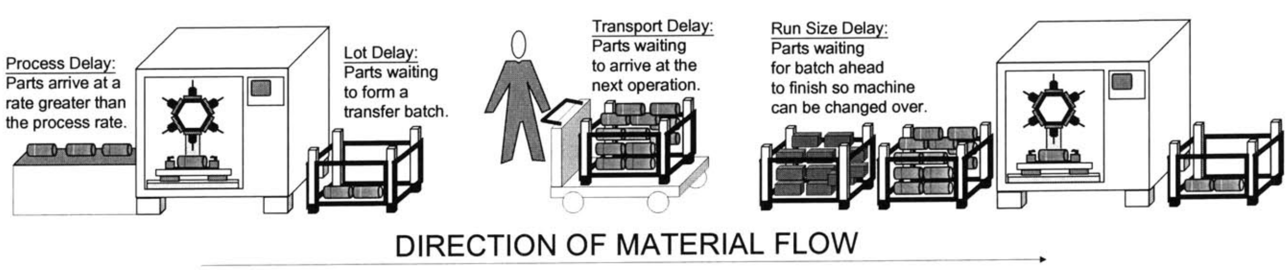


Figure 3.32 Types of delays in serial manufacturing operations.

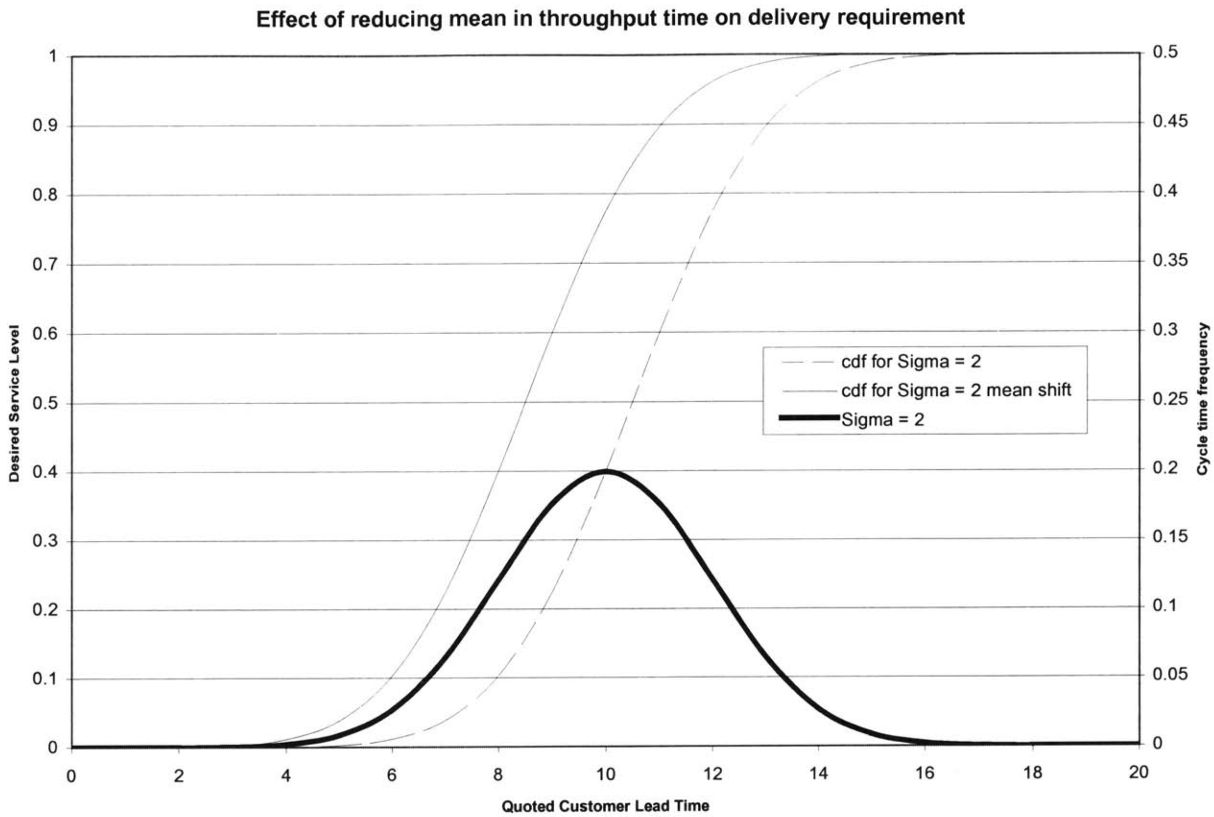


Figure 3.33 Reduction of mean throughput time, modified from (Hopp and Spearman, 1996).

FR-T1 Reduce lot delay

Lot size delay is the result of parts waiting to form a transfer batch after they have been processed at a machine. Transfer batches are sized according to the utilization and capability of the material handling resource. Thus, to reduce lot size delay depends on decreasing the sizing of the transfer batch and the corresponding ability of the material handler to adequately supply downstream operations. Single piece production (DP-T1) within a cell can eliminate lot delay. With a lot size of one, a part does not have to wait for any parts to finish being processed. Once the part itself is finished being processed it can be immediately transported.

FR-T2 Reduce process delay

Parts experience process delay when the part arrival rate (r_a) is greater than the service rate (r_s) at the machine. The amount of process delay depends on the system configuration (i.e. layout and flow paths) and can be calculated using queuing theory (for a given machine configuration and arrival/service distributions). Queues are the result of unbalanced processing times where a faster process feeds a slower one. In general, this occurs when the arrival batch size at a process is larger than the process batch size, or when the arrival rate is faster than the process (or service) rate. Process delay is a result of unbalanced machine cycle times and variability in machine reliability. In the MSDD, process delay is reduced by design of the system configuration for balanced production using an average takt time (DP-T2).

FR-T3 Reduce run size delay

Run size is the number of parts of type A that must be produced before a changeover to production of parts of type B. The smaller the run size, the closer a manufacturing system can satisfy the demand mix of the customer. Run size delay occurs when there is a difference in the number of scheduled parts versus the number of actual demanded parts. For example, in Figure 3.32, assume there are 20 cylindrical parts being produced on the second machine according to a production schedule. If in reality only eight parts have been actually demanded by the customer, then the rectangular parts experience a run size delay equal to the processing time of the 12 cylindrical parts ahead of them. Therefore, to reduce run size delay requires greater fidelity of production with actual demand. A schedule (or other production control mechanism) eliminates run size delay by determining the desired mix and quantity of actual demanded parts to produce during each interval (DP-T3). Further decomposition of DP-T3 leads to information (demand data) and equipment design requirements (for changeover capability).

The FRs T1, T2, T3 together specify that production must be based on actual demand. If forecasts are used to generate schedules for production, then the production rates (takt times) calculated will be inaccurate and the system will be unable to meet the real customer demand. Design of the production system with accurate knowledge of actual customer demand (as opposed to overly optimistic or conservative forecasts) is essential to reducing the possibility that production will end up as costly in-process inventory or finished goods. Production based on actual demand keeps in-process inventory at a minimum level and therefore the delivery time (FR-112) may be decreased over time.

The customer may not always order the same product in the same quantity, therefore the manufacturing system must be able to deliver different products in the correct mix (ratio) that the customer requires. To produce the correct mix and quantities demanded, level production requires that small batch sizes (DP-T1) be produced and conveyed. These requirements are achieved with rapid changeover capability (DP-T32), and an information system (DP-T31) to signal the mix that must be produced. To aid the up stream process to produce only what is demanded, an information system should be employed to send signals upstream and, in effect, "pull" production. Further decomposition of DP-T31 can yield the requirements for design of a shop-floor control system (such as one based on kanban cards).

FR-T4 Reduce transportation delay

Transportation delay is the time parts wait while being moved from one operation to another. System layouts that locate processing equipment in close proximity to each other reduce this delay (DP-T4) because material flow distances are smaller. Paths of material handlers and operators are considered in determining the required reduction in transportation delay.

FR-T5 Reduce systematic operational delays

Systematic operational delays are those that have a known cause. Also, such delays are non-random and frequently recur. To reduce the occurrence of systematic delays requires avoidance of unplanned interactions amongst manufacturing system resources (DP-T5). The subsystem design requirements that DP-T5 decomposes into are:

FR-T51 Ensure that support resources don't interfere with production resources.
FR-T52 Ensure that production resources (people/automation) don't interfere with one another.
FR-T53 Ensure that support resources (people/automation) don't interfere with one another.

Frequent causes of disruptions to the production flow include performing routine maintenance, removing by-products of the manufacturing process, supplying material to the sub-system or individual station/machine. Disruptions to production occur when the path of parts intersects the path of maintenance personnel, and therefore machines and stations should be designed to avoid production disruptions due to such routine tasks. For example, the location of equipment subsystems determines the path that maintenance personnel have to take when performing repair tasks. These locations affect accessibility and whether production flow is potentially disrupted. To satisfy the above FRs, designers of equipment must consider maintenance access points, extraction direction and location of the collection/storage of by-products, and material supply direction and access (DP-T51).

Some subsystems (i.e. cells) have operators whose interaction with equipment is critical during every cycle to maintain production output. Crossing an operator's walk-path and workspace can immediately cause systematic operational delays. Interference between routine maintenance and an operator's work can be reduced by providing access for maintenance personnel at the rear of the station (DP-T52). Material replenishment activities should not disrupt production either. Material handler must be able to replenish stock at stations without disturbing the work of the operator. As with maintenance access, material that is fed from the rear of a station eliminates interruptions to the operator at the front of the station (DP-T51).

3.6 Lessons Learned on the Usage of Axiomatic Design in MSDD

This section examines the results of applying Axiomatic Design to manufacturing system design and makes observations on the structure and development of the functional and physical decompositions. In particular, four major aspects of the MSDD have been identified that are attributable to the nature of conceptual design of manufacturing systems. Though these observations describe decomposition issues that have arisen in this particular axiomatic design application, the issues are not exclusive to manufacturing. The observations described in the next subsections have been obtained by examining parent and child FR/DP pairs for patterns and repeating trends in the decomposition. During the design process itself, no conscious effort was made to follow any specific decomposition approach (other than the zig-zagging method prescribed by axiomatic design). Therefore, these observations are a study of the manufacturing system design decomposition process. The four main aspects of the decomposition process described are all related to each other by the usage of language and the selection of words and phrases used to describe functional requirements and design parameters.

3.6.1 Decomposition of FRs and DPs in the MSDD

Axiomatic design dictates a strict decomposition approach whereby a FR maps to a DP (the process of design) and next this DP is decomposed into lower level FRs (also referred to as sub-FRs). This approach called "zig-zagging" is the process by which the functional and physical hierarchies evolve. To examine the results of this process, the 24 sets of FR/DP pairs (each set having a corresponding design matrix) in the MSDD were searched for indications of common trends. The technique used to characterize decomposition patterns was based on viewing the relation between the parent level FR and the children FRs.

Three main types of patterns emerge from the examination of these relations: decomposition by precedence, by combination, and by component. These three types of decompositions are shown in Figure 3.34. The precedence type describes a DP that is decomposed into a sequence of sub-FRs whose entire sequence denotes the parent FR. In Figure 3.34, the requirement 'Do X' consists of the series 'Do x1, x2, and x3'. The basis of the precedence requirements may be temporal, or purely sequence-based and independent of time. Combination decomposition describes all of the possible ways that sub-FRs (see X and Y sub-FRs in Figure 3.34) combine to cover the full range of requirements for the parent level FR. The third type is decomposition based on the components of the parent FR. Another way of thinking about this type of decomposition is that it is the aggregate set of requirements that make up the parent level FR.

Precedence decomposition is observed to arise in cases where a DP that is a method or procedure for achieving the parent-level FR is decomposed into a series of steps. This case is shown in Figure 3.35 where the steps to improving process capability are given by the sequence of FR-Q1, FR-Q2, and FR-Q3. This sequence describes the requirements for a manufacturing system to have production processes with minimal variation from the design target (DP-111). The DP is production processes with a quality descriptor. The descriptor provides the guide for decomposition of the DP into sub-FRs because it introduces the concepts of minimal variation and design targets not contained in the original FR. However, how these concepts are achieved is only made explicit upon mapping of the sub-FRs into the individual steps DP-Q1, DP-Q2, DP-Q3. In essence, these three lower level DPs satisfy the original FR-111 and DP-111 is simply an intermediate design stage used to generate and refine the lower level DPs.

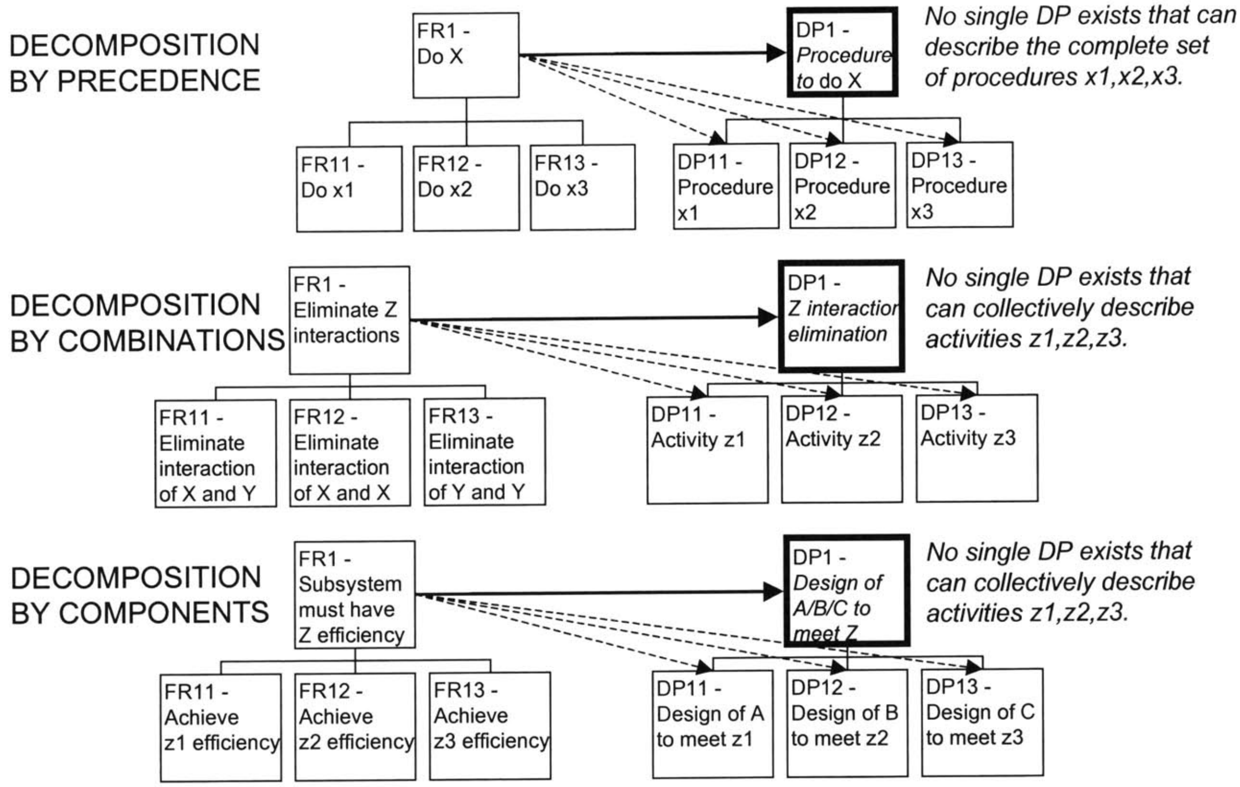


Figure 3.34 Observed decomposition patterns in the MSD decomposition. Intermediate DPs used as mechanisms to get to lower level sub-FRs and more concrete DPs.

The second type of decomposition pattern identified is that based on enumerating all possible combinations of sub-FRs. Combinations are found to arise in cases where specific relational conditions must be met and all the possible interactions have to be described. A generic example is given in Figure 3.34 where the requirement to eliminate Z interaction is further refined at the next level into combinations of interactions between entities X and Y. In this case, the Z interaction is decomposed into a set of possible X and Y interactions. An example of this type of decomposition was discussed in the previous section for reducing systematic operational delays. Here, production interruptions caused by interactions between support and production resources is analogous to X and Y interactions in Figure 3.34. In this case, the DP is not a specific physical object, rather it refers to a general design task (subsystem design) and instead it is the descriptor that provides the guidance for how to decompose the sub-FRs.

Third, the decomposition of a parent level FR into components is the most prevalent type in the MSDD. Component type decompositions are identified by a parent FR which represents an aggregation of the child FRs. In the decomposition, the most readily observed FR aggregation is based on analytical relations of the type shown in the lower decomposition pattern in Figure 3.34.

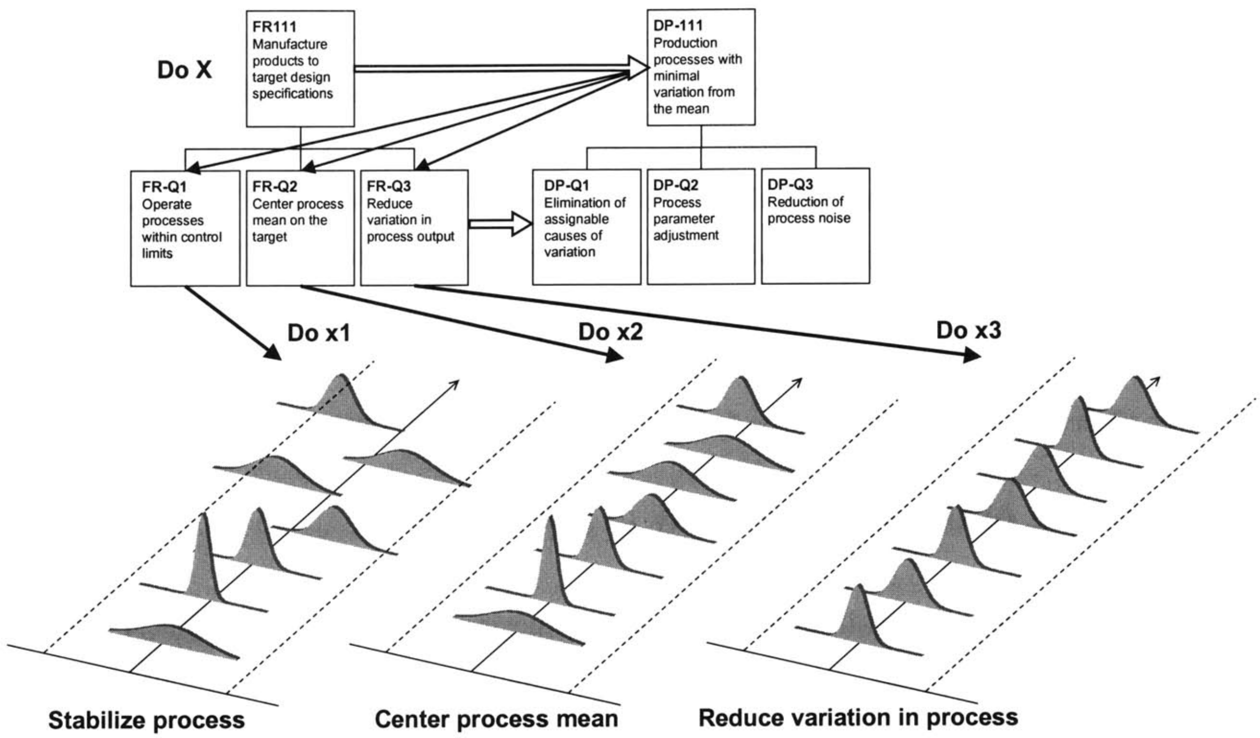


Figure 3.35 Example of precedence decomposition in quality branch of MSD decomposition.

For example, a parent FR for a system efficiency requirement is the product of a set of component efficiencies. An availability requirement such as FR-P1 – minimize production disruptions is decomposed into availability requirements for information, equipment, operators, and material. The reduction of mean throughput time discussed in Section 3.5.4.2, is decomposed according to the delays that comprise non-value added throughput time (see FR-T1,T2,T3,T4,T5 in Figure 3.31).

In summary, the words used in describing the DP to satisfy a FR can sometimes be "intermediate" in the sense that no single term exists that can completely capture the set of sub-FRs that arise in decomposition. In cases where no clear DP is evident, the DP will be a refinement of the FR (the FR is restated as a noun along with additional description) so that the decomposed set of sub-FR reflects the parent FR. The three types of decomposition identified above are used as mechanisms used to get to lower level DPs that can be more concretely expressed in terms of how they satisfy the sub-FRs.

3.6.2 Objectives and Requirements

The development of the decomposition took place in the absence of a specific case, therefore to retain generality of the decomposition of the manufacturing system design, FRs are stated as objectives. The statement of objectives is a result of looking at the problem from a very general, non-specific point of view. The approach taken in the decomposition is that in a specific design case these objective statements would be replaced by measurable values for the requirements. For example, FR-P1 – Minimize production disruptions could be replaced by FR-P1 – Total system disruption time X hours. In this way, the objective requirement is transformed into a quantifiable value that can be verified by a performance measurement system. The distinction between objectives and requirements is described in more detail in Chapter 4.

3.6.3 Nature of the DP Hierarchy in the MSDD

This section examines the resulting structure and composition of DPs in the "physical" domain of the MSDD. The "physical" domain in axiomatic design is the set of DPs that satisfy the FRs and whose physical integration gives the embodiment of the design. In conventional product design, DPs state "how" the FRs is to be achieved and are either physical entities or attributes of such entities. Some examples of DPs may be a geometrical attribute of an object such as its width, or a DP may be a single physical component within a product assembly such as a shaft belonging to a motor. However, a manufacturing system as defined in Section 2.2.1 consists of more than just physical entities and therefore its decomposition can be expected to be different from that of a conventional physical product.

To examine the composition and structure of the DP hierarchy requires analysis and classification of the DPs that emerge from the design process. The analysis approach employed was to identify the main noun in the text for each DP in the MSDD. The benefit of identifying the main DP noun is that it indicates exactly "what" the DP is. In this way, the analysis of the text that makes up each DP is objective because it is based on the grammatical definitions of the parts of speech. Table 3.3 and Table 3.4 show the main DP noun underlined in boldface for all seventy DPs in the decomposition.

An initial observation is that all DPs are noun phrases, that is they are a collection of words that act together as a noun. Furthermore, the main noun is modified in all of the DPs with the modification being reflected by the presence of adjectives before or after the noun. Adjective phrases such as prepositional or participial phrases are used in more extensively modified DPs. Examples of the identification of the main DP noun are given in Figure 3.36 showing two possible types of adjective phrases. In the first case, the DP is the workforce in the manufacturing system. In the second case, the DP is a system, however, since a system by itself is an abstract thing, it requires three adjectives to provide greater description. Similar examples of DP-P133 include DP-111, DP-D23, DP-T21, and DP-T223. Having identified the main DP nouns for all the DPs, it becomes possible to more easily characterize the "physical" domain based on this set of main nouns since they have been stripped of modifiers.

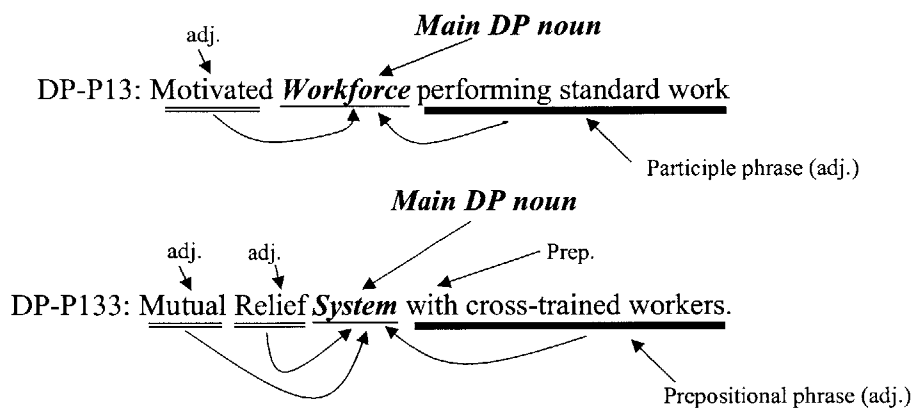


Figure 3.36 Examples of identification of the main DP noun and related parts of speech.

By identifying main DP nouns in this manner, seven DP-types were derived from the resulting list in Table 3.3 and Table 3.4. The seven DP-types are identified in the MSDD shown in Figure 3.37. In the same figure, a graph is given of the number of occurrences of each DP-type in the MSDD. For some types, the main DP noun itself determined the DP-type with nouns such as design, method, system, and program. These nouns occur with modifiers to differentiate them from other instances. It is clear that these DP types as standalone words are abstract and can assume different meanings. There may also be some overlap of DPs that fall into each category. The following paragraphs discusses each of these nouns.

An activity is a broad type of category that includes any single action, or set of actions to accomplish a specific objective. For example, *DP-Q1 – Elimination of assignable causes* refers to the activity that describes reducing the occurrence of assignable causes. This activity may be one single task that is performed or a series of tasks. The activity DP-type describes many abstract nouns that are formed by converting a verb by use of a *–ion* ending. Hence, main DP nouns such as reduct*ion*, convers*ion*, eliminat*ion*, definit*ion* or grouping (a gerund) fall into this category. A DP-type that could be defined as an activity but instead appears as a separate category is the noun design. Though design is also an abstract activity (in the sense that it has multiple interpretations), the DPs having the word design are made explicit by the use of modifiers. For example there may be different ways to carry out *DP-D2 – Design of workstations/workloops to facilitate operator tasks*, but the objective of the design task remains clear despite not stating specific design tasks.

The manufacturing process DP-type describes all the nouns related to production, operations, and core physical transformation processes. Since a manufacturing process was defined in Section 2.2.1 as the transformation of materials from one state into another with the use of energy and information, DPs such as *DP-D3 – Balanced workloops* and *DP-I2 – Seamless information flow* fall into this category.

The physical entity DP-type includes all the DPs that are actual physical objects in the manufacturing system such as equipment, people, materials or other tangible items (i.e. *DP-D12 – Workers trained to operate multiple stations*). Methods and procedures together fall under the method DP-type.

A method is a set of tasks that must be undertaken to satisfy the FR. For this reason, a procedure may be used interchangeably with method as given in the *DP-R1 – Procedure for detection and response to production disruptions*.

The word system is an abstract noun, and therefore depends on the modifiers to specify exactly "what" type of system the DP refers to.

Finally, the program DP-type arises in cases where the DP may be a set of methods but likely includes other attributes. For example, *DP-Q14 Supplier quality program* may include methods to certify a company as a high quality supplier, but could also include information sharing protocols to provide better knowledge of assignable causes of variation.

Given this preliminary classification of DPs in the hierarchy, the structure may now be examined in greater detail for patterns and relationships. First, the seven types of DPs are abstract concepts and therefore require much qualification and modification to clarify and make their usage more specific. A direct effect that the abstract nature of the DPs have on the structure is that no distinct architecture nor linkages between DPs can be seen solely by examining the main DP nouns. Also, there is no pattern of parent-child relationships amongst the seven types of DPs. Furthermore, since the selection of some of the main DP nouns is dependent on the designer, the DP-types methods, procedures, programs are interchangeable. However, extensive use of adjectives and adjective phrases to clarify meaning is offset by a possible reduction in the strength of the main DP noun (i.e. *DP-R111 Increased operator sampling rate of equipment status*). Also, there is a risk of not being able to clearly identify the noun with the use of multiple adjectives.

In Figure 3.37 the biggest group of DP-types are activities which may be also augmented by design, methods, programs, and manufacturing processes. These four DP-types may also be defined as activities because they represent tasks that must be further specified in detailed design of the manufacturing system. In comparison, the physical entities do not represent completed designs, rather the entities are qualified by adjectives that describe how they should be designed to satisfy the FR. Such abstract DPs further reflect the conceptual design nature of the MSDD.

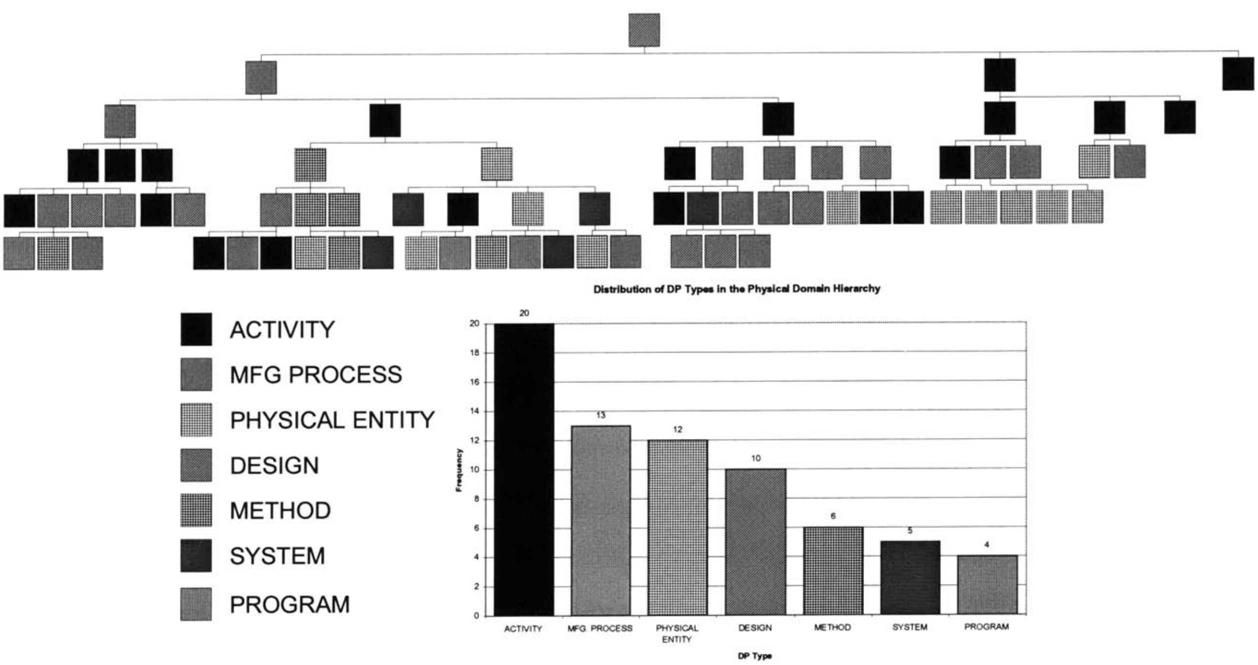


Figure 3.37 DP-types in the physical domain and the frequency of each type.

Figure 3.37 also permits examination of the MSDD physical hierarchy to view how these types of DPs are interconnected or integrated. An initial examination for patterns or concentrations of DP-types in the hierarchy does not reveal any significant pattern. Also, there are no discernible patterns from high to low levels between the types of DPs. However, different branches of the MSDD reflect the type of detailed system design that must later occur. For example, the quality branch is made up of three activities that must be carried out to ensure high quality processes. The quality branch also contains specification of manufacturing processes that must be designed so as to in agreement with the high-level quality requirements.

Another pattern that is discernible in Figure 3.37 is the distribution of physical entities that are dispersed throughout the hierarchy. The dispersion of physical entities DPs reflects that the MSDD is not a hardware representation, but rather a collection of components of a manufacturing system that become specified through later detailed design. For example, the DPs describe attributes of equipment but no specific self-contained piece of equipment emerges in the DP hierarchy. This is an important finding since no system architecture is developed as a result of decomposition. A system architecture only becomes evident once other systems-design tools and methods are applied to meet the set of FRs contained in the MSDD.

Table 3.3 Analysis and classification of the DP hierarchy.

Pair	DP showing **Main DP noun**	DP Type
1	Manufacturing system **design**	DESIGN
11	**Production** to maximize customer satisfaction	MFG. PROCESS
12	**Elimination** of non-value adding sources of cost	ACTIVITY
13	**Investment** based on a long term system strategy	ACTIVITY
111	Production **processes** with minimal variation from the target	MFG. PROCESS
112	Throughput time variation **reduction**	ACTIVITY
113	Mean throughput time **reduction**	ACTIVITY
121	**Elimination** of non-value adding manual tasks	ACTIVITY
122	**Reduction** of indirect labor tasks	ACTIVITY
123	**Reduction** of consumed floor space	ACTIVITY
D1	Human-Machine **separation**	ACTIVITY
D11	**Machines & stations** designed to run autonomously	PHYSICAL ENTITY
D12	**Workers** trained to operate multiple stations	PHYSICAL ENTITY
D2	**Design** of workstations / work-loops to facilitate operator tasks	DESIGN
D21	**Machines & stations** configured to reduce walking distance	PHYSICAL ENTITY
D22	**Standard tools & equipment** located at each station (5S)	PHYSICAL ENTITY
D23	Ergonomic **interface** between the worker, machine and fixture	PHYSICAL ENTITY
D3	Balanced **work-loops**	MFG. PROCESS
I1	Self directed work **teams**	PHYSICAL ENTITY
I2	Seamless information **flow**	MFG. PROCESS
P1	Predictable production **resources** (people, equipment, info)	PHYSICAL ENTITY
P11	Capable and reliable information **system**	SYSTEM
P12	**Maintenance** of equipment reliability	ACTIVITY
P121	**Machines** designed for serviceability	PHYSICAL ENTITY
P122	Regular preventative maintenance **program**	PROGRAM
P13	Motivated **work-force** performing standard work	PHYSICAL ENTITY
P131	Standard work **methods** to provide repeatable processing time	METHOD
P132	Perfect Attendance **Program**	PROGRAM
P133	Mutual Relief **System** with cross-trained workers	SYSTEM
P14	Standard material replenishment **system**	SYSTEM
P141	Standard **work-in-process** between sub-systems	PHYSICAL ENTITY
P142	**Parts** moved to downstream operations according to pitch*	MFG. PROCESS
Q1	**Elimination** of assignable causes of variation	ACTIVITY
Q11	Failure mode and effects **analysis**	ACTIVITY
Q12	Stable **output** from operators	MFG. PROCESS
Q121	Training **program**	PROGRAM
Q122	Standard work **methods**	METHOD
Q123	Mistake proof **operations** (Poka-Yoke)	MFG. PROCESS
Q13	Process plan **design**	DESIGN
Q14	Supplier quality **program**	PROGRAM
Q2	Process parameter **adjustment**	ACTIVITY
Q3	**Reduction** of process noise	ACTIVITY
Q31	**Conversion** of common causes into assignable causes	ACTIVITY
Q32	Robust process **design**	DESIGN

Table 3.4 Analysis and classification of the DP hierarchy (con't).

Pair	DP showing **Main DP noun**	DP Type
R1	**Procedure** for detection & response to production disruptions	METHOD
R11	Subsystem **configuration** to enable operator's detection of disruptions	DESIGN
R111	Increased operator sampling **rate** of equipment status	ACTIVITY
R112	Simplified material flow **paths**	MFG. PROCESS
R113	Context sensitive **feedback**	ACTIVITY
R12	**Process** for feedback of operation's state	METHOD
R121	Specified support **resources** for each failure mode	PHYSICAL ENTITY
R122	Rapid support contact **procedure**	METHOD
R123	**System** that conveys what the disruption is	SYSTEM
R13	Standard **method** to identify and eliminate root cause	METHOD
T1	**Reduction** of transfer batch size (single-piece flow)	ACTIVITY
T2	**Production** balanced according to takt time	MFG. PROCESS
T21	**Definition or grouping** of customers to achieve takt times within an ideal range	ACTIVITY
T22	**Subsystem** enabled to meet the desired takt time	SYSTEM
T221	**Design** of appropriate automatic work content at each station	DESIGN
T222	**Design** of appropriate operator work content/loops	DESIGN
T223	Staggered **production** of parts with different cycle times	MFG. PROCESS
T23	**Arrival** of parts at downstream operations according to pitch	MFG. PROCESS
T3	**Production** of the desired mix and quantity during each demand interval	MFG. PROCESS
T31	Information **flow** from downstream customer	MFG. PROCESS
T32	Quick changeover **design** for material handling and equipment	DESIGN
T4	Material flow oriented layout **design**	DESIGN
T5	Subsystem **design** to avoid production interruptions	DESIGN
T51	**Subsystems and equipment** configured to separate support and production access req'ts	PHYSICAL ENTITY
T52	**Coordination and separation** of production work patterns	ACTIVITY
T53	**Coordination and separation** of support work patterns	ACTIVITY

3.7 Chapter Summary

This chapter presented the development of the Manufacturing System Design Decomposition (MSDD). The motivation for its development was to provide a tool and a method to guide the initial concept design phases for manufacturing systems from the statement of high-level business objectives to detailed design requirements. Also, the basic assumptions and the scope of the MSDD were given. Furthermore, a classification technique based on the parts of speech was used to identify decomposition patterns and structural characteristics of the MSDD.

This chapter also presented a comparison with the FRs/DPs of the MSDD to the six steps of the INCOSE systems engineering process. The result of the comparison was that the majority of high-level FRs corresponded to the system objectives definition stage. The high-level description of the MSDD was given by examination of the ROI, Customer Satisfaction, Quality and Delivery branches. Also, the application of Axiomatic Design to manufacturing system design was considered in the analysis of the main DP nouns. The analysis of the main DP was performed to characterize the DP hierarchy. The results indicated that the DP hierarchy is predominantly a specification of general activities such as manufacturing processes, methods, and programs.

Section 3.6 also showed that decomposition at the conceptual manufacturing system design stage is difficult because high-level FRs and DPs are not yet specified in detail. Therefore, any type of hardware design at this stage is premature. Furthermore, intermediate DPs arise through decomposition by precedence, combination, and components because the zig-zagging decomposition method prescribed by Axiomatic Design requires statement of a DP for each FR. However, in the absence of detailed knowledge of a specific DP at conceptual design, the intermediate DP i.e. *subsystem design*, *procedure to…* instead must be used. Designers should be aware of these decomposition patterns when decomposing at high levels of abstraction. Clausing (1989) has indicated that designers can be confused when using relatively subjective and unstructured decomposition approaches when analyzing disparate decomposition trees.

Finally, it was observed that the semantics of FRs and DPs affect the textual representation and understanding of the design decomposition. Thus, the descriptive nature of the FRs and DPs from the highest to lowest levels depends on the selection of words by designers. The sequences and patterns of decomposition are not always simple nor obvious. Recognition of the different types of patterns that may arise along with examples was performed on the MSDD using grammatical analysis. The next chapter considers the development of an approach that introduces systems engineering tools to allow usage of FRs/DPs from the MSDD for equipment design.

Chapter 4 An Equipment Design Approach

4.1 Introduction

The Manufacturing System Design Decomposition (MSDD) presented in Chapter 3 provides a description for high-level system objectives. However, this decomposition is the starting point for subsequent detailed design of subsystems including equipment. Since manufacturing plants typically have many different types of equipment, it is important to have a process by which diverse system requirements can be communicated to designers of all types of equipment. Therefore, the focus of this chapter is the presentation of an approach that provides a process to design equipment that meets the requirements of the manufacturing system. The approach is an integrated set of steps that describe the procedural aspects leading to the specification of an equipment design.

The purpose of this equipment design approach is twofold. First, the approach addresses how a decomposition of manufacturing system requirements can be extended to design equipment. Second, the approach incorporates methods that deal with decomposition issues that arise from the application of Axiomatic Design to manufacturing system design. In particular, these issues include the nature of the resultant manufacturing system physical hierarchy, the textual expression of design parameters, and the decomposition process for generating sub-FRs. The approach consists of four steps:

1. Identification of the set of manufacturing system requirements that affect equipment design.
2. Transformation and communication of requirements to the various types of equipment designers.
3. Analysis of system requirements
4. Design and decomposition of system requirements into equipment parameters

Details of each step are explained using an example equipment decomposition of a CNC lathe and the steps are given in the context of an equipment design lifecycle.

4.2 Overview of the Equipment Design Process

This first section describes what is meant by design of equipment and the activities that define an equipment lifecycle. Also, the field of equipment design is reviewed to illustrate both the type and scope of design problems and approaches available both in research and in industrial practice. In this work, the activity that is equipment design is assumed to take place in companies that manufacture physical goods. The equipment design lifecycle is given by the sequence of events beginning with the identification of the required equipment function, its design and engineering, through to operation and its eventual decommissioning.

4.2.1 Equipment Design Definition

The words machine and equipment are often used interchangeably and therefore the potential exists for confusion about the respective meanings. According to the Merriam-Webster Dictionary (1993), a machine is defined as "an assemblage of parts that transmit forces, motion, and energy one to another in a predetermined manner." Equipment is defined as "the implements used in an operation or activity." The former definition is focused more on the mechanical behavior and interaction of a machine's components, whereas the latter definition is more general and focused on the purpose of equipment to perform an operation. In this work, the term "equipment" is used because of this more general and non-component specific definition.

Also, since the context of this work is manufacturing systems, the term equipment should reflect the idea that equipment is meant to perform operations. Therefore, equipment is defined in this work as a device that directly or indirectly transforms a product from one state to another and/or supports other equipment. Equipment can also include material transport devices (i.e. forklifts) and facilities equipment (i.e. building air conditioners) that despite not transforming the physical state of a product, are necessary for the proper functioning of other equipment within the manufacturing system. The term equipment design also applies to the design of equipment subsystems. For example, a material handling device (i.e. robot arm) that loads and unloads parts would also be considered equipment though it does not directly transform the product.

4.2.2 The Equipment Design Environment

In developing an equipment design process, it is not only important to define the tasks, but also to consider and describe the external influences placed on the designer. Therefore, the equipment design environment may be characterized by the types of challenges faced by designers. First, the dynamic nature of product development, with new products continually being introduced and existing products being modified, creates a great deal of uncertainty in expected future requirements and performance of equipment. In addition, equipment designs have to be robust to operate in manufacturing systems that can often have a great deal of variability in operational conditions. For example, the inherent variability that exists with human operators favors robust design solutions to meet requirements.

Also, equipment design is carried out in increasingly more distributed and decentralized organizational structures, and therefore traditional command and control project management approaches are no longer as effective (Gouvinhas, 1999). For example, many companies outsource the design of equipment and therefore the management of the equipment design process relies on how well people within the company itself understand its equipment needs (Fine, 1996). Equipment design companies in turn outsource the design of subsystems and components to other suppliers. The result is an equipment design supply chain that must be viewed from the same system perspective as that of the manufacturing system. Therefore, the equipment design process extends beyond the boundaries of any single company in this chain and information sharing approaches become critical to ensuring all requirements are met.

Another characteristic of the design environment is that it is highly variable in terms of the methods used and customer applications. Furthermore, equipment designers do not often have access to large amounts of operational data in the context of manufacturing systems. Also, the quantity of equipment manufactured is generally lower compared to the quantity of the products manufactured. Moreover, in cases where equipment designs are subject to frequent customization by the customer, the use of standardized design methods is difficult to implement since there is much iteration in the design process. Gouvinhas (1999) in a survey of British machine tool companies found that formal design methods are rarely used and instead informal design review meetings and brainstorming sessions are the most common design approach employed. Gaining operational knowledge and advancing along the learning curve is difficult since relatively few pieces of equipment are built by one manufacturer (Hayes, 1984). Gathering data to improve future generations of designs is complicated by the diversity of manufacturing systems and the operating conditions into which equipment is placed. Designers are often faced with the difficult task of developing standard equipment to meet such a wide breadth of operating requirements. Equipment designs must also have the flexibility to be modified and improved to fit into the manufacturing system, since not every possibility can be modeled or simulated ahead of time.

4.2.3 General Equipment Design Activities

This section defines the scope of activities for an equipment design approach. First, it is difficult to completely distinguish the activities performed during equipment design from those of a general product design process. The activities associated with the design of a product are in reality no different than those associated with equipment. However, the difference that exists between a consumer product and a piece of equipment lies in the respective functional requirements. The main functional requirement of a piece of equipment[12] is to transform a product from one state to the next, whereas a product must perform specific function(s) to satisfy the needs of its customer. If equipment is also assumed to be designed for a customer (i.e. a downstream process), then the description of product design activities may be viewed from an equipment design perspective without any loss of generality.

There are many valid descriptions and representations of the steps that occur during design. The work of researchers such as (Shigley, 1983; Ulmann, 1992; Pahl. 1984; Eppinger, 1995) are some well known texts from the design literature. Though each of these design processes is slightly different, all give similar descriptions of the design process. These design processes may be broadly summarized in the main steps shown in Figure 4.38 and augmented with the equipment design perspective.

Design begins with the search for a solution to satisfy a recognized customer need. There may be different ways to satisfy the need and the purpose of concept generation is to develop many feasible solutions so that the concept with the greatest likelihood of best satisfying the customer need is found. Slocum (1992) proposes the use of the Analytical Hierarchy Process

[12] Equipment have additional FRs such as transferring parts, removing waste by-products, etc.

(AHP) (Saaty, 1980) to select amongst early equipment design concepts. Other concept selection methods such as the Pugh conception selection matrices may be also used (Pugh, 1991).

Once a concept has been selected the next step is to create the system-level description of the chosen design. The description includes development of the physical architecture that will provide the desired product function. Specifying system architecture includes defining the types of components that will be integrated or connected to one another. At this level of abstraction, a general description of the components is sufficient, for example it is important to know the number of axes that a machine will have as well as approximate estimates for characteristics of the motors that will drive each axis (i.e. hp, feedrates).

The last stage in this description of a general equipment design process is that of detailed engineering design where nominal values are assigned for component parameters based on performance requirements. Tolerances on these parameters are allocated based on manufacturing cost models and process constraints (Krishnaswami, 1994; Chase, 1991; Greenwood, 1988). For example, in equipment design, the mounting locations (and their tolerances) for components to mate onto the structure are determined at this stage. The engineering description of the equipment design is complete at this point and further steps serve to refine the design by use of prototyping, testing, and optimization tools, i.e. Robust Design (Feng, 1997).

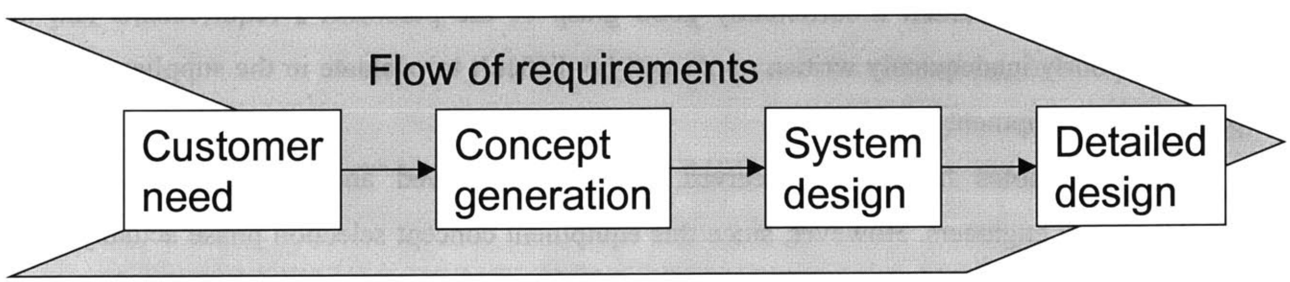


Figure 4.38 A general design process also applicable to an equipment design process.

4.2.4 The Equipment Design Lifecycle

Many texts written on machine design (Shigley, 1983; Spotts, 1998) focus on the design of the elements or components that make up a machine. However, relatively little mention is made of the design of the assemblage of components that make up a machine system. Recently, texts on machine design (Slocum, 1992; Haramata, 1999) have mentioned the machine as a system and the development of a machine design. Haramata proposes specific tasks that comprise a machine design process.

Figure 4.39 below illustrates a typical sequence of steps that companies follow when acquiring new equipment. Initially, product and manufacturing system design concurrently contribute to the generation of equipment requirements[13]. The capability to write specifications that capture the requirements of a system has been described as a key core competency representative of successful advanced manufacturing firms (Whitney, 1993). The next step in the process is the request for quotes. In large companies, this is a structured and controlled step in which the purchasing organization is usually involved. For smaller companies, request for quotes result from informal meetings with equipment representatives.

During this period of time, companies familiarize themselves with the equipment offerings of the suppliers. Equipment suppliers are then given a certain period of time to generate equipment concepts and submit pricing. This time period will vary depending on the size of project and available production ramp-up time. The amount of time allotted to suppliers here is important because it often affects the quality and thoroughness of the resulting quoted concepts. Companies will often reduce this time and thus place much pressure on its potential set of equipment suppliers. The risk in following this practice is that the equipment quoting engineers will not be able to attain a sufficiently good grasp of the purchaser's requirements and the resulting poorly/inadequately written quote will be difficult to evaluate in the supplier selection phase of the equipment purchase.

Once quotes have been received, they are reviewed and analyzed by primarily manufacturing engineers. However, since this equipment concept selection phase actually is the first stage of equipment design (Figure 4.38), the viewpoints of as many future stakeholders should be considered in the evaluation process. In evaluating a supplier's concept, the details of the quote are checked against the specified system requirements. Not only is evaluation important from a contractual basis, but more importantly, if a key specification has been misunderstood or inadequately satisfied at the concept phase, then high costs may be incurred in correcting the deficiency at later detailed phases.

[13] The writing and generation of these requirements is discussed in greater detail in Chapter 5 of the compressor design case.

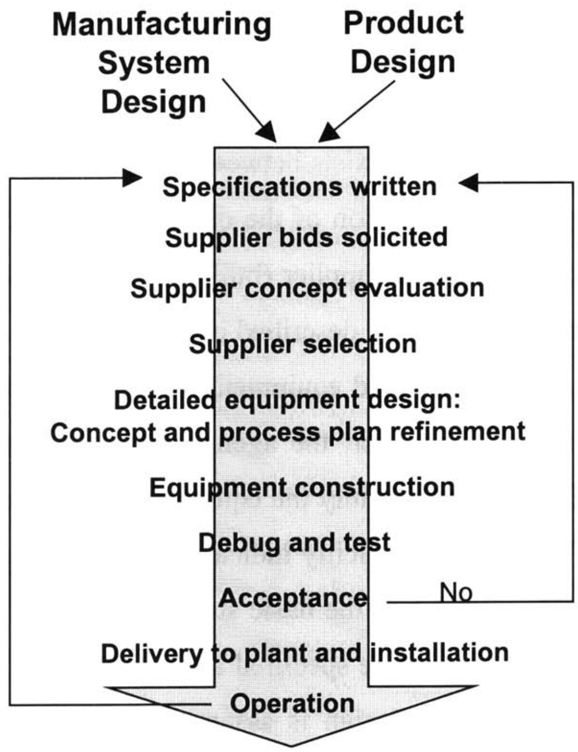


Figure 4.39 Common series of steps involved in the design and acquisition of equipment.

After a supplier has been selected, the detailed design work begins and the requirements that were used to generate approximate concept designs must be translated into actual designs that will be manufactured. During this phase, the initial concept is refined as well as the original process plan for the product. Design of equipment at this stage is a highly multidisciplinary activity involving not only various types of engineers but varying levels of management as well. For this reason, it is important that system requirements be expressed in a form that can be understood by all involved in the equipment design process so that designs can be correctly evaluated and finished according to budget and schedule. Though construction and testing are illustrated sequentially, these two phases should be done concurrently whenever possible. While early component testing does not guarantee an error-free system, risks can be mitigated by testing before completion of system.

Finally, this set of steps is cyclic because the operating knowledge, as well as the experienced gained during design should be fed back to product and manufacturing system designers for each new design. Also, based on each equipment design cycle, specifications should be modified and updated to reflect these recent experiences and additional understanding.

4.2.5 Requirements Definition in Equipment Design Relationships

The successful design of equipment depends on effectively communicating requirements according to the design relationship that exists between the customer and the equipment builder. This section therefore presents a description of the different types of design relations that may exist between purchaser (customer) and supplier (builder). Furthermore, this description is used as a reference for the approach that will be described in Section 4.3.

The previous sections have defined equipment design and the various activities that are undertaken to develop a design. However, the agents (customer and builder) that realize the design must also be described to explain fully the equipment design process. The design process shown above in Figure 4.38 does not explicitly indicate the respective roles of the customer and builder and how they are related (beyond the basic statement of need). In particular, the type of requirements that are transmitted has to be specified according to the relationship between these two agents. In this work, equipment design is assumed to be a collaborative design activity carried out simultaneously by companies that purchase the equipment and by companies that build the equipment. Since there is a wide spectrum of equipment design capabilities that exist in manufacturing firms, the possibility exists that the customer and designer may be both inside the same company. Such is the case at Nippondenso with its own Machinery and Tools division that builds equipment in-house (Whitney, 1993). Alternatively, some companies almost completely turn over the design of equipment to third parties.

To describe the uniqueness of requirements that may arise in these different types of relationships between customer and designer, two characteristics of equipment design are considered. The first is the level of collaboration, or concurrency in the development of the equipment. The second characteristic is the level of customization of equipment to the customer's specific needs. A matrix is given in Figure 4.40 to illustrate the uniqueness of requirements and the development for each category corresponding to the two characteristics of equipment design relationships.

Concurrency (El-Gizawy, 1993; Grigely, 1993; Nevins, 1989) indicates the extent to which the customer and equipment builder design a piece of equipment together. Concurrency in equipment design also reflects the communication and inclusion of requirements into a given design. For example, a standard machine will not require much concurrent design effort with any specific customer because it is meant to satisfy the requirements of a broad set of customers. On the other hand, a greater amount of concurrent engineering is needed when a machine must fulfil a unique set of requirements.

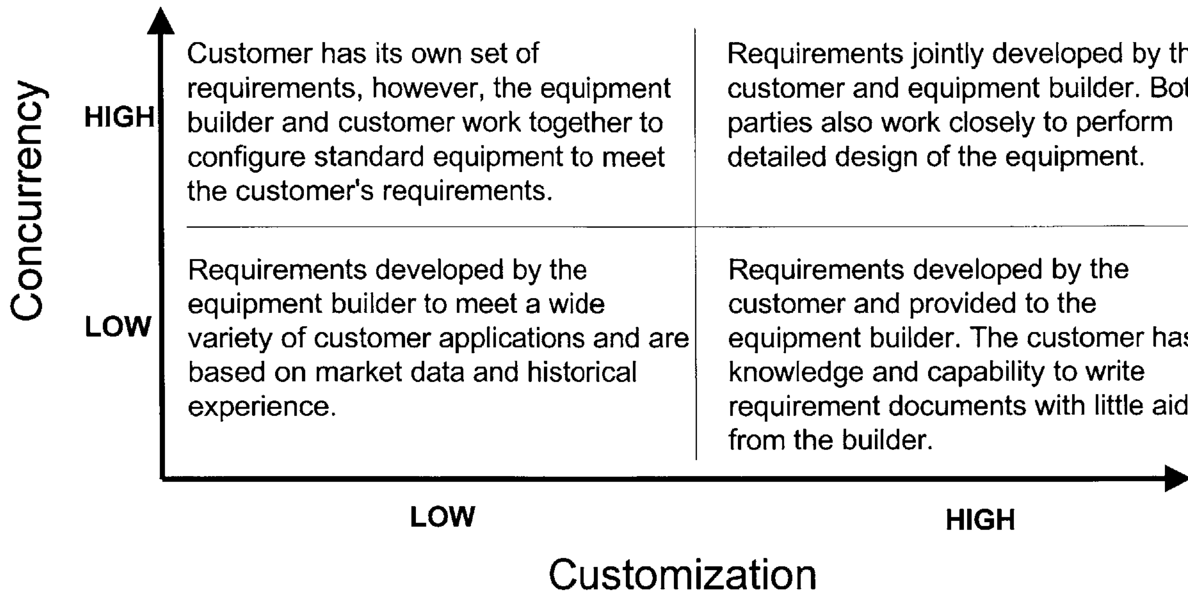


Figure 4.40 Development of equipment requirements in different customer/builder relationships.

The uniqueness of product and manufacturing system requirements is reflected in the degree of equipment customization. If a standard piece of equipment exists that a company may readily purchase for its needs, then requirements that have been used by the builder to develop the equipment for a general market are sufficient. However, if the customer's application calls for design of a custom piece of equipment, then requirements unique to the application have to be developed. Customers that possess strong process knowledge are able to write their own requirements independently of the equipment builder and thus do not need extensive concurrent engineering to develop requirements. In this case, periodic design review meetings are used to ensure that requirements are understood and are correctly being satisfied by the equipment designers.

Finally, the quadrant that a company and its equipment builder depends on a number of different factors. These factors include the complexity of the product and whether equipment builders have built similar (standard) equipment in the past for such products. Also, the size of the company's engineering resources will determine how much in-house design can be done and thus the amount of concurrency undertaken.

4.3 Motivation for an Approach to Equipment Design

Given the previous equipment design lifecycle (Section 4.2.4), the types of requirements and the relations between customer and designer, important attributes for an equipment design process can be proposed. An equipment design process should:

1. Offer improved coordination of related design tasks for members of the design team by knowledge of task dependencies to avoid duplication and errors in work.
2. Capture design reasoning for ongoing and repeated decisions as well as the tradeoffs made between alternative solutions. Such design knowledge helps to avoid repetition of similar design scenarios (i.e. overall station architecture) and increases the speed of the design process.
3. Offer reusability for both the equipment designer and manufacturer in future design projects in terms of specific hardware designed as well as design sequence used.
4. Recognize where and when existing knowledge or tools can be integrated at critical steps in the equipment design process.
5. Offer ease of management and make possible tracking of tasks to ensure that high-level objectives are being met. Also, the equipment design approach should provide the capability to integrate project management tools. With such tools the equipment design approach makes conceptual or time-based bottlenecks "visible."
6. Be well integrated with the manufacturing process plan to ensure product requirements are met. Equipment designers should be able to communicate with product engineers to review product tolerances.
7. Offer support for queries that equipment designers will potentially make of manufacturing system objectives and the relation to other parallel design processes. Queries can be based on hierarchy (from decomposition) or dependency (from design relations).
8. Have the flexibility to handle information in its various representations and map it into the respective decompositions. Design process information can range from machine computable form to strictly human interpretable forms.

Thus, to meet the above attributes this dissertation proposes an Equipment Design Approach (EDA). An approach is defined as the steps by which an equipment design is generated. The main objective of the approach is to address how the MSDD may be used to carry out and support subsystem design in the context of Axiomatic Design.

The approach consists of the four major steps shown in Figure 4.41. The first step deals with identifying the set of system requirements that influence equipment design. Second, this set must be transformed in a manner that permits the requirements to be understood by the various parties involved in the design of equipment. Third, objectives stated in the MSDD must be converted into quantifiable statements of requirements that can be used by equipment designers. The fourth step is to design the equipment to these requirements by use of either Axiomatic Design or an alternative formal design method.[14] The next four sections explain the details of each step.

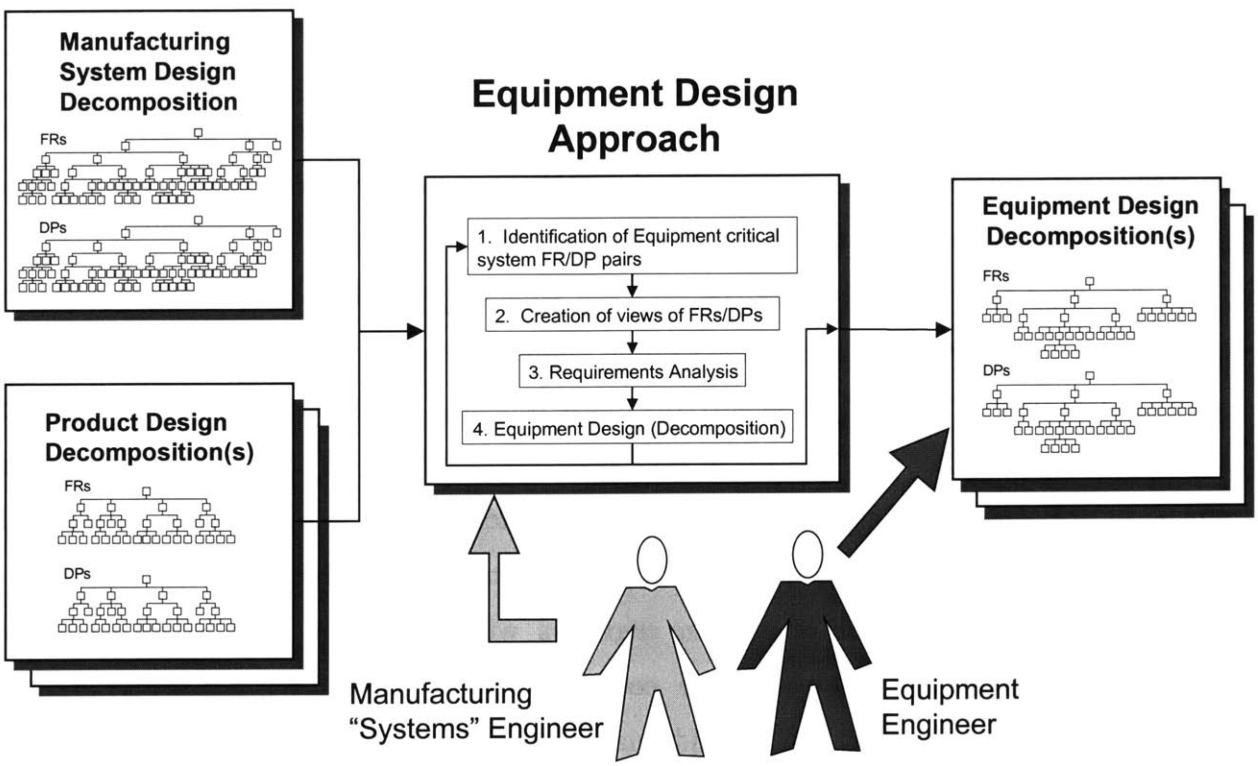


Figure 4.41 Four major steps involved in the Equipment Design Approach (EDA).

[14] The approach gives designers the flexibility to use other design methods that they may already be familiar with. The approach acknowledges that since there is no universally accepted 'best' design methodology, designers should have the freedom to choose the methodology that is appropriate for the design problem at hand.

4.4 Equipment Design Responsibilities and Assumptions

The EDA described above in Figure 4.41 makes several assumptions about the existence of manufacturing system requirements and product design requirements. First, the EDA assumes that such a set of manufacturing system and product design requirements have been generated prior to design of equipment. The EDA makes no assumption about the method employed to generate the set. However, in this work, Axiomatic Design is the method used to decompose manufacturing system requirements (Section 3.6). Similarly, the EDA does not prescribe any specific method for development of product design requirements.

Another assumption that is made reflects the number of distinct sets of requirements. The approach assumes that there is a single manufacturing system decomposition, and a minimum of one or more product decompositions. Also, the EDA can lead to the design of one or more different equipment designs. In the development of the EDA described in the next section, the base case of MSDD requirements is developed and product designs are assumed to exist. Furthermore, conflicts and constraints between manufacturing and product development are assumed to be handled by concurrent engineering tools prior to submittal to the EDA. It is also assumed that product design is the starting point for the EDA.

The third type of assumption concerns the knowledge of high-level configurations of equipment. It is assumed that the manufacturing engineers have a fundamental knowledge of major subsystems that they will either specify or have designed. The scope of the EDA is limited to conventional equipment designs where such basic understanding of the machine function is known. In the case of a completely new custom machine, the basic physics of material transformation can be used as the starting point for equipment design. For example, for a known part geometry, the manufacturing system engineers will have basic knowledge about the equipment structure as in Figure 4.42 (i.e. configurations available for lathes for cylindrical parts) and therefore how a part can be held (via a workholding device) and hold tools (turrets, tool magazines).

The third assumption concerns the abilities of the engineers on the design team. The engineer at the company acquiring the equipment is the manufacturing 'systems' engineer shown in Figure 4.41. Such an engineer is assumed to have the manufacturing system knowledge and is involved in the generation of manufacturing system requirements. Furthermore, through use of concurrent engineering methods and tools, this same engineer has a good understanding of product design requirements. The equipment engineer in addition to core design skills is assumed to have knowledge of other related equipment in the system that interact with his own machine. This knowledge about interactions and dependencies is provided by the MSDD.

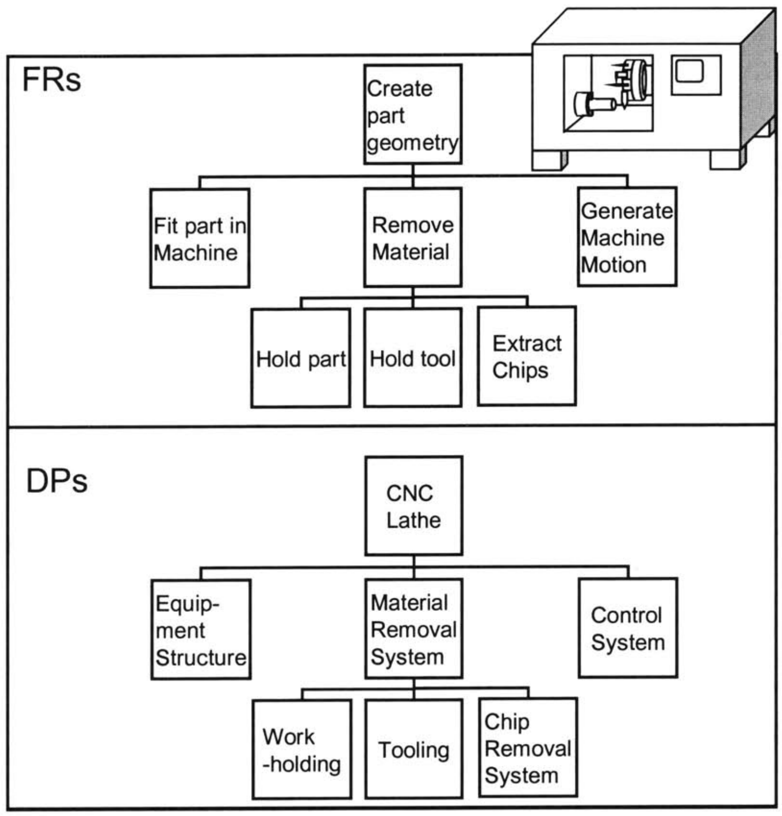


Figure 4.42 High-level subsystem knowledge of a piece of equipment.

Given these abilities and skills of the two representative engineering types they are assigned specific areas of responsibility corresponding to the four EDA steps shown in Figure 4.43. Since the first three steps deal primarily with the transformation of manufacturing system information, this is the responsibility of the manufacturing systems engineer. However, the manufacturing system engineer with high-level knowledge is able to create views of MSDD requirements. The equipment engineer does detailed design, however, the requirements engineering analysis and verification of requirements is a step that he is also aware of. The equipment design engineer must have intimate knowledge of detailed specifications upon which equipment will be expected to perform. Finally, throughout the EDA, it is assumed the requirements from the MSDD are the language for extensive communication and discussion.

Through such rich communication improved understanding of the system results. The next four sections describe the individual steps of the EDA in greater detail.

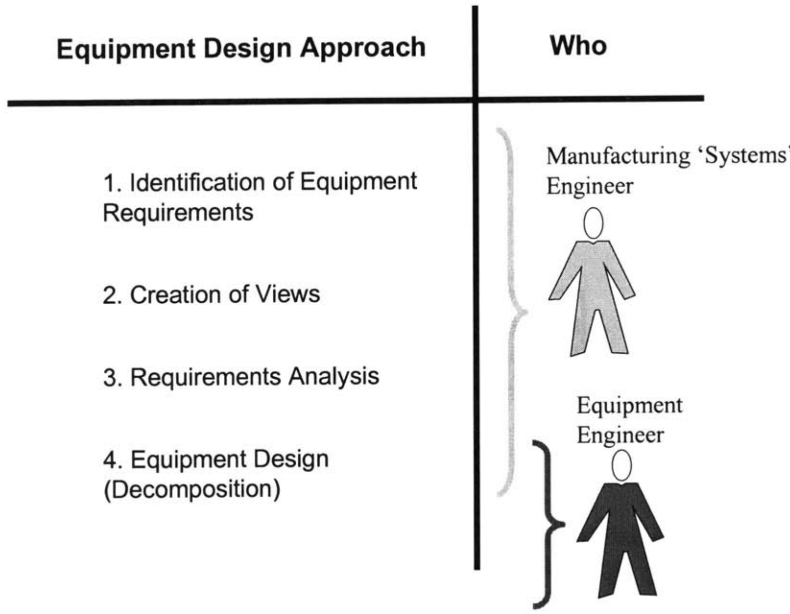


Figure 4.43 Design responsibilities between manufacturing system engineers and equipment engineers.

4.5 Step 1: Identification of Equipment System Requirements

The first step in the equipment design approach is the identification of equipment pertinent FR/DP pairs from the respective MSDD and Product Design (PD) decomposition hierarchies. In a design decomposition of a manufacturing system or a product, there are many pairs that can potentially influence the design of any given piece of equipment. Conceptually, the identification of equipment requirements from the MSDD is shown in Figure 4.44. It is important to examine all system requirements and identify those that are relevant to equipment since overlooked requirements jeopardize operation of the manufacturing system. Moreover, these FR/DP pairs will arise at different stages and levels of detail in the equipment design decomposition. A characteristic of the representation of the MSDD (Section 3.6) is the limited textual descriptions contained in FR/DP "boxes." Concise descriptions are needed to represent all system requirements in a manageable document. However, the tradeoff that is made is that these concise descriptions increase the potential for a designer to overlook a system requirement that influences equipment design. Furthermore, if an equipment designer is simply presented with a long list of system requirements, a systematic method of selecting those that affect specific equipment of interest is also needed.

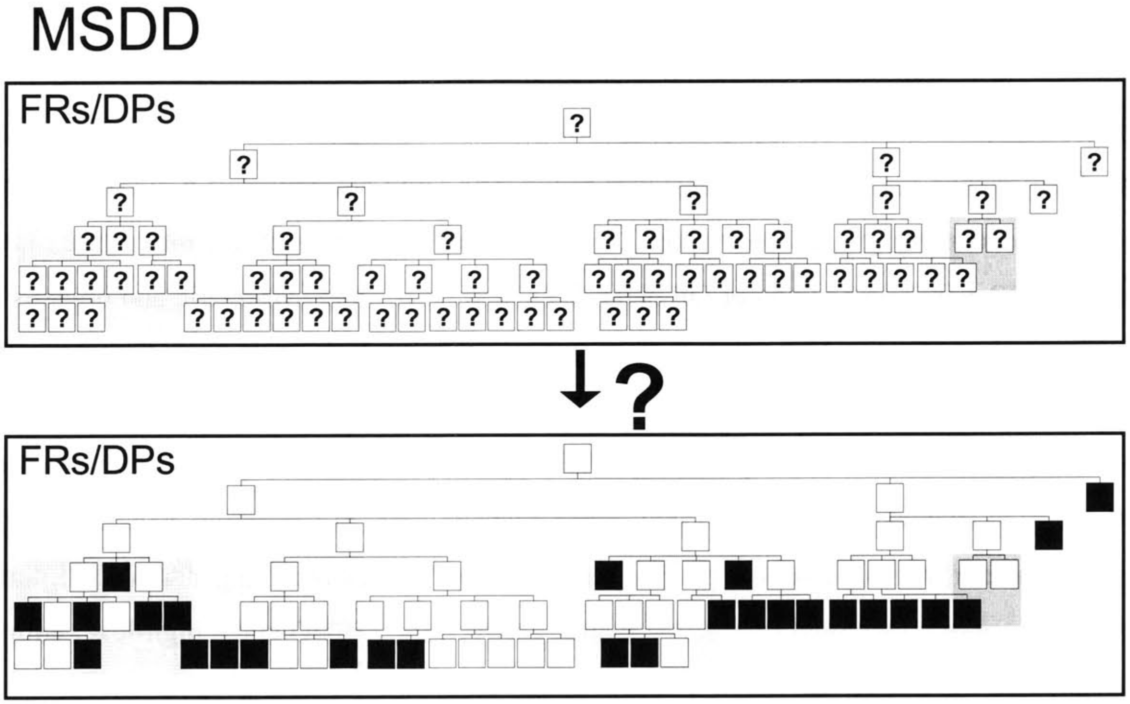


Figure 4.44 Identification of equipment FRs/DPs from the MSDD.

In conventional equipment design procurement (described earlier in Section 4.2.4) the manufacturing system engineers at the most detailed level of design typically select from a long list of requirements. In these situations, equipment design engineers must read through the entire set of requirement documents and manually select the requirements deemed to affect their area of design responsibility. This approach to requirement extraction is highly susceptible to missing important requirements, and perhaps even more critical is the risk of not fully recognizing their importance to the performance of the system. To overcome the obstacles associated with unstructured, text-based searches the first step of the equipment design approach provides two complementary methods:

1. During development of the MSDD and PD decompositions, each FR/DP pair that can influence equipment design in some way is tagged for future usage or other types of searches.

2. A general equipment decomposition is used to test whether a system FR/DP pair affects the equipment design. Alternatively, a knowledge base of data from previously

designed equipment may be used. Using such a database promotes reusability of equipment design data and increases learning for future design projects.

Tagging (identification) of FR/DP pairs during decomposition of either the manufacturing system or product design is performed by immediately asking the question: "Does the FR/DP pair affect the design of equipment?" The accuracy of this method depends on the level of experience that the system designer has in designing equipment. An alternative method is to use a general equipment decomposition that can be used to check for interactions between system FR/DP pairs and equipment DP pairs. This method is more systematic and objective than manual search methods. Also, the method ensures the general equipment decomposition is updated from one design generation to the next (thus providing reusability in the design process).

There are various FR/DP pairs in the MSDD that do not affect equipment and therefore it is necessary to systematically extract equipment-relevant FRs. For example, existing equipment designs combined with operational performance data can also be used to generate the interaction matrix. The use of a weighted interaction matrix between the MSDD and a high-level equipment decomposition is shown in Section 4.5.1 along with the weighting scale for determining influence.

4.5.1 Identifying FR/DP pairs via Interaction Matrices

Since the purpose of the first step is to identify the sources of influence of system requirements on equipment design, interaction matrices are well suited to identify influence relationships. Interaction matrices are a frequently used tool in systems engineering for determining patterns and relationships between sets of requirements (Sage, 1992). Further, cross-interaction matrices (comparisons between two different sets of information) provide additional understanding of structure because links between multiple requirements are also revealed. These patterns of relations at the equipment design level can be then traced back to the identified functional requirements in the MSDD and PD decompositions. A further benefit of using interaction matrices is that they may also be represented as digraphs[15] to which graph theoretic analysis may be applied.

[15] In mathematical graph theory, a digraph is a directed graph composed of unidirectional arcs that connect nodes.

Figure 4.45 shows how an interaction matrix between MSDD FRs/DPs and Equipment DPs is constructed to identify requirements. The equipment DPs originate from a high-level decomposition of a CNC lathe[16] (described in Section 4.4). Each MSDD FR/DP pair is compared against each equipment component and the relationship is ranked according to the amount of influence that the system has on the equipment. The average influence across all equipment components is calculated and indicates the extent to which the MSDD affects equipment. The resultant set of equipment FRs in the MSDD may be then highlighted in the functional hierarchy as indicated in Figure 4.46.

Influence Scale:
3 - Strong influence
2 - Moderate
1 - Weak
0 - No influence

MSDD FRs / DPs		Equipment DPs: DP111: Axes geometry	DP1212: Part clamping devices.	DP1222: Tool block clamping mechanism	DP1225: Tool magazine
FR-Q2	Center process mean on the target	1	0	0	0
DP-Q2	Process parameter adjustment				
FR-Q11	Eliminate machine assignable causes	3	3	3	1
DP-Q11	Failure mode and effects analysis				
FR-Q13	Eliminate method assignable causes	0	3	3	3
DP-Q13	Process plan design				
FR-Q14	Eliminate material assignable causes	0	0	0	0
DP-Q14	Supplier quality program				

Figure 4.45 Interaction matrix used to identify MSDD FRs that influence equipment design DPs.

Once the interaction matrix has been generated for the entire decomposition, the range of influence of MSDD requirements on the equipment may be further analyzed.

[16] Alternatively, other previous equipment designs may be used as the source of DPs in the interaction matrix.

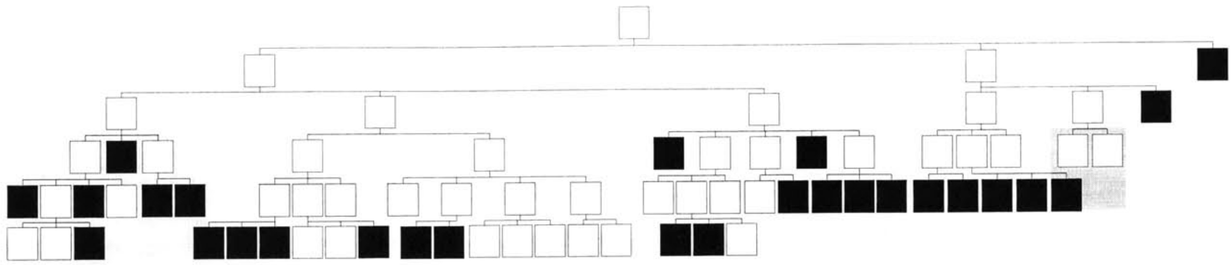


Figure 4.46 MSDD with tagged FR/DP pairs that influence equipment design

4.6 Step 2: Creation of Views of System Requirements for Designers

Once the set of all possible MSDD FRs/DPs that are critical to equipment design have been identified, the set must then be further refined prior to usage by designers. Therefore, the objective of the second step in the approach is the generation of "views" from this initial set of FRs/DPs. A view is a subset of requirements based on equipment design characteristics. It clarifies equipment design by extracting relevant information and can be augmented by explanations to provide designers with further systems understanding.

Views are important for a variety of reasons. Alternate views help to eliminate unnecessary details that detract from the focus of the designer (i.e. the rest of the decomposition). Views also offer different perspectives allowing the designer a better understanding of the manufacturing system. This greater understanding of the system is possible because views are traceable to other system objectives outside of the view. It is important to create views because of the disperse pattern of DPs in the MSDD physical hierarchy that integrate the FRs and maintain functional independence. Recall that in Section 3.6.3, the physical DPs that were identified are spread throughout the hierarchy without a clear physical relationship to bind them together. Since there is no distinct description of how equipment DPs in the MSDD are connected, views must be generated to provide equipment designers with a common base for making associations between DPs.

To create a view first requires a criterion for selecting a subset from the total set of equipment related DPs in the MSDD. There are many types of criteria to extract such a subset. One possibility is to base the criteria on domain experts. In this way, DPs are allocated to the designer with expertise in the discipline (i.e. control, mechanical, electrical engineering). The result is a set of views that are specific to each one of the possible design disciplines. The drawback of this type of criteria is that it has limited effectiveness in projects that depend on a great deal of multidisciplinary interaction such as in concurrent engineering. Another criteria possible is the use of equipment subsystem domains. Using previous design knowledge[17], the equipment DPs may be grouped into sets resembling the equipment subsystems[18]. As a proxy for this prior design knowledge, an example equipment design decomposition from a CNC lathe is used as the basis for creating views. Figure 4.47 below gives the reduced set of requirements (shaded in gray) from the MSDD that correspond to those that a designer of workholding devices would have to meet.

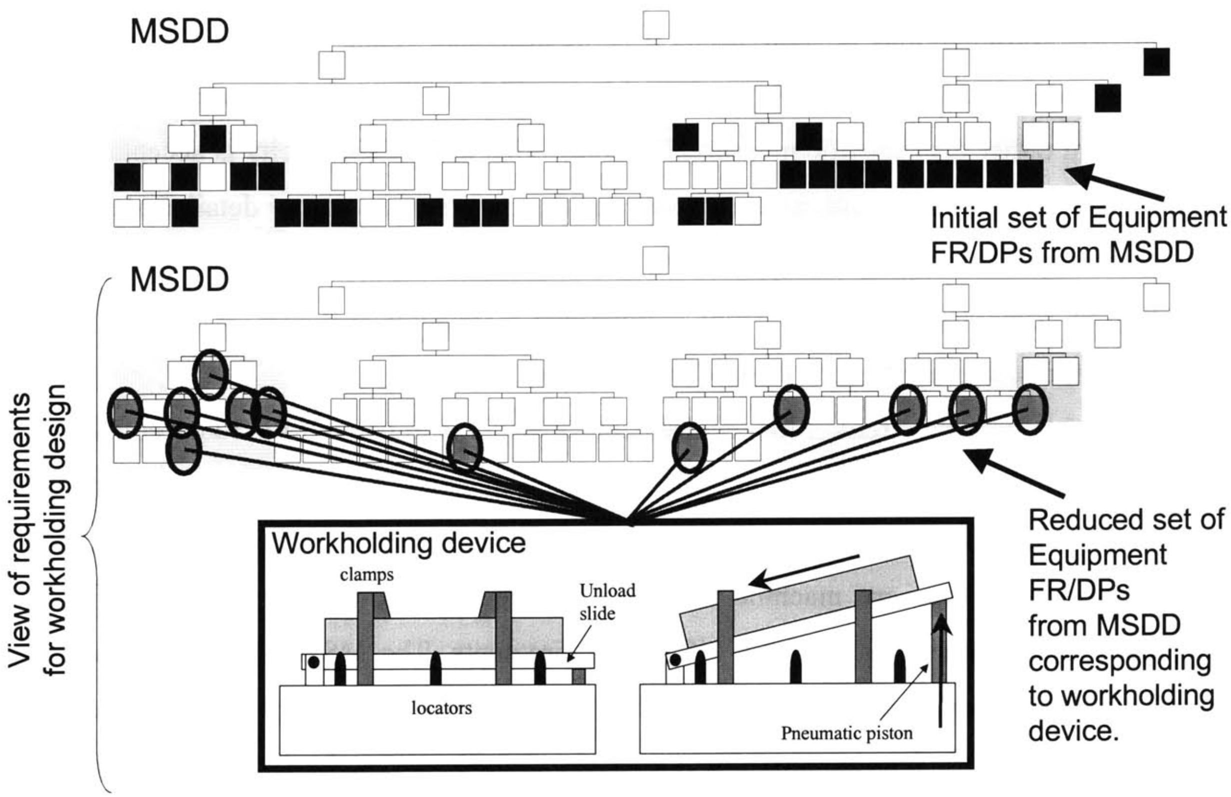


Figure 4.47 View of requirements for workholding design.

Depending on the equipment subsystem the view of MSDD requirements may result in a list of specification values that the equipment must meet, or the view may additionally require explanations to augment the values. An example of the former case is a process plan (a list of steps with specific values) derived from product design requirements. In the latter case,

[17] See Section 4.4 for assumptions about initial high-level equipment knowledge.

specifying the interaction of the operator with equipment may require supplementary descriptions to fully explain the behavior of the user interface. Another reason for augmenting specification lists with contextual descriptions is to provide system understanding for managers and project leaders. These managers while not directly involved in detailed design, still require an abstracted level of understanding because of their roles as decision-makers.

4.7 Step 3: Requirements Analysis of the MSDD Equipment FRs

The third step in the equipment design approach is to express equipment FRs from the MSDD in a quantitative form that may be more easily used by designers. Since the MSDD is developed at a conceptual design stage, many FRs are stated in an objective form that express desirable goals of the system rather than specific measurable values. This lack of specificity is acceptable in the early concept design stages, but, as equipment design reaches increasingly detailed stages, there is a need to express design goals in a form that can be used for detailed engineering design. It is necessary to convert goal-like FRs into requirement statements that can be verified through measurement or other verification techniques.

Another important reason for requirements analysis is to convert the requirements closer to a form that can be used for design and automated analysis. Since the requirements in the MSDD exist in a natural language form they cannot be analyzed quantitatively or executed automatically until they are machine recognizable. The first level conversion that must be performed is the classification of the MSDD requirements. The MSDD is small enough that classification may be manually performed, however, if manual techniques are infeasible for larger decompositions, then automatic text analysis algorithms may be substituted. Developing data associations and assigning variables to the natural language forms for the FRs/DPs then follows after the initial classification. Though beyond the scope of this work, search algorithms can be used later to organize and translate natural language requirements into forms that automated tools can verify and check for consistency.

The next section reviews a preliminary classification scheme that can be used to organize the equipment FRs into categories that aid in the conversion to specific requirement statements.

[18] Those the criteria is derived from "bottom" information, it does not change the "top-down" nature of the decomposition process, the criteria is only used to create views, not to decompose.

Also, examples are given to illustrate the conversion of FRs in an objective form to a more quantitative and verifiable form along with a summary of the analysis.

4.7.1 Relation to Requirements Engineering

The third step of the equipment approach borrows analysis concepts from the field of requirements engineering. Requirements engineering is an integral part of systems engineering particularly in the initial stages of a systems design project. The requirements engineering field has been traditionally influenced by military, aerospace, and government projects. In these types of projects techniques have been developed to deal with the many volumes of documents containing the rules, regulations, and procedural requirements that have to be met to create a successful project proposal. Also, these projects are very large and employ thousands of people along with many suppliers for the delivery of a single final product. Thus, management of this huge quantity of technical information has led to the development of many requirement tools, analysis, management, and modeling capabilities. More recently, these same tools and methods have migrated to the software development industry because of similar requirements related project management issues (Wasserman, 1996).

4.7.2 Use of a Requirements Classification Taxonomy

One novel aspect of applying the Axiomatic Design method to manufacturing system design is the resultant type of requirements generated. Since a manufacturing system (defined in Section 2.2) is comprised of physical and non-physical elements, equipment designers must be able to simultaneously understand a large variety and amount of interactions. Design problems that are primarily physical in nature lead to homogeneous design parameter hierarchies whose structure resembles that of a product bill-of-materials (Suh, 2000). However, in design problems where there are non-physical aspects to consider, the decomposition of requirements reflects the heterogeneity of both types of elements. Therefore, for decompositions with greater variety in requirements, a classification of scheme can be useful to understand the goals of the design and the overall architecture of the system.

One useful classification scheme is a general taxonomy of requirements that has been developed by Oliver (1997). The classification taxonomy is part of an OO-based systems engineering process and is used to gather and analyze initial information about system requirements. Specifically, systems engineers use the taxonomy during the information requirements definition and assessment phase of the systems engineering process. Oliver developed the taxonomy to "provide a consistent basis" for discussing natural language text requirements along with the method for analyzing all of the information important to systems engineering. Figure 4.48 below gives the taxonomy using the format of Object-Modeling Technology (OMT) graphical symbols that specify the different types of possible associations between requirements.

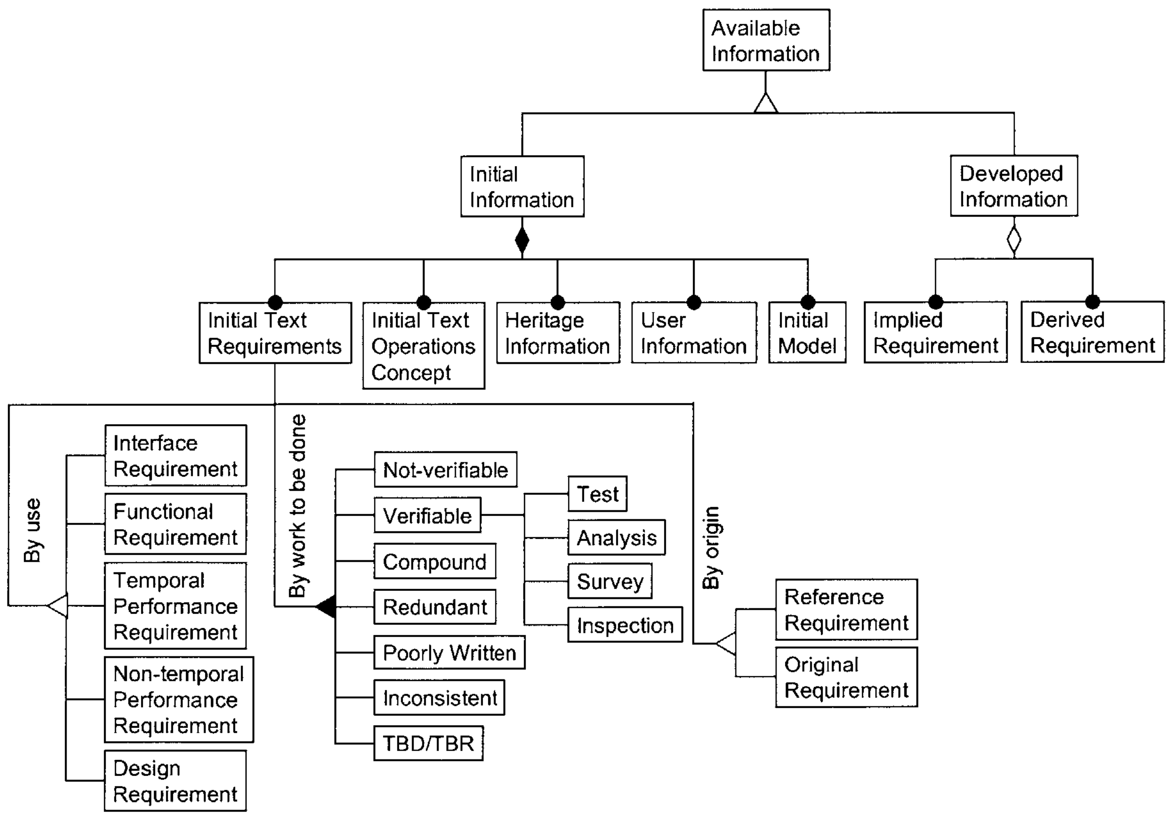


Figure 4.48 Classification and association of requirements based on available information, (Oliver, 1997).

Thus, the third step of the equipment design approach adopts Oliver's taxonomy as a tool to analyze the diverse types of requirements contained in the MSDD. In this step, the taxonomy is interpreted here to reflect the context corresponding to the design of a manufacturing system. The perspective assumed for the taxonomy is that of the manufacturing systems engineer who must organize and classify the requirements in the MSDD so as to communicate them to an equipment designer.

The set of information requirements available to the manufacturing systems engineer is one of two types: initial and developed information. Initial information, as the term suggests, consists of requirements that have already been developed and exist prior to commencement of the formal process of designing the manufacturing system. Developed information refers to requirements that are developed after the design process has begun and are often generated from the initial requirements. The initial information requirements are classified into one of five types: text, operations concept, heritage information, user, and model. Text requirements are the general category for those requirements existing in the form of specification documents or similar forms of publications. Such documentation can be quite voluminous in the case of large manufacturing systems and in companies with many regulatory procedures that must be met.

The initial text operations concept in Figure 4.48 captures the behavioral requirements between the system and its environment. In manufacturing system design, the operations concept may be thought of as the textual description of the relations between a manufacturing system and suppliers. The operations concept also describes the various elements of a manufacturing system from a high level of abstraction.

Heritage information requirements do not have any formal or rigorous development and simply reflect the history and evolution of requirements in other similar systems. In manufacturing systems, heritage requirements are analogous to existing system layouts and equipment that have been evolved over time without use of any specific structured design method.

User requirements originate from the customer, and in manufacturing system design the definition of the customer depends on the scope of the design (i.e. single manufacturing line, section of a plant, plant, group of plants, entire company). Finally, initial model requirements is a general category for any type of model that may have been developed to generate requirements based on order of magnitude estimates. The initial model may exist in the form of a first order simulation, or lumped parameter model that provides basic manufacturing system requirements in the absence of more data and prior to more detailed analysis.

Initial text requirements are further classified in three ways: by origin, by work to be done to correct them, by use. The origin of a requirement may be from a reference source such as a standard (ISO, ASTM, OHSA) or from an original expectation or objective of the manufacturing system stated early in the life of the project (i.e. from a high level management meeting). Some requirements may need to be changed or altered before they can be properly used by the systems engineering team. For example, requirements may need work to correct them because they are unverifiable, redundant, inconsistent, etc. If requirements need verification, test, analysis, survey, or inspection methods can be used to determine nominal values. The third classification of initial text requirements is by use for either modeling or systems analysis (i.e. Functional, Temporal, Nontemporal, Interface, and Design). A description of each of these categories along with two FR examples is given in the next section.

4.7.2.1 Classification of MSDD FRs Using Oliver Taxonomy

The classification of MSDD FRs was performed by considering conventional sources of requirement information available to manufacturing systems engineers. The classification must also include a company's own internal sources of specification documents that provide additional system information. Two examples are shown in Table 4.5 to illustrate potential sources of requirement documents for the category from the taxonomy and how FRs are classified. The definition column provides a general description of the requirement classification category in the context of manufacturing system design.

Table 4.5 Examples of classification of MSDD FRs.

Requirement Classification Category	**Definition**	**FR-Q123** Ensure Operator human errors do not translate to defects.	**FR-R1** Respond rapidly to production disruptions.
Interface Requirement	Requirements that specify the connections between subsystems and components. Includes input/output, flow types and quantities, and timing of these exchanges between subsystems.	Specification of the man-machine interaction. Machine user interfaces (controls, fixtures, sensors)	-
Functional Requirement	State what the system must do. (what it shall do.)	Errors made by human operators shall not result in defects.	The production system shall respond rapidly to disruptions in production.
Temporal Performance Requirement	Requirements that have a time dependence and will change over the life of the system. Dictate the dynamic response of the system to control inputs and noise.	-	Specifies the response time to production disruptions.
Non-temporal Performance Requirement	Specification of time invariant requirements of the system. Includes static quantities such as cost, efficiency, availability, space.	This FR is always true for the life of the production system.	-
Design Requirement	This is a design element that has been already selected. For example, a plant's use of a standard machine switch, or cutting tool holder type. (May be accepted or rejected after further analysis)	-	Plant may have previous response time that it uses.

The first example, FR-Q123 is classified as an interface requirement because it determines the man-machine interaction. In addition, the design of the interaction is subject to meeting a company's safety regulations for controls and sensors on equipment designs. Thus, the equipment designer must design an appropriate user interface that meets the MSDD objective and satisfies safety regulations. FR-Q123 is also classified as a Functional Requirement (in the terminology of Oliver) because it states what the man-machine system must do – it must not produce defects.

The second example, FR-R1 is also classified under three categories.[19] As with FR-Q123, FR-R1 is a Functional Requirement because it states that disruptions shall be responded to rapidly. Since the adverb rapidly is used and implies a time specification, FR-R1 is a temporal performance requirement. Third, FR-R1 is Design Requirement since operational data from the manufacturing system can be used to specify required response times.

The remainder of the MSDD FRs were classified in the manner indicated in Table 4.5 and analyzed by the number of FRs in each requirement category of the taxonomy. The results are given below in Figure 4.49 and show three broad groups that are listed in the legend. The first group identifies the type of requirement as described in the first column of Table 4.5. The second and third groups in the legend further classifies these six types of requirements according to whether they are verifiable (VR) or not (NVR). Almost all of the MSDD FRs (97%) are not verifiable because no measurable parameter is explicitly stated that designers can later use to determine if the system has been correctly designed. This quantity is a reflection of the general goal/objective form of expressing FRs in the MSDD that arise early in concept design. A consequence of general FRs is the need for further explanation that can be provided by view creation in Step 2.

[19] Note that an FR may be classified under more than one category since the categories are not mutually exclusive.

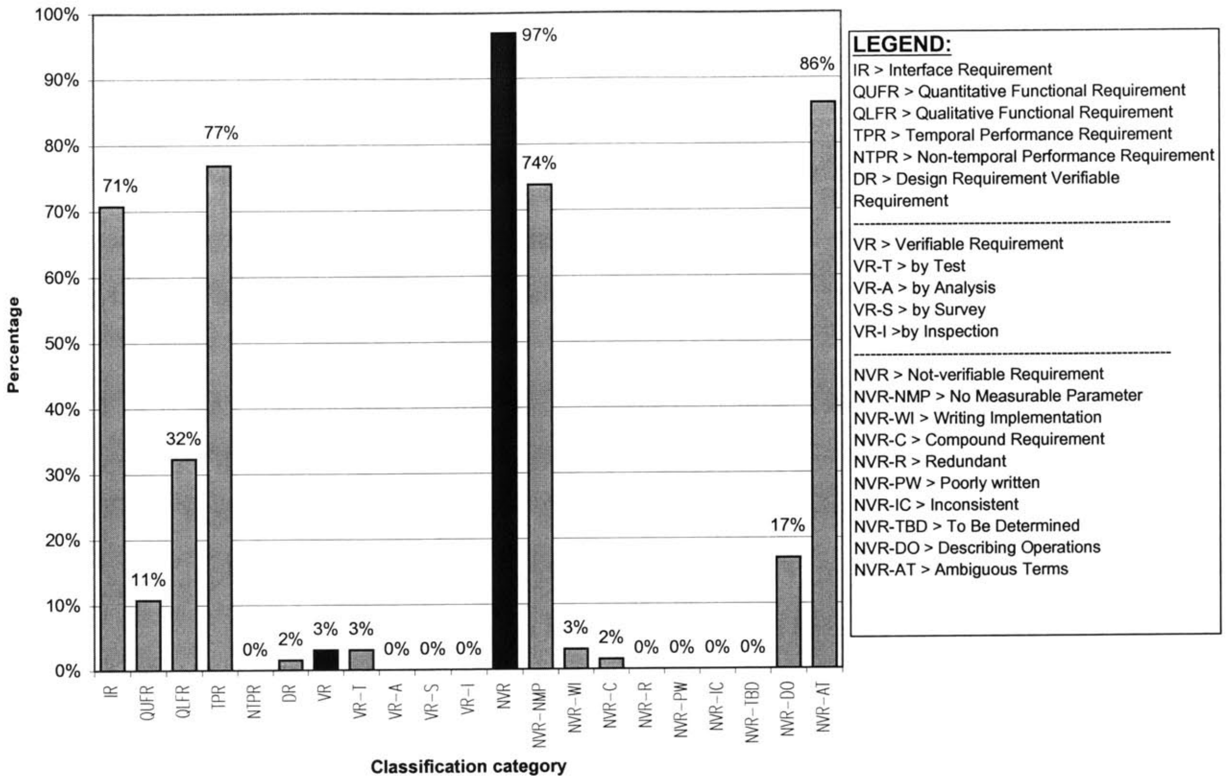


Figure 4.49 Classification of FRs in MSDD.

4.8 Step 4: Equipment Design Decomposition

The fourth step in the approach is the establishment of the link between the MSDD and equipment decomposition(s). Two key elements of this step are the descriptions of how these decompositions are related and how the decomposition process is carried out. Note that this last step is based also on using Axiomatic Design to develop the equipment design. However, the first three steps are independent of design method.

The description of the relationship between decompositions is based on the nature of the DP hierarchy observed in Section 3.6.3. The combination of DPs ranging from physical to non-physical DPs such as methods and activities leads to a different relation between system and subsystem decomposition than that expected from the direct application of axiomatic design. The second element in this step is the process description for how decomposition may be carried out given the types of DPs described above.

4.8.1 Relation between system and subsystem decompositions

In Section 3.6.3 it was observed that the DP hierarchy is not exclusively made up of design objects that appear solely as leaf DPs. That is, terminating leaves are not necessarily specific components that can be integrated into a clearly defined system architecture. Instead, the DPs that arise in the MSDD are a collection of activities, methods, programs that direct or specify the design of various components that may be either physical or non-physical. To contrast this unique characteristic of the MSDD with a typical axiomatic design decomposition of a system, three cases exist for the relation between system-level FR/DP hierarchies and those of single/multiple subsystem/component level hierarchies:

(i) System decomposition and single subsystem decomposition
(ii) MSDD and single ED decomposition
(iii) MSDD and multiple ED decompositions

The first case is shown in Figure 4.50 where a leaf DP is decomposed into two sub-FRs at the subsystem level. Normally, when carrying out the system design decomposition, this type of a leaf DP normally would not be decomposed further because it is a completely described entity in the system architecture. For example, a DP such as an electrical switch would not be further decomposed in the design decomposition for a user control interface[20]. However, if the leaf DP is a distinct subsystem instead of simple component, then in order to continue with the decomposition of the DP requires another hierarchy at a more detailed subsystem level of design as shown in the lower half of Figure 4.50. This process of decomposition across system and subsystem hierarchies is described by the decomposition/mapping Relation 4.1:

$$FR^{system}1113 \xrightarrow{maps} DP^{system}1113 \xrightarrow{decomposes} \begin{Bmatrix} FR^{subsystem}11131 \\ FR^{subsystem}11132 \end{Bmatrix} \xrightarrow{maps} \begin{Bmatrix} DP^{subsystem}11131 \\ DP^{subsystem}11131 \end{Bmatrix} \quad (4.1)$$

[20] Decomposition of FRs must be done until design task can be implemented without further decomposition, Suh (2000).

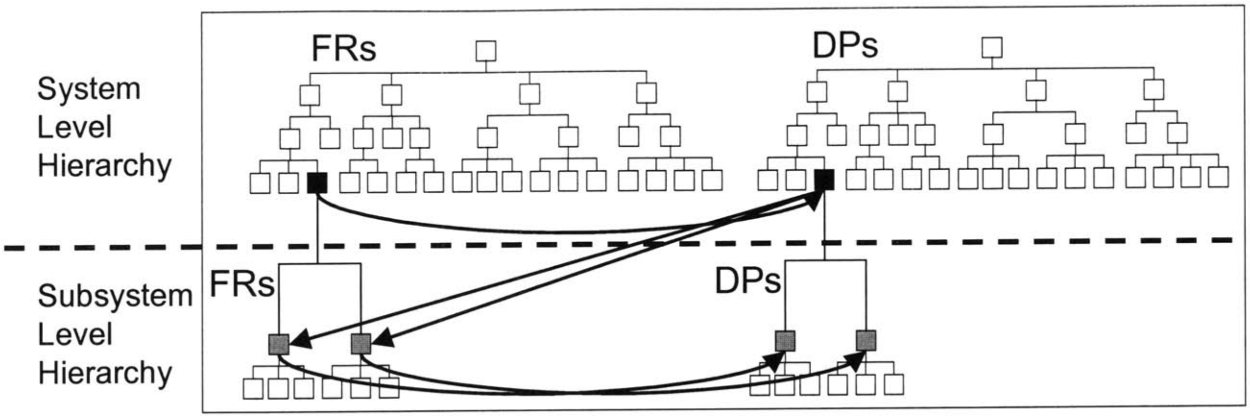


Figure 4.50 Case (i) Single subsystem decomposed from a system decomposition.

This first case illustrates a decomposition process across system and subsystem levels that can be considered a single decomposition as the dashed line in Figure 4.50 indicates. However, the link between the MSDD and equipment decomposition(s) in the second and third cases is discontinuous given the nature of the MSDD DP hierarchy. Specifically, these MSDD DPs do not decompose into FRs at the equipment design level because such DPs are neither equipment subsystems nor equipment components. Rather, these DPs contain further requirements for the design of specific equipment subsystems and components that affect the achievement of system FRs.

For example, DP-D12 *Machines/stations configured to reduce walking distance* is not a DP that can be directly decomposed into sub-FRs at the equipment level because it describes a general attribute that machines and stations must have. Other DPs which are similar in their expression of general equipment attributes include DP-T221, DP-T222, DP-T32, and DP-D23. Figure 4.51 shows how some of these DPs from the MSDD (identified in Step 1 of Section 4.5) are linked to the component DPs in the equipment decomposition below. Thus, physical integration of the DPs at the MSDD level does not occur until the equipment subsystem DP is designed and specified.

The third case shown in Figure 4.52 reflects that the MSDD directs the design of not just one piece of equipment, but all equipment in the manufacturing system as well as requirements on their interconnections with other resources. The physical architecture of the system is therefore formed by the integration of equipment hardware into complete machines, and the equipment is further organized into manufacturing subsystems such as cells or conventional transfer lines. Furthermore, a DP can influence the design decomposition of many different pieces of equipment and related subsystems at various levels.

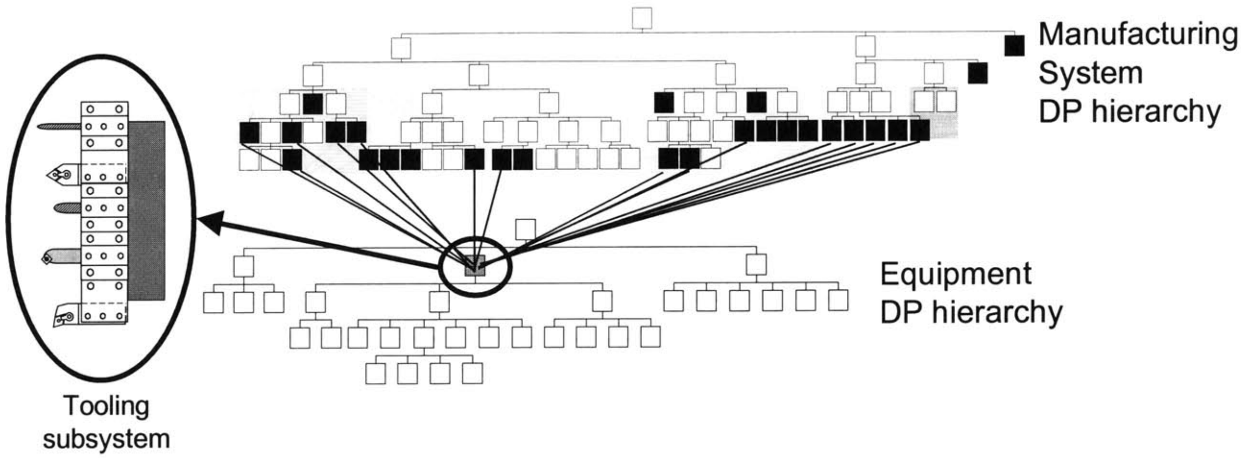


Figure 4.51 Case (ii) Link between DPs in MSDD and ED decompositions showing the case for tooling design.

A DP that applies to multiple design decompositions may at first seem to violate the Independence Axiom and the concept of zig-zagging between domains. However, in this situation the MSDD is completely separate and distinct from that of the equipment decompositions and therefore zig-zagging does not take place from the manufacturing system to the equipment design. Moreover, since no single piece of equipment appears as a DP in the MSDD hierarchy it is not possible to "zag" back to the functional domain. Therefore, the process of decomposing from the MSDD to an equipment design requires a modified decomposition process. The next section presents a model for decomposing between the MSDD and an equipment decomposition.

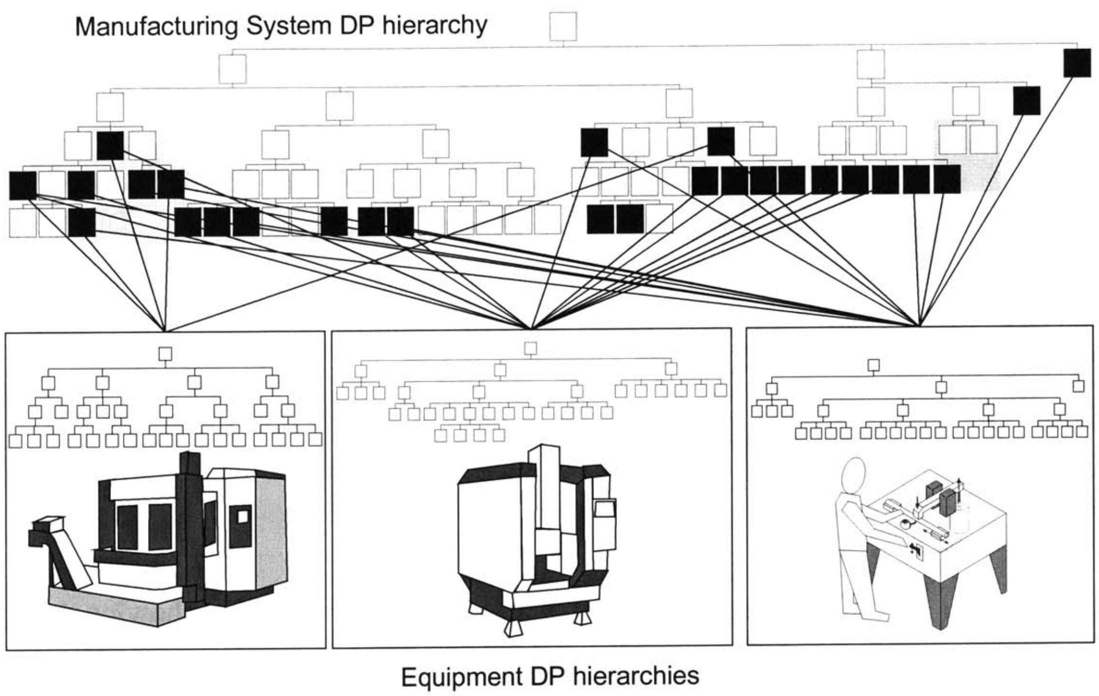


Figure 4.52 Case (iii) Relation between the MSDD and multiple equipment designs.

4.8.2 Process for Equipment Design Decomposition

This section describes the process for decomposition that takes place at the equipment design level. Given that the MSDD requirements have already been generated, the design process for equipment decomposition has to next incorporate the manufacturing system design (MSD) and product design (PD) requirements. The specific equipment decomposition depends on the requirements of the system in which it must operate and therefore all possible sources of requirements must be considered. Figure 4.53 gives a descriptive decomposition model showing that an equipment design parameter is decomposed into any combination of sub-FRS derived from the system, product, or equipment FRs. Specifically in Figure 4.53, the model denotes the decomposition of a general equipment $DP|_{ED}^{k}$ (at an arbitrary level k in the hierarchy) into a set of equipment, manufacturing system, and product sub-FRs at a lower $k+1$ level. The two terms in this set $FR(MSD)|_{ED}^{k+1}$ and $FR(PD)|_{PD}^{k+1}$ are read as "the Equipment Design (ED) sub-FR derived from the MSD and PD functional requirements." This notation is used to make clear the origin of the sub-FRs and to distinguish from the actual functional requirements that belong to the MSDD and PD decompositions.

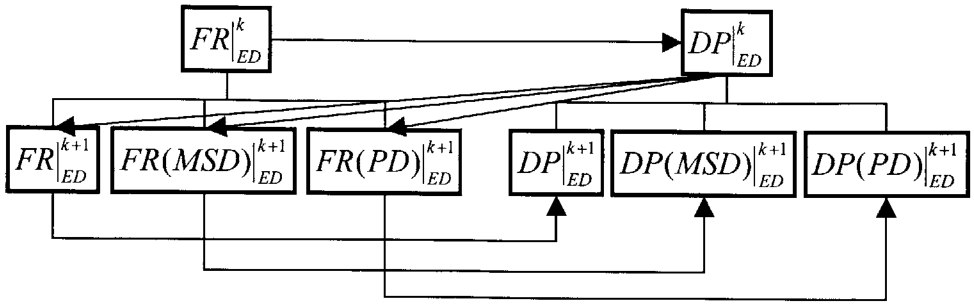


Figure 4.53 Equipment decomposition model with MSD and PD derived sub-FRs.

The procedure for obtaining any of these three different types of sub-FRs terms is the same and begins once a $DP|_{ED}^{k}$ has been designed to meet the $FR|_{ED}^{k}$.

The first type of sub-FR, $FR|_{ED}^{k+1}$ is solely an equipment derived requirement and is obtained independently from system considerations. An example of such an FR is one that specifies what a component has to do for a given equipment subsystem to perform as desired. Thus, the component has no interaction with the external environment (i.e. the manufacturing system) and decomposition originates from strictly equipment requirements.

Next, the decomposition of $DP|_{ED}^{k}$ into equipment $FR(MSD)|_{ED}^{k+1}$ is shown by the series of *dashed* direct arcs in Figure 4.54. The decomposition process begins with the identification of requirements in the MSDD that correspond to $DP|_{ED}^{k}$. This identification is performed in Step 1 of the equipment design approach. If the equipment DP is a major subsystem, then a view will exist that has been created in the second step of the approach. This view will contain all of the DPs in the MSDD that reference the design of the equipment DP. If the DP is not a major equipment subsystem, then a search of the MSDD has to be performed independently of a view. This identified set of DPs in the MSDD can then be easily traced back to the source FR. This trace needs to be performed because the FRs alone do not indicate the aspect of the equipment that must be designed to meet the MSDD requirements. This set of source FRs in the MSDD that affect equipment design may now be used to generate the equipment sub-FRs.

To use the above set of FRs in decomposition requires formulation of a specific sub-FR consistent with the $DP|_{ED}^{k}$. The *dotted* arc in Figure 4.54 indicates this step. For the MSDD used in this work, no general method has been found that can be used to express FRs at the system level into FRs at the equipment level. However, if there exists a relationship between the MSDD

FR and an equipment variable, then such a variable can be used to express the MSDD FR as an equipment sub-FR, $FR(MSD)\big|_{ED}^{k+1}$. An example from the design of a tooling subsystem shows how such a formulation may be used in decomposition.

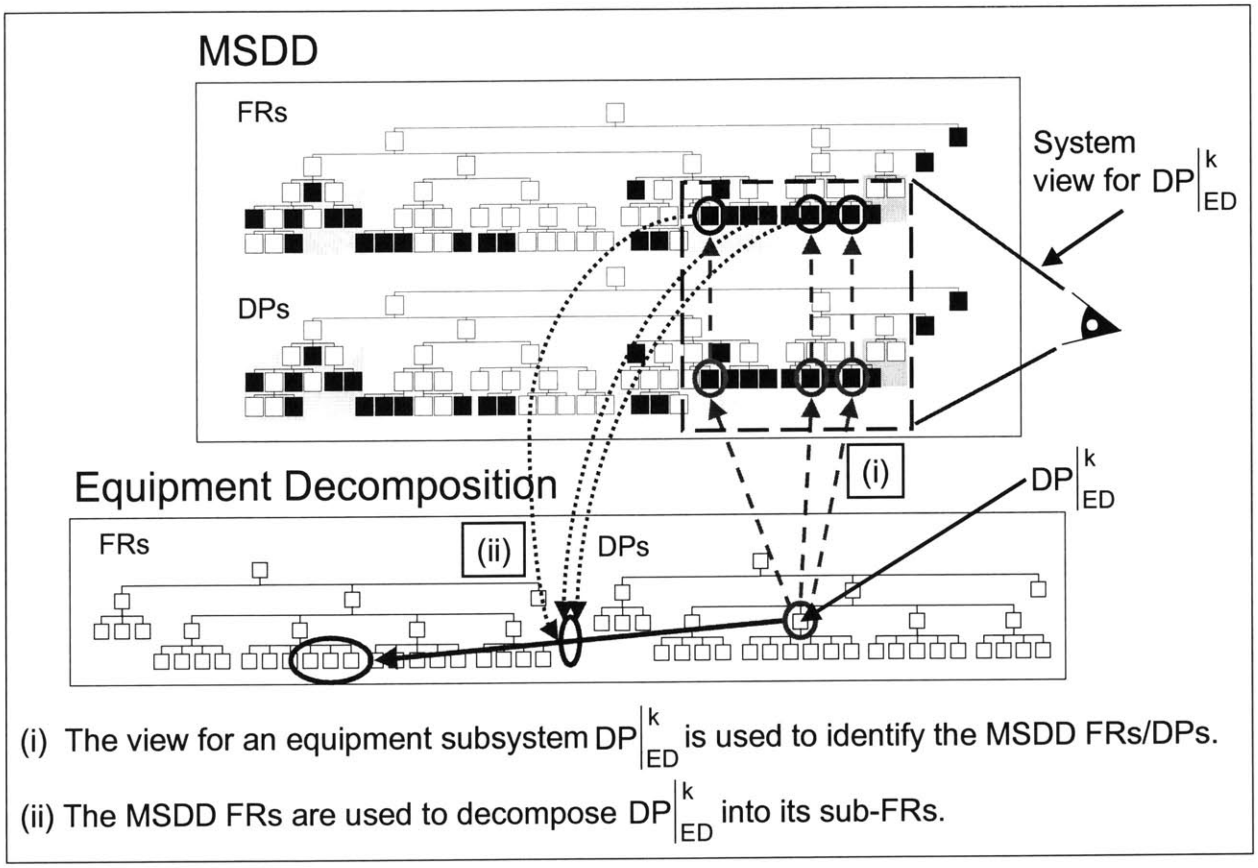


Figure 4.54 General sequence for decomposing an equipment DP to meet a MSDD FR.

To illustrate the above decomposition process an example is taken from the design decomposition of a tool turret for a setup reduction project described in greater detail in Chapter 6. The tool turret is a major subsystem of a CNC lathe and is the structure that holds tools and indexes to the position for the cutting operation specified by the process plan[21]. Thus, the tool turret is the DP that satisfies the FR – *Hold tools for machining operations*. The first step in the sequence shown in Figure 4.54 is to use this equipment $DP\big|_{ED}^{k}$ - *Tool turret* to either search for a similar DP in the MSDD or to use a view previously created in Step 2 of the approach. In this case, the DP from the MSDD that is identified is DP-T12 *Design quick changeover for material*

[21] The process plan exits in the form of NC code and represents the translated form of product design requirements (i.e. geometry that the tool has to generate).

handling and equipment because the turret is a subsystem that must be reconfigured during a changeover from a production run of one part type to the next.

FR-T12 *Ability to produce sufficiently small run size* may be specified in different ways according to the design selected for the manufacturing system. In a make-to-stock manufacturing system, the lot size (or run size as defined here) is calculated by minimizing the total inventory cost which is the sum of the holding and ordering costs (Equation 4.2). The optimal run size q^* (Equation 4.3) commonly known as the Economic Order Quantity (EOQ) is a function of the setup cost K, holding cost h and annual demand D. The setup cost K is a function of the setup time taken to changeover production resources.

$$TC = \frac{KD}{q} + pD + \frac{hq}{2} \tag{4.2}$$

$$q^* = \sqrt{\frac{2KD}{h}} \tag{4.3}$$

Alternatively, JIT manufacturing is a make-to-order system design that determines run size using a different approach. JIT seeks to meet customer demand by producing the correct mix and quantity of actual customer demand and therefore setup time is regarded as a variable that must be reduced to meet such a production plan. Monden (1993) uses a queuing model with a mixed model schedule to determine the optimal run size. Using this approach he calculates the optimal run size q^* for a specific case given by Equation 4.4:

$$q^* = \frac{S}{(2-\sqrt{2})t'-t} \tag{4.4}$$

where S = setup time

t' = average time for consuming one part in subsequent process

t = unit processing time per part

Using a result such as Monden's above, the variable q^* exists in the MSDD and S is used to decompose the equipment sub-FR. Thus, in Figure 4.55 the dashed line indicates the use of the view to transform a system requirement q^* into an equipment requirement S. These two relations show how a specific formula's functions can aid decomposition.

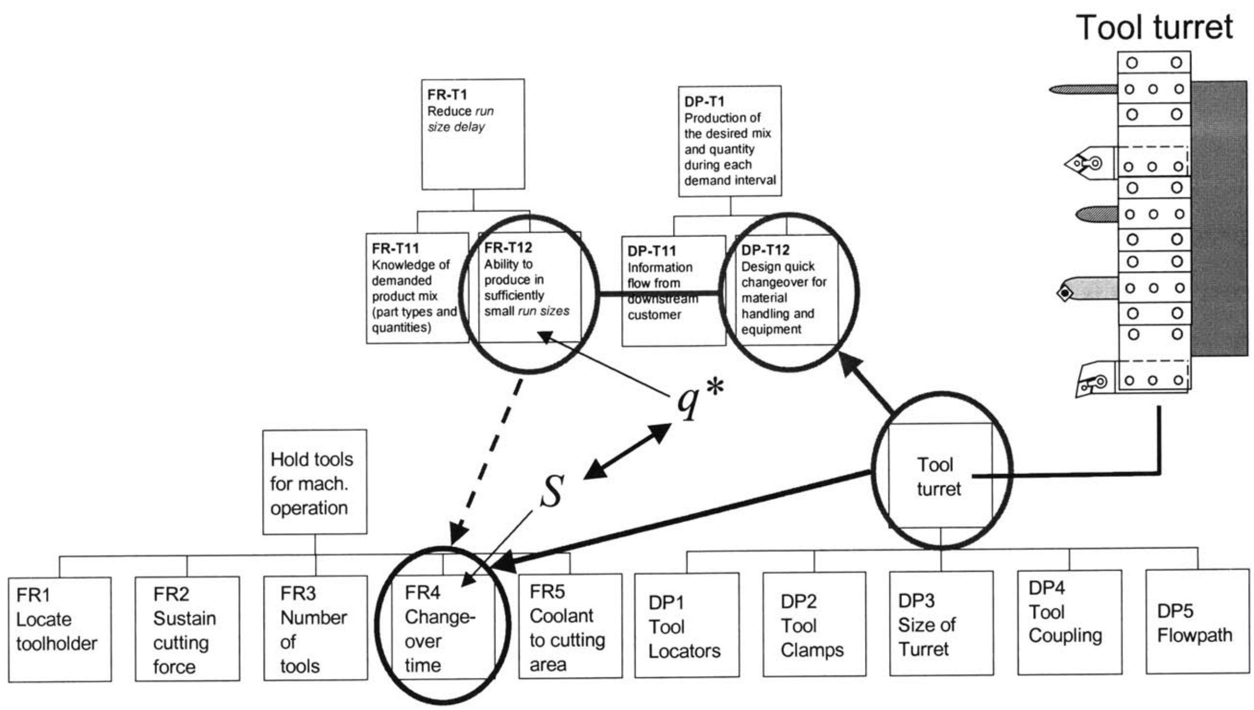


Figure 4.55 Detailed example of equipment decomposition process linking DP hierarchies.

4.8.3 Axiomatic Design Decomposition of Equipment

An axiomatic design decomposition was generated for a hypothetical machine (a CNC lathe) to examine the influence of MSDD and PD requirements on design of equipment subsystems and components. This decomposition serves as a test case to identify FRs/DPs in the interaction matrices described earlier. This design decomposition is not meant to be an example of the complete design of a machine but rather to develop the design of certain subsystems so that they can be used illustrate application of the general equipment design approach.

4.8.3.1 Description of the Equipment Decomposition

To initiate the equipment design, the common industrial need to transform the geometry of a part was assumed to be the highest level requirement for the decomposition. Thus assuming a given set of part features, the requirement FR1 is to create the geometry of the part on an incoming piece of raw material. A CNC lathe, DP1, is chosen because it is capable of generating both cylindrical and prismatic features. Once such a piece of equipment is selected, many known sub-FRs immediately arise since CNC lathes have been previously designed. Therefore the subsystems are assumed to be understood by the manufacturing systems engineers. In this regard, there already exists knowledge about the physical components of a CNC lathe that is implied and does not have to be reinvented. However, this does not mean that simply selecting DP1 as being a CNC lathe completes the design simply because so many lathes have been designed in the past, rather it means the function of some subsystems and components do not have to be derived from first principles. For example, tools and motors are well known and understood machine components that do not need to be described in detail for high level equipment decomposition. This distinction is important because there is a difference between designing a machine using off-the-shelf components and an entirely custom machine that must be designed from basic high level functional requirements. The range of possible equipment requirements for varying levels of concurrency and customization was discussed in Section 4.2.5. In the latter case, care must be taken not to pre-assume design solutions in decomposing the sub-FRs of a custom machine.

4.8.3.2 Second level of decomposition

The second level decomposition of the sub-FRs for a CNC lathe has three branches that describe the basic requirement to machine the part. The first requirement is that the part physically fit inside the machine and is expressed as a minimum work volume that the machine must have. Secondly, since the incoming state of the part is known (i.e. cast dimensions) and FR1 defines the required outgoing geometrical state, FR12 is the material that must be removed to achieve the necessary output state. The third requirement FR13 is that the machine be capable of generating the motion to trace the path of the desired part geometry.

The mapping of these three relatively general FRs results in similarly general DPs that represent entire subsystems. The machine structural design, DP11, though not exactly a modular subsystem, is the physical entity by which the subsequent DPs are physically integrated. These structural design characteristics determine the machine's work volume and hence satisfy FR11. The requirement to remove excess material is achieved by the material removal system. At this level of abstraction in the decomposition, DP11 cannot be described in greater detail until the subsystem is decomposed into constituent subsystems. The third DP13, is also an aggregation of subsystems, and is the motion control system that drives the various components of the machine structure along the required geometrical path. The design matrix that results from the mapping of these FRs to DPs is:

$$\begin{Bmatrix} FR11 - \textit{Machine work volume} \\ FR12 - \textit{Remove excess material} \\ FR13 - \textit{Generate machine motion} \end{Bmatrix} = \begin{bmatrix} \times & 0 & 0 \\ \times & \times & 0 \\ \times & 0 & \times \end{bmatrix} \begin{Bmatrix} DP11 - \textit{Machine structural design} \\ DP12 - \textit{Material removal system} \\ DP13 - \textit{Motion control system} \end{Bmatrix} \quad (4.5)$$

The above design matrix (4.5) is triangular and hence is decoupled. Design matrix element a_{21} is nonzero since the machine structural design affects how the excess material is removed. Further decomposition reveals that the stiffness of the machine structure affects surface finish requirements (a sub-FR of the material removal system). The other nonzero off-diagonal matrix element a_{31} also reflects the influence of the machine structure. With element a_{31}, the machine structure determines how the machine motion is achieved. For example, two different structural configurations for machine axes can have entirely different motion characteristics.

4.8.3.3 Third level of decomposition

At the third level of decomposition there are two branches that must be decomposed, DP11 Machine structural design and DP12 Material removal system. The sub-FRs for DP11 are machine stiffness, damping and subsystem mounting locations. The corresponding DPs are the geometry of machine axes, structural member materials, and structural fasteners. See (Slocum, 1992) for a description of basic structural machine design. The design matrix is the following:

$$\begin{Bmatrix} FR111 - \textit{Machine stiffness} \\ FR112 - \textit{Machine damping} \\ FR113 - \textit{Subsystem mounting locations} \end{Bmatrix} = \begin{bmatrix} \times & 0 & 0 \\ \times & \times & 0 \\ \times & 0 & \times \end{bmatrix} \begin{Bmatrix} DP111 - \textit{Machine axis geometry} \\ DP112 - \textit{Structural materials of members} \\ DP113 - \textit{Structural fasteners} \end{Bmatrix} \quad (4.6)$$

The second DP branch that must be decomposed is the material removal system. To remove material, a system must provide the capability to hold the part and tool while the tools move relative to the part and also to eliminate chips from the machine. These three material removal FRs are met by further decomposition into three subsystems, namely the workholding, tooling, and chip removal system. The resulting design matrix is uncoupled:

$$\begin{Bmatrix} FR121 - \textit{Hold part} \\ FR122 - \textit{Hold tool} \\ FR123 - \textit{Remove chips from machine} \end{Bmatrix} = \begin{bmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ \times & \times & \times \end{bmatrix} \begin{Bmatrix} DP121 - \textit{Workholding system} \\ DP122 - \textit{Tooling system} \\ DP123 - \textit{Chip removal system} \end{Bmatrix} \quad (4.7)$$

4.8.3.4 Fourth level of decomposition

The fourth level is the beginning of detailed subsystem design and definition of component requirements. The sub-FRs for the workholding subsystem are to locate and secure the part rigidly while the tool cuts. Workholding locators fix the position of the part by establishing the datum reference plane. Secondly, clamping devices secure the part against the locators and resist the forces that arise during the machining process. The resulting design matrix is uncoupled:

$$\begin{Bmatrix} FR1211 - \textit{Locate part at specific position} \\ FR1212 - \textit{Secure part against forces} \end{Bmatrix} = \begin{bmatrix} \times & 0 \\ \times & \times \end{bmatrix} \begin{Bmatrix} DP1211 - \textit{Workholding datum locators} \\ DP1212 - \textit{Part clamping devices} \end{Bmatrix} \quad (4.8)$$

As with the two FRs of the workholding system, the first two FRs of the tooling system state the requirement to locate and clamp, the only difference being that in this case it is the cutting tool instead of the workpiece. The third sub-FR of the tooling system, FR1223 specifically states the requirement that the tool create a chip. The material removal process is described by the equations of chip formation in metal cutting (Kalpakjian, 1995) that depend on the cutting geometry between tool edge and workpiece. This geometrical relationship is established by the characteristics of the cutting insert DP1223. In the majority of metal cutting environments there is the need to channel a stream of coolant onto the tool as it cuts the workpiece (such as for improved surface finish, tool life, chip evacuation). Therefore, the fourth requirement of the tooling system is to provide a directed flow of coolant to the cutting edge. The coolant path from the reservoir through the tool block to the cutting edge, DP1224, achieves this requirement. The last two requirements of the tooling system are traceable to the highest level FR1- create part geometry that implies the need for multiple tools. Therefore, the tooling system must have both the capacity to carry the required amount of tools in the machine and to automatically switch from one tool to the next (FR1225 and FR1226). The tool magazine design satisfies the tool capacity requirement DP1225, and the indexing mechanism enables the machine to switch tools during processing of the part, DP1226.

$$
\begin{Bmatrix} FR1221 - \textit{Locate toolholder} \\ FR1222 - \textit{Secure toolholder against cutting force} \\ FR1223 - \textit{Create chip at tool - workpiece interface} \\ FR1224 - \textit{Provide coolant to cutting edge} \\ FR1225 - \textit{Hold all tools for part geometry} \\ FR1226 - \textit{Switch between tools} \end{Bmatrix} = \begin{bmatrix} \times & 0 & 0 & 0 & 0 & 0 \\ 0 & \times & 0 & 0 & 0 & 0 \\ 0 & \times & \times & 0 & 0 & 0 \\ 0 & \times & 0 & \times & 0 & 0 \\ \times & \times & 0 & 0 & \times & 0 \\ 0 & 0 & 0 & 0 & 0 & \times \end{bmatrix} \begin{Bmatrix} DP1221 - \textit{Tool block locating features} \\ DP1222 - \textit{Tool block clamping mechanism} \\ DP1223 - \textit{Cutting insert} \\ DP1224 - \textit{Coolant path through tool block} \\ DP1225 - \textit{Tool magazine} \\ DP1226 - \textit{Tool magazine indexing mechanism} \end{Bmatrix} \quad (4.5)
$$

Nonzero off-diagonal element	**Explanation of dependency**
A_{32}	Attributes of the tool clamping mechanism determine the rigidity of the tool and thereby influence the creation of chips.
A_{42}	The type of clamping mechanism selected affects how coolant is delivered to cutting edge. Components of the mechanism may be in the path of coolant flow and require alternate routing of the flow to the cutting edge.
A_{51}	The geometry of the tool block locating features determines block-to-block spacing and hence the number of tools that may be held in the tool magazine.
A_{52}	The size of clamping mechanism is related to the total number of available tool positions in the magazine and therefore determines whether all the tools for the part geometry may be stored.

Table 4.1 Explanations for nonzero offdiagonal elements in tooling system design matrix.

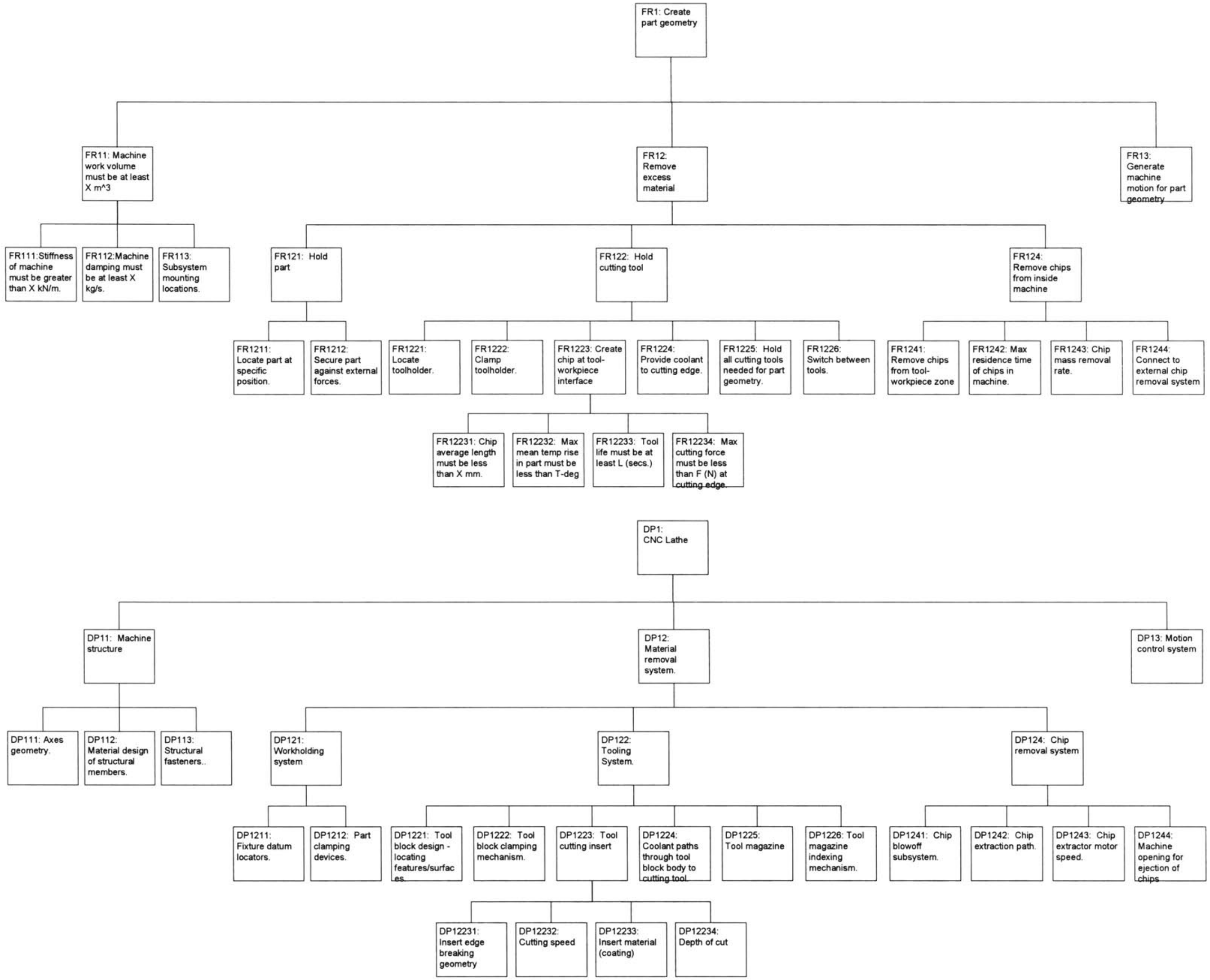


Figure 4.56 Design decomposition for an example CNC lathe.

4.9 Chapter Summary

The Manufacturing System Design Decomposition (MSDD) presented in Chapter 3 provided the description for high-level system objectives for detailed design of subsystems such as equipment. This chapter focused on the development of an approach that provides a process to design equipment. The EDA is an integrated set of steps that describe the procedural aspects leading to the specification of an equipment design. Also, the approach incorporates methods that deal with decomposition issues that arise from the application of Axiomatic Design to manufacturing system design. The four steps of the EDA were presented along with descriptions of tools such as interaction matrices used at various points in the steps.

The scope and assumptions for use of the EDA were presented along with assigned responsibilities for manufacturing system and equipment engineers. With this specification of tasks, the EDA offers improved coordination for members of multi-disciplinary design teams. Also, these assignments make management easier to ensure that the high-level MSDD objectives are met.

The EDA presented also addresses issues including the nature of the resultant manufacturing system physical hierarchy, the textual expression of design parameters, and the decomposition process for generating sub-FRs that were discussed in Chapter 3. Finally, views of MSDD FRs/DPs can be augmented by further explanations. Views are provided with explanations because the FRs/DPs have limited textual description (Section 3.6). Such types of translated requirements with additional explanations may be also thought of as guidelines. The compressor manufacturing system design case presented next in Chapter 5 presents the use of guidelines in the equipment design approach.

Chapter 5 Equipment Design for a new Manufacturing System

5.1 Introduction

This chapter describes a project in which the MSDD was used at a company as a design aid for the design of a new automotive compressor manufacturing system. This project represented a challenge to the equipment procurement process of both the company and its suppliers. The company's manufacturing engineering group was faced with a new set of manufacturing system objectives that were considerably different from systems that had been designed in the past. Specifically, existing knowledge and experience with manufacturing systems and equipment had been in high production volume environments. As a result, neither internal engineers nor suppliers could rely on prior experience to design appropriate equipment. Therefore, one objective of this project was to provide an equipment design process that could make up for the limited low volume production knowledge while simultaneously designing a new manufacturing system.

It was in the course of providing such equipment knowledge that the first three steps of the Equipment Design Approach (EDA) were developed. To show this development, the chapter is structured according to Figure 4.4 of the EDA as it was integrated with the company's existing equipment procurement process. First, the influence of general product requirements on the design of the manufacturing system is given. Second, the design of the actual manufacturing system is described along with examples of the specific subsystems and equipment that resulted from applying specific aspects of the EDA. Also, these examples show cases where low-level equipment design decisions did and did not satisfy high-level system requirements. The examples also illustrate how machine and process designs were selected during the design phase of machining and assembly equipment. In addition to the application of the EDA, the equipment in this chapter is also evaluated based on the use of views derived from the MSDD. The evaluation consists of categorizing MSDD design parameters and evaluating elements of a design against the parameters. A matrix-based ranking method is employed that evaluates the level of MSDD design parameter implementation in the actual system design.

5.2 Overview of Automotive Compressors

Generally, the designers of automotive compressors are faced with increasingly stringent noise (NVH), weight, durability, and efficiency performance requirements. Furthermore, an automotive compressor shares many similar operational requirements with engines. Compressors operate at rotational speeds greater than 10,000 rpm and in the same thermal environment as the engine. The heat of the engine compartment makes thermal expansion an additional concern for leakage across sealing surfaces. Therefore, seal design is critical to contain the working gas at the required high pressures (~ 300 psi depending on refrigerant). For this reason, select fits are required to achieve the necessary gap tolerances (in the range of 0.2 to 0.5 micron classes). To achieve such tight tolerances and high surface finishes requires high precision grinding and polishing processes.

The compressor in this particular project had been recently designed and developed in-house and is of the rolling-piston type (Figure 5.57 shows a mechanically simpler version). A shaft (driven by the clutch pulley from the engine belt) drives a roller-piston eccentrically that creates two rotational compression and expansion chambers. Vanes separate the suction and discharge chambers while reed valves control gas flow through the compressor. Design advantages of rolling piston compressors include fewer parts, lower sliding velocities (compared to double-acting pistons), and simpler part geometry. Some disadvantages are the relatively higher tolerances for sealing surfaces and select fits needed for mating vanes and piston to the compressor housing.

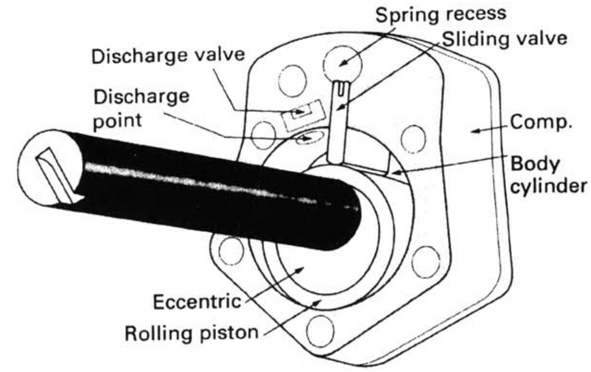


Figure 5.57 Rolling piston compressor (Trott, 1989).

5.3 Development of the Manufacturing System Design

The design of the manufacturing system was derived mainly from product design characteristics and reflected the evolution of the product development process. The compressor project offered the opportunity to simultaneously design the product and manufacturing system to meet customer requirements. Initially, the requirements of the manufacturing system were based on the processes that had been developed during the compressor prototype and pilot production phases. Figure 5.58 shows such requirements as input information for the manufacturing system design approach employed in the project. The approach was not a formal one, however instead it was a collection of specific design and analysis activities. For example, using operator assembly times obtained during prototype production, standard operator work charts were developed and analyzed for different operating patterns. Similarly, designs for system layouts and process plans were also developed using pre-production knowledge. A system simulation was developed to analyze transfer batch sizes between subsystems (i.e. machining and assembly).

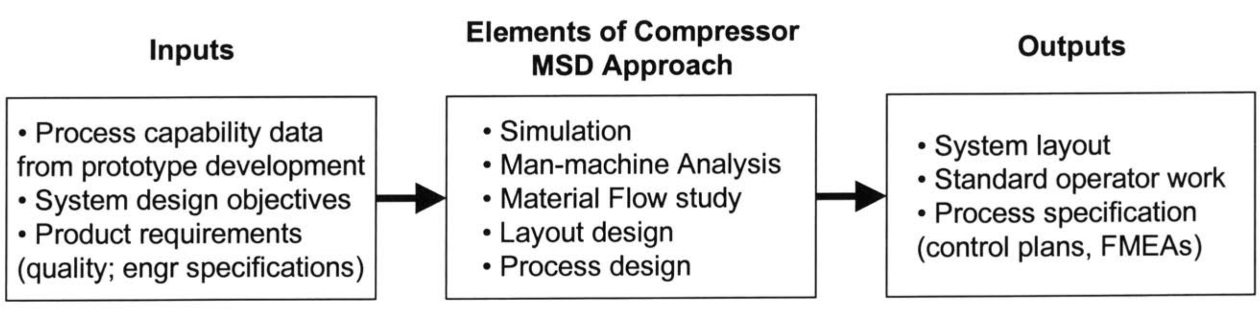


Figure 5.58 Overview of manufacturing system approach followed in compressor project.

Figure 5.59 provides an approximate sequence of design and manufacturing activities followed during development of the compressor. Manufacturing process development lagged initial product design as a consequence of the early concept discovery phase that preceded the formal specification of processes. Manufacturing processes that were concurrently developed with the compressor prototypes comprised the operational building blocks of the manufacturing system design. The development of processes that preceded the design of the system reflects an MSD approach that is not entirely top-down. Specifically, aspects of a bottom-up approach were evident later in manufacturing system design because specific product-process requirements were constraints for high-level system objectives.

A barrier to following a pure top-down design approach was the limited customer knowledge available. As a result of this incomplete customer information, the baseline of prior manufacturing process knowledge was instead used as the source for general quality, cost, rate, and flexibility goals. The last activity shown in Figure 5.59 is equipment design shown beginning shortly after commencement of the manufacturing system design. The challenge here was to design equipment before important manufacturing system objectives had been expressed as quantitative requirements. This challenge and others to the equipment design process are discussed in greater detail in Section 5.4.

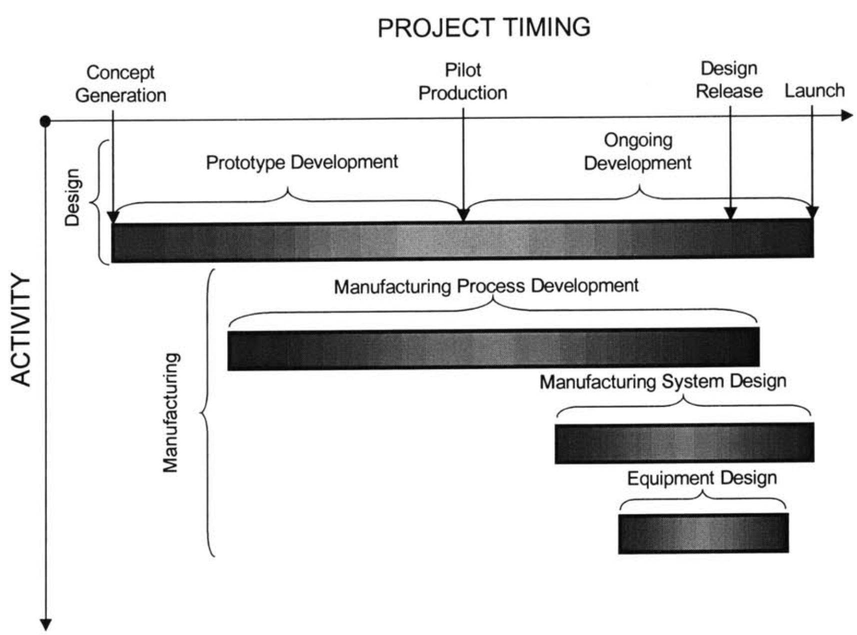


Figure 5.59 Approximate timing for development of product and manufacturing system for the new compressor.

5.3.1 Flexibility

Since the compressor was developed prior to having detailed customer specific knowledge, a major objective of the manufacturing system was to have flexibility to accommodate future product varieties. Also, in addition to unknown customer product requirements (i.e. external packaging, capacity), production volume requirements (and variances) were also unknown at the time of system design. This lack of customer demand knowledge led to two flexibility objectives: ability to accommodate different demand patterns (volume flexibility) and ability to accommodate different product configurations (product flexibility). The next two subsections describe the selection of a manufacturing system concept from amongst two candidates based on the ability to satisfy these two flexibility objectives.

5.3.1.1 Volume Flexibility

Two customer demand growth profiles were forecast to analyze the ability of two system design concepts to provide the necessary future capacity. Two general system types A and B were considered for the capability to add capacity. In each case, the incremental amount of capacity was examined to determine the investment cost associated with over-capacity.

System A is a cellular manufacturing system and therefore capacity may be increased by adding new equipment at the bottleneck operation. In this system design concept, rate is limited by equipment capacity and not by the human operator.[22] System B by contrast is a system containing more fixed automation and is commonly known as a transfer line. In such a system a palletized conveyor links all machines. Introducing additional equipment or modifying existing processes is difficult to do without simultaneously modifying other equipment on the line. Capacity in this type of system can only be added by replicating the entire transfer line.[23] The greater amount of hard tooling makes reconfiguration of the line costly.

Figure 5.60 and Figure 5.61 show two forecasts for demand growth over a seven year period. This forecast was based on potential customers and associated demand. No variance data existed for these forecasts, however, estimates were available on upper and lower bounds on demand

[22] Investment cost in this project was reduced by minimizing the number of machines required for a given production rate and thus capacity is limited by equipment and not operators.
[23] In some cases it is possible to improve single stations but this does not provide significant amounts of additional capacity.

growth. In Figure 5.60, System A needs to add equipment in years 2,3,6, and 7 corresponding to 120k, 300k, 180k, 200k units of annual capacity to meet the forecast. System B only needs to add 600k units of capacity in year 6. However, System A has less average annual excess capacity than System B, 47k compared to 321k (Table 5.2). Similar results hold in Figure 5.61 for the high growth rate case. Here, System A adds equipment in years 2,3,4,5 in quantities of 300k, 420k, 180k, 200k respectively to meet the forecast. System B adds 600k units of capacity much earlier in year 3 to meet the increase in demand. Though the difference in average annual excess capacity is less, 60k compared to 243k, System A still more closely approximates the forecasted demand. System A was therefore selected since it provided less risk for over capacity and hence a better return-on-investment. Furthermore, the ability to add smaller increments of capacity provides the capability to compete for lower volume customers.

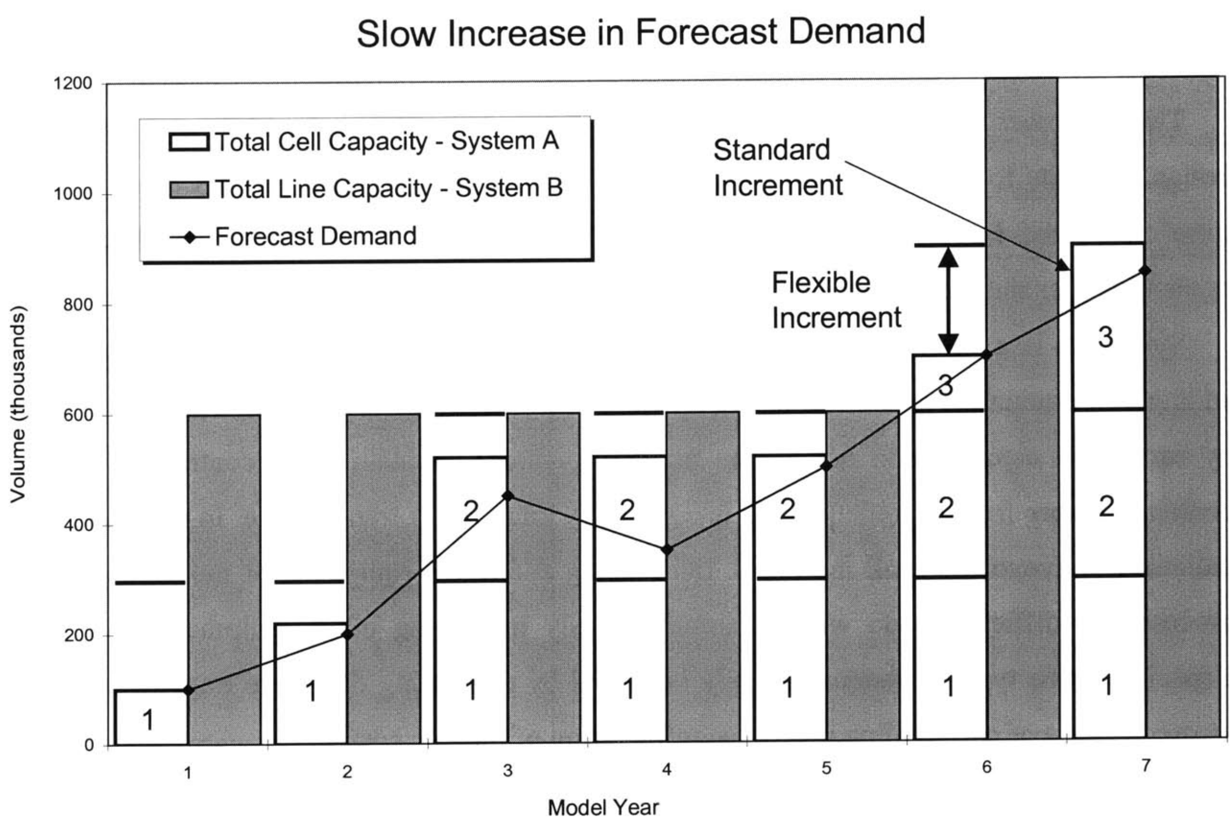


Figure 5.60 Annual installed capacity for slow increase in demand.

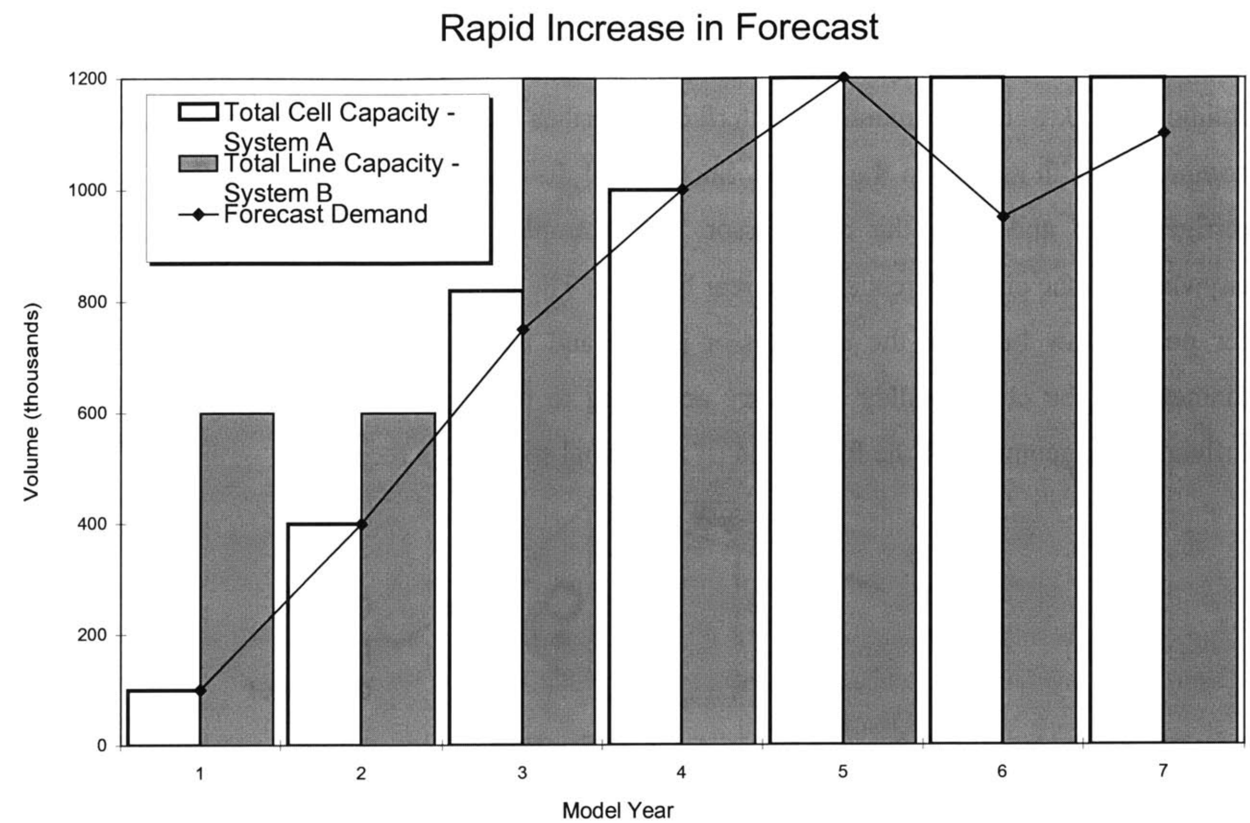


Figure 5.61 Annual installed capacity for rapid increase in demand.

Table 5.2 Excess capacity for Systems A and B; Low and high demand forecasts.

Low Forecast Data						High Forecast Data					
	System A		System B				System A		System B		
Year	Installed Capacity	Excess Capacity	Installed Capacity	Excess Capacity	Forecast Demand	Year	Installed Capacity	Excess Capacity	Installed Capacity	Excess Capacity	Forecast Demand
1	100	0	600	500	100	1	100	0	600	500	100
2	220	20	600	400	200	2	400	0	600	200	400
3	520	70	600	150	450	3	820	70	1200	450	750
4	520	170	600	250	350	4	1000	0	1200	200	1000
5	520	20	600	100	500	5	1200	0	1200	0	1200
6	700	0	1200	500	700	6	1200	250	1200	250	950
7	900	50	1200	350	850	7	1200	100	1200	100	1100
	average	47	average	321			average	60	average	243	

5.3.1.2 Product Flexibility

The second type of flexibility that the manufacturing system had to meet was that of external packaging features on the compressor. These packaging features are product design requirements that originate from the characteristics of the vehicle application. Specifically it is the customer requirements that derive from the engine type and configuration that determine the interface requirements between engine and compressor. Three possible types of interfaces exist: mounting, fluidic, and power. The mounting interface describes the location of fastening bolts on the compressor with respect to the engine. Suction and discharge ports specify the flow location of refrigerant to and from the compressor. For example, the discharge port may be located anywhere on the circumference of the rear housing. The third general interface provides the path for power flow between the compressor pulley and the engine drive belt. In this case, the diameter of the clutch pulley will vary according to the engine and can also simultaneously influence the geometry of the front head (if additional stiffness is required).

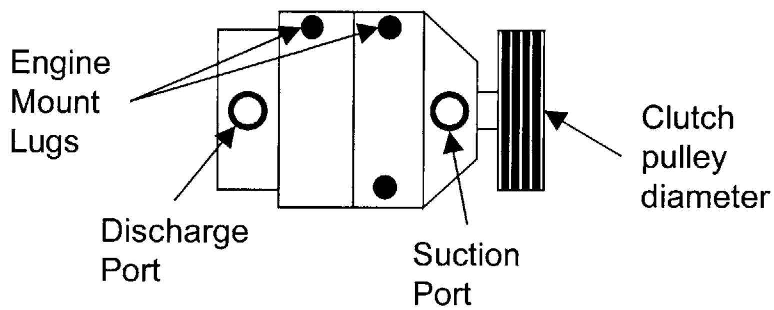


Figure 5.62 Compressor product features that vary according to customer application.

5.3.2 Use of the MSDD to Structure Objectives

The remaining manufacturing system objectives beyond those related to flexibility may be described by mapping them to the MSDD. Table 5.3 shows a list of seven general management goals and objectives of the manufacturing system. However, this initial list lacks structure as it is presented. Therefore, the list was mapped to the MSDD to provide structure via the hierarchy of the MSDD. Since the objectives are not prioritized nor ordered in any particular manner the mapping also serves to highlight other related requirements that have not been explicitly specified. For example, the objectives for the labor force (third item in leftmost column of Table 5.3) are fully described in terms of eleven FR-DP pairs. However, an important result is that the third management objective does not consider or include the relation of direct labor with indirect labor. The MSDD makes clear the importance of indirect labor requirements through management of self-directed work teams that are managed by indirect labor.

requirements that derive from the engine type and configuration that determine the interface requirements between engine and compressor. Three possible types of interfaces exist: mounting, fluidic, and power. The mounting interface describes the location of fastening bolts on the compressor with respect to the engine. Suction and discharge ports specify the flow location of refrigerant to and from the compressor. For example, the discharge port may be located anywhere on the circumference of the rear housing. The third general interface provides the path for power flow between the compressor pulley and the engine drive belt. In this case, the diameter of the clutch pulley will vary according to the engine and can also simultaneously influence the geometry of the front head (if additional stiffness is required).

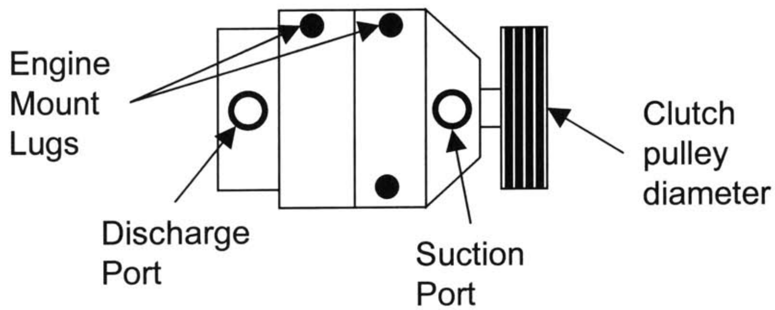


Figure 5.62 Compressor product features that vary according to customer application.

5.3.2 Use of the MSDD to Structure Objectives

The remaining manufacturing system objectives beyond those related to flexibility may be described by mapping them to the MSDD. Table 5.3 shows a list of seven general management goals and objectives of the manufacturing system. However, this initial list lacks structure as it is presented. Therefore, the list was mapped to the MSDD to provide structure via the hierarchy of the MSDD. Since the objectives are not prioritized nor ordered in any particular manner the mapping also serves to highlight other related requirements that have not been explicitly specified. For example, the objectives for the labor force (third item in leftmost column of Table 5.3) are fully described in terms of eleven FR-DP pairs. However, an important result is that the third management objective does not consider or include the relation of direct labor with indirect labor. The MSDD makes clear the importance of indirect labor requirements through management of self-directed work teams that are managed by indirect labor.

Finally, the last result of mapping management objectives to the MSDD is that general statements are decomposed into their constitutive requirements. The fifth objective illustrates how a general goal to reduce inventory in the system can be structured according to the elements of delays that contribute to overall inventory.

Figure 5.63 Mapping of prior compress manufacturing system objectives to MSDD.

5.3.3 Description of the System Design

The design of the system layout was the first activity undertaken to define the implementation of DPs from the MSDD. The layout of the system (shown in Figure 5.64) was based on the manufacturing processes derived from product requirements (geometry and tolerances). The manufacturing system design consists of two machining cells, one final assembly cell, and various intermediate batch processes. The overall system was designed as a linked-cellular system (Black, 1991) in which machining cells feed final assembly cells. From machining, three aluminum die cast parts move to a batch impregnation process located in another building and then are washed through a large capacity flow washer prior to arrival in final assembly. The other three parts are machined and also proceed to the flow washer prior to final assembly. The cells were designed so that each machine was dedicated to a specific process for single-part processing. Furthermore, the layout of the cells specified that equipment be placed closely to one another to reduce transportation delay.

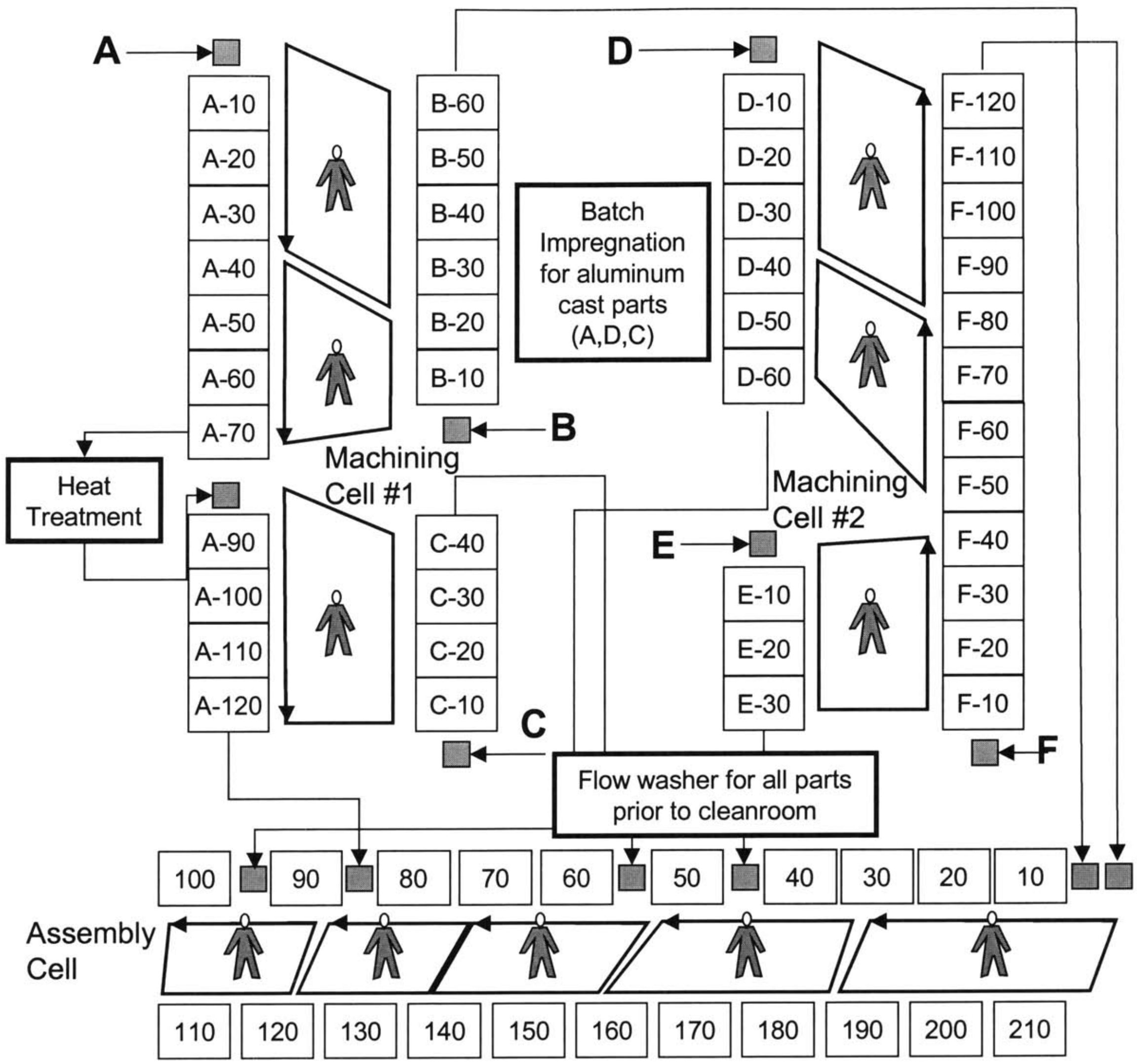


Figure 5.64 Overview of actual manufacturing system design.

5.3.3.1 Machining Cells

The machining cells (one of the two shown in Figure 5.65) consist of milling, turning, grinding, and finishing machines. Parts requiring machining arrive either as castings (iron and aluminum) or forgings (steel and aluminum) into one of six locations at the machining cells. Machining cells are organized in parallel rows with operators walking inside adjacent rows. Operators in the cell are multi-skilled and capable of running and setting up any given machine in the cell. Operators trained in this manner permit work to be redistributed within the team of operators for varied manufacturing volumes.

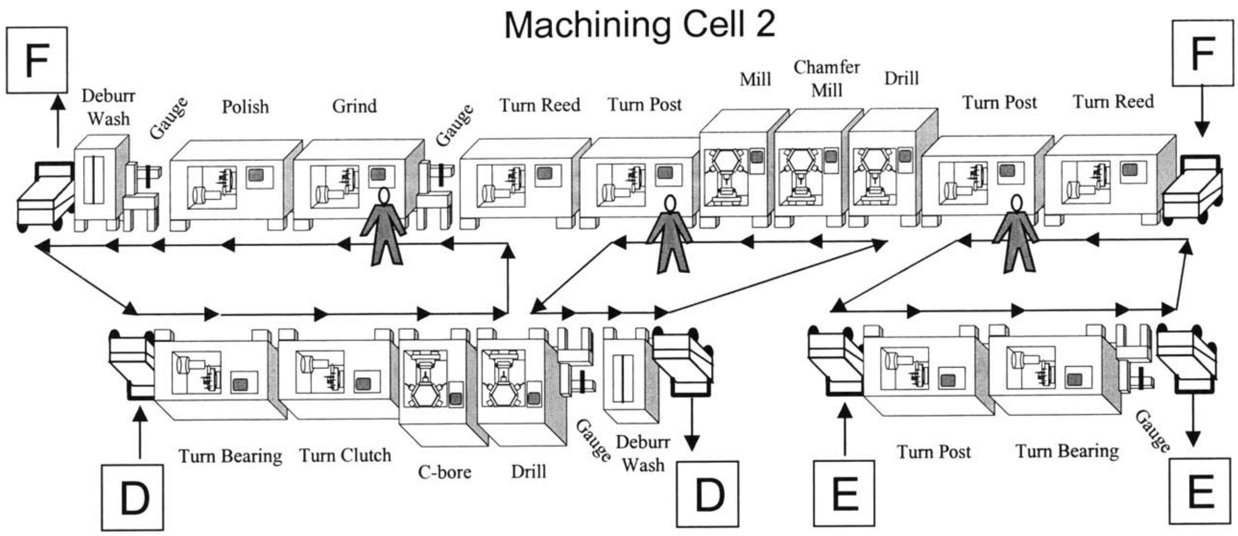


Figure 5.65 The second of two machining cells for the fabrication of six components.

5.3.3.2 Intermediate Batch Processes

In addition to the machining and assembly cells, there are four batch processes in the manufacturing system: impregnation, heat treatment, tin coating, and washing. The impregnation process seals die cast aluminum parts and has a capacity equivalent to approximately 300 castings. Heat treatment is a three-station carburization process that is performed on the forged steel part. The heat treatment process takes place in the middle of the machining process meaning that the part leaves the machining cell for heat treat and then is returned to the cell for the rest of its machining steps. Batch sizes for the shaft component in machining are smaller than impregnation and range from 100 to 200 parts. Tin coating consists of a number of small stations that process small batches of aluminum forging and are manually indexed by a dedicated operator. The smallest batch sizes are those for tin coating which range from 10 to 20 parts with correspondingly shorter cycle times. The fourth batch process is that of a flow washer through which all components must pass. Cleanliness requires that parts be washed immediately prior to assembly to minimize contamination by airborne particles.

5.3.3.3 Assembly Cell

The assembly cell contains all the processes for combining both in-house machined components and externally sourced parts into the final product for shipment to the vehicle assembly plant.

The assembly cell has a mixture of semi-automatic and manual subassembly stations as well as various types of test stations. As in the machining cells, the assembly cell operates according to single piece flow and is managed by a team of operators who all work within the cellular configuration. The operators pace the manufacturing by following standard work loops whereby compressors in various build configurations are advanced one at a time from station to station. The operators are multi-skilled and can manage any number of stations within the cell.

5.4 The Equipment Design Process

Having defined the manufacturing systems objectives and a basic system design concept, the next stage in the project was the specification and design of equipment. It was during the equipment design stage that the system design (Section 5.3.3) along with product requirements were communicated to a set of selected suppliers. The formal process for equipment design (See Section 4.2.4 for a general overview) began with a pre-selection of candidate suppliers that were invited to bid on specific processes. The formal design process concludes with the acceptance by the company after the equipment is tested and is shown to meet all requirements in the actual production environment. This section therefore describes the participating designers and the integration of the equipment design approach in the design process up to and including detailed design and construction. However, testing in the actual production environment is not discussed since it had not yet occurred at the time of writing of this dissertation.

5.4.1 Equipment Designers

The design of equipment for the compressor manufacturing system involved numerous people in various organizations at various levels of responsibility. Figure 5.66 shows the functional organization of equipment designers. There are four main organizations to which designers belong: manufacturing plant, central product and manufacturing development, equipment manufacturer, and suppliers to the equipment manufacturer. These four different organizations may be thought of as the supply chain for equipment (Fine, 1996). The supply chain here shows all of the groups of people that must receive design information. The end user of the equipment is clearly the manufacturing plant, however, in this project, manufacturing engineering co-located with central product development managed and initiated the bulk of the design process.

Also, the majority of communication and design review occurred between the two innermost organizations in Figure 5.66. Results from the design reviews were then communicated to the outermost organizations. Thus the equipment manufacturer dealt primarily with its suppliers while central development dealt with engineers from the manufacturing plant. The communication that occurs across a supply chain such as Figure 5.66 provides the context for applying the equipment design approach.

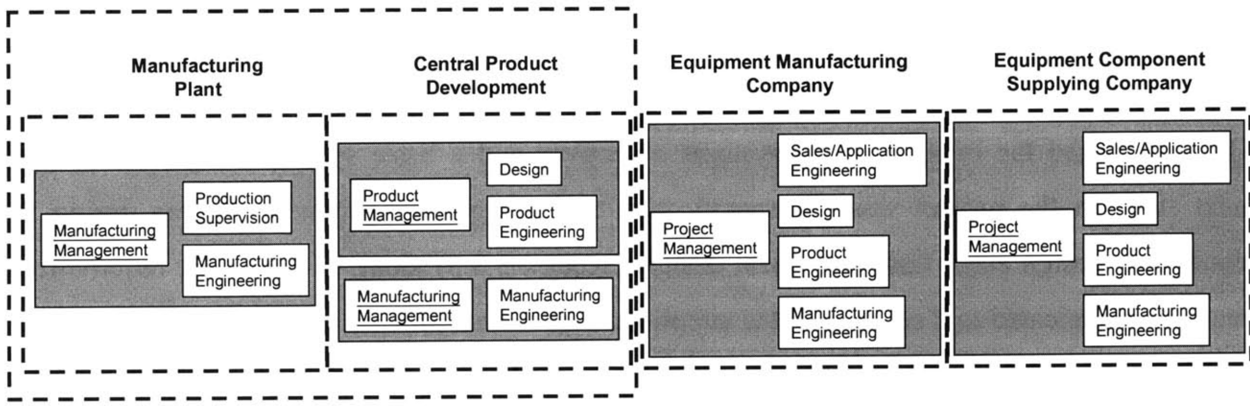


Figure 5.66 The supply chain for equipment design in the compressor project.

5.4.2 Integration of the EDA into Existing Procurement Process

All companies that buy equipment follow or have some procurement process in place. This process may be quite formal in the case of large organizations having many departments that must approve and participate in the process. Or, in the case of smaller companies, it is an informal process with relatively less defined steps that have to be completed prior to acquiring new equipment. In the compressor manufacturing system design, the EDA had to be integrated with the company's existing formal equipment procurement process. Figure 5.67 shows an overview of the company's procurement process and the integration of the EDA steps.

There were four points in the procurement process where the results of the EDA were applied. For the specification writing stage, the first three steps of the EDA apply to the line-up meeting of equipment manufacturers. The line-up meeting is a formal meeting at which a selected group of candidate suppliers are presented with an overview of the manufacturing systems objectives. All suppliers in attendance are provided with information that consists of timing, product drawings, and general descriptions of both product and manufacturing system requirements. To provide suppliers with such information requires carrying out the first three steps of the EDA that are necessary to generate a design guideline document. The writing of specifications and guidelines therefore precedes the line-up meetings and integrates the first three steps of the EDA.

Once suppliers had submitted concepts for evaluation, these concepts had to be selected for an initial equipment design. This decision process represents the early stages of high-level equipment design (decomposition) since initial structural configurations and machine platforms were chosen at this point. In the case of compressor machining equipment, the decision corresponds to selection of vertical turning and machining centers.

The next stage in the procurement process is detailed design. During this stage, equipment subsystem designers used views that were created in Step 2 of the EDA. In design reviews, the guideline document created in Step 2 served as a reference to clarify FRs/DPs amongst the equipment manufacturing and component supplying companies (see Figure 5.66 above). The last step for application of the EDA was the debug and test stage. For this stage, FRs in the MSDD were stated in a verifiable form that was used to evaluate the machining and assembly cells. The next sections examine and give examples of the application of the EDA in the context of the company's procurement process.

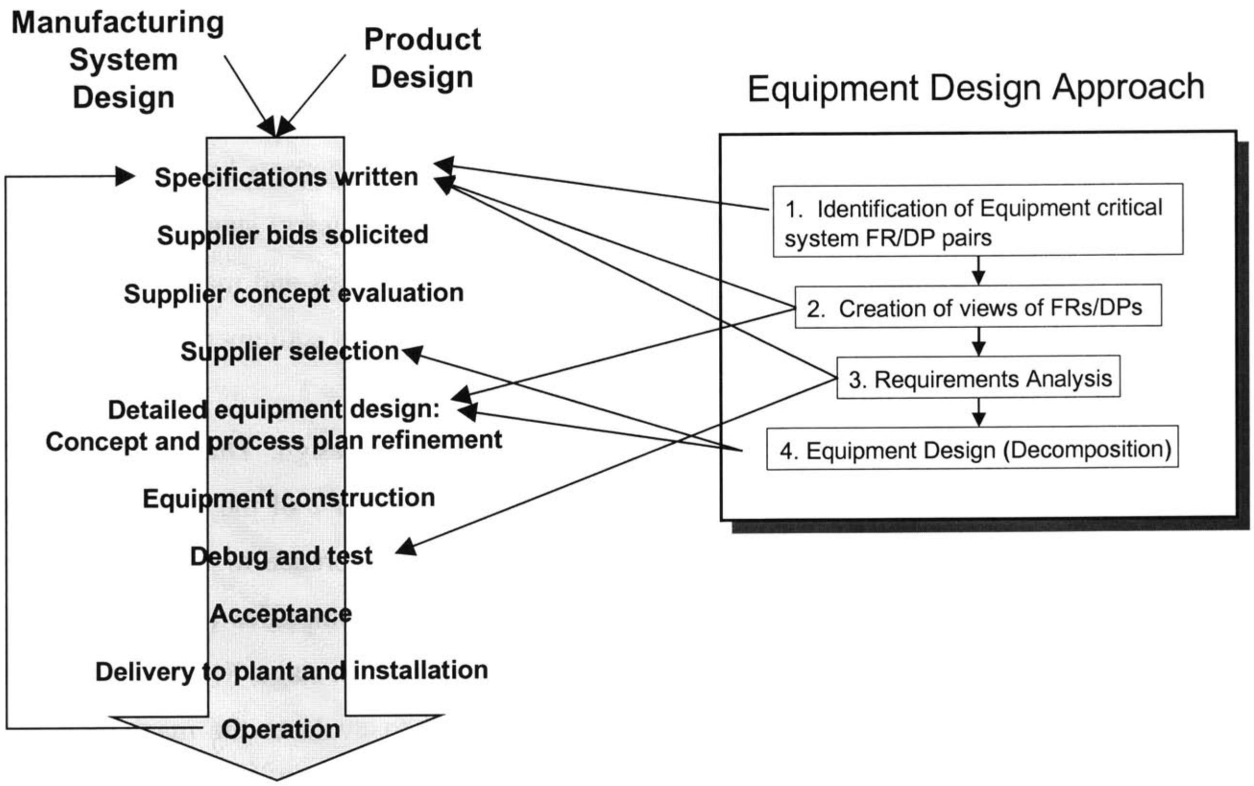


Figure 5.67 Steps where Equipment Design Approach applies to conventional equipment procurement.

5.4.3 Step 1 – Identification of Equipment System Requirements

In the first step of the EDA, FR/DP pairs from the respective MSDD and Product Design (PD) decomposition hierarchies that affect equipment design are identified. Chapter 4 described the use of interaction matrices to examine the level of influence from the MSDD to high-level subsystems known to the manufacturing systems engineer. In the compressor project, high-level knowledge of CNC turning equipment was known and used together with the equipment decomposition for a lathe give in Chapter 4 to generate the interaction matrix.

Figure 5.68 shows the MSDD FR/DP pairs that were identified as influencing the equipment design decomposition. The level of average influence is plotted in descending amount and reflects a high degree of influence for mainly the fifth and sixth levels of the MSDD. Also, note that there is no specific pattern of level in relation to degree of influence since the MSDD

FR/DP pairs can arise at different stages and levels of equipment design. This basic set of equipment requirements forms the basis for generating views discussed in the next sections.

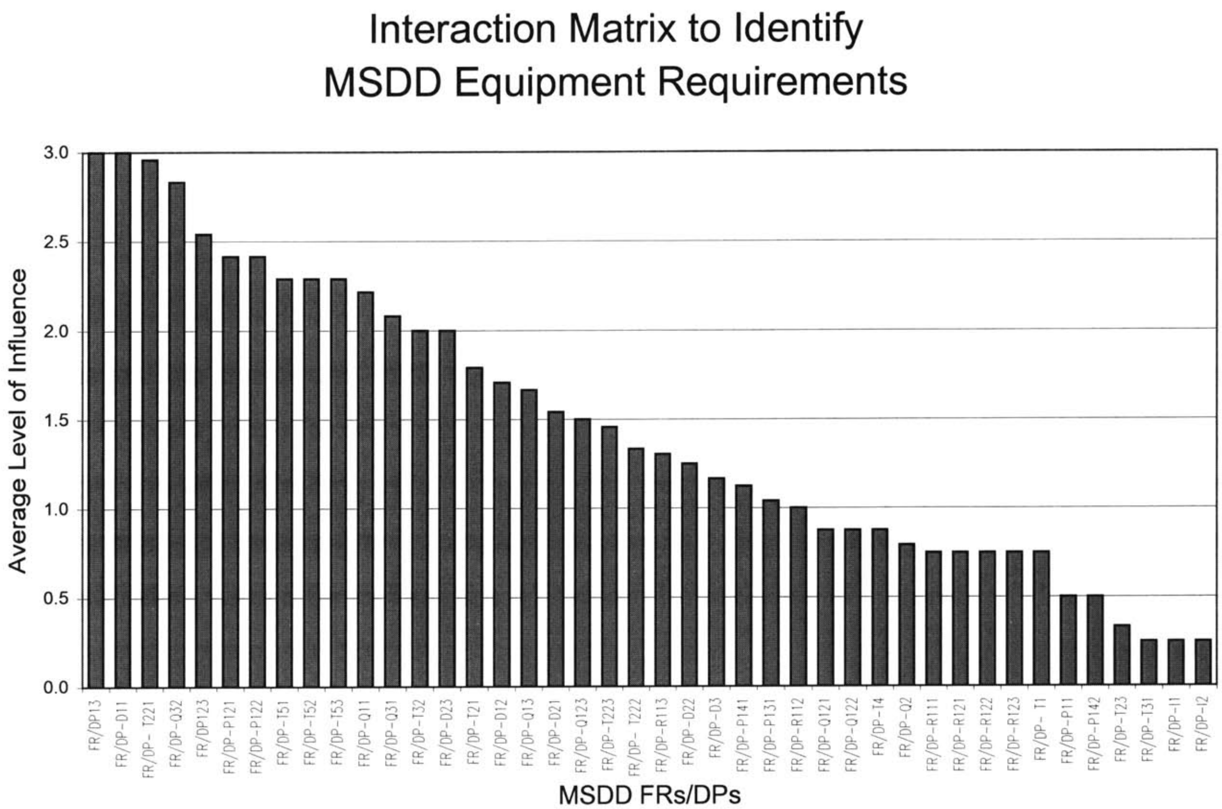


Figure 5.68 Results of using interaction matrix for Step 1 of the EDA.

5.4.4 Step 2 - Creating Views

The next sections describe different views created from the MSDD. Recall that a view is a subset of requirements based on equipment design characteristics. With the exception of the cell view, the other four views were generated based on the high-level subsystems of the equipment decomposition described in Chapter 4. These high-level subsystems were general to all of the equipment considered in this project. Each view is described in terms of the design domain that it represents and the specific FRs/DPs that have to be considered by the designer responsible for the view. Section 5.4.6 gives specific design examples from the view.

5.4.4.1 Cell Design View

The cell design view is not specifically an equipment design view, but rather it is a view of how equipment should be integrated into subsystems. Subsystems are self-contained units of production such as transfer lines, cells, or collections of machines with a common attribute. In this project, subsystems refer to cells. Cells are dynamic combinations of man and machines that have the capability to be changed whenever improved, alternative methods for manufacturing processes are discovered. Equipment in manufacturing cells is organized according to process sequence with single stations assigned to each operation. As a result of this organization, operators in cells can more easily improve quality through error prevention mechanisms and greater visibility of problems that might appear. Therefore, the view of a cell (Figure 5.69) can provide the context to describe how: operators deliver high quality products, cells are organized, and equipment is integrated to identify and resolve problems. Furthermore, the view provides description of how operators in cells control production and interact with other cells in a linked cellular system.

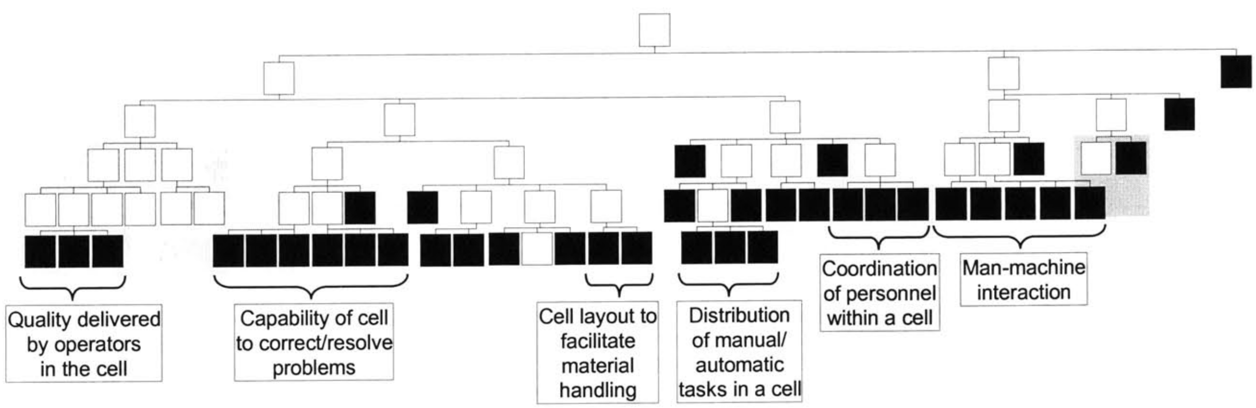


Figure 5.69 Cell Design View

The ability to identify and resolve problems in the context of a cell is an important set of FRs/DPs contained in this view (FR-R111 to FR-R123). The view describes the advantage of workers not being physically isolated in cells so that teamwork is improved and hence supports rapid response to problems. An example of a procedure designed according to the cell view is the case of a production stoppage in which every worker is to converge on the station experiencing downtime and resolve the problem as a team. Sharing the responsibility of problem resolution is important since any operator may be called upon to operate any station in a cell. The more knowledge operators have about each station's process the better prepared they will be when called upon to operate it.

The cell view is not given to manufacturers of individual pieces of standalone equipment but instead to system integrators. For example, the cell view is particularly important to a single integrator such as the builder of an assembly line. In this compressor project, the assembly supplier was provided with the view of the cell because they had the responsibility to design the entire cell not only individual machines. Furthermore, the assembly supplier had to integrate third party machine builders. These examples are described in Step 4 of the equipment design approach in Section 5.4.6.

Another situation where a subsystem view is necessary is when there are many different types of equipment and no external systems integrator to concurrently design equipment for a common system. In the machining cells described in 5.3.3.1 there are a variety of processes and suppliers of equipment. In these cells, the cell design view is used internally by the manufacturing engineers in the central development organization of Figure 5.66.

5.4.4.2 Equipment Structure View

The structure of a piece of equipment is the underlying frame onto which all subsystems are connected. The structure defines material flows through equipment by the configuration of load carrying and moving members. Also, the structure defines the "flows" or paths of support and production personnel. The interface between the man and machine is a function of the external shape and location of subsystem specified by the mounting locations of subsystems onto the frame. The ease by which a machine is moved or reconfigured depends greatly on the design of the equipment structure. However, it is the basic accuracy requirements that initially determine the frame's configuration (i.e. open C, closed portal) and which originate from the product's tolerances and geometrical requirements.

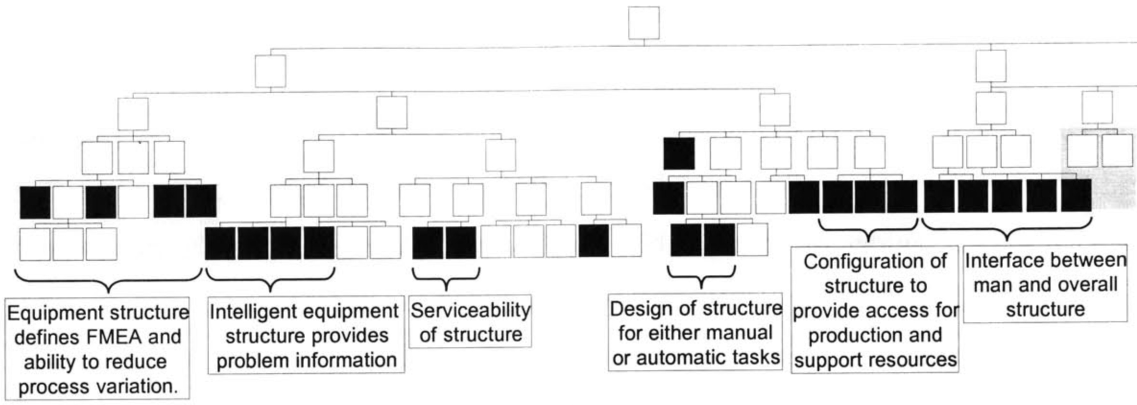


Figure 5.70 FRs/DPs selected from the MSDD to create the equipment structure view.

The view of equipment structure is generated from the basic machine requirement to accommodate the size of the part and thereby specify the machine's work volume. The FRs/DPs selected from the MSDD affect the physical structure of the machine and how the subsystems of the machine are integrated. For example, MSDD FRs/DPs that specify material flow paths affect the structural design of the equipment in that the system layout desired determines feasible flow of parts through a machine. MSDD FRs/DPs that affect equipment structure are not limited to obvious physical system requirements. Quality and product delivery are branches of the MSDD that yield information requirements for which the equipment structure must be appropriately designed. The ability to eliminate machine assignable causes (FR-Q31,Q32) must be designed into the equipment structure to avoid costly modifications at the operational stage of system implementation. The equipment structure view also contains requirements to improve the identification and resolution of problems by meeting FRs-R111 -> R121. The equipment structure should be able to provide intelligent information to the process so that problems are quickly identified.

5.4.4.3 Workholding View

A workholding device (i.e. fixture) is any piece of hardware on a piece of equipment that grasps the part while it is being processed. Grasping of a part occurs for two different reasons. One reason is to grasp a part to move it and change its position with respect to the machine structure. For example, to transfer a part into and out of a machine. The second reason to grasp a part is to locate and secure it accurately while it is being processed. These two basic functions of a workholding device define the relation amongst the process, operator, and machine. Therefore, creating a workholding view involves extracting MSDD requirements that specify process, operator, and machine in the context of holding the part for either of the two reasons described above.

Figure 5.71 shows the FRs/DPs that represent the workholding view. The six text boxes provide an explanation of each sub-branch that has been extracted from the general set of equipment FRs. The quality branch FRs (FR-Q121, Q122, Q123, Q11, Q13, Q2, Q32) determine the process requirements that the workholding design has to satisfy. Incorporating devices to prevent defects or SPC adjustment capability in a workholding device are different ways the equipment designer can achieve MSDD quality requirements. The workholding view also provides information about problems that do not necessarily originate as a result of failure to meet quality requirements.

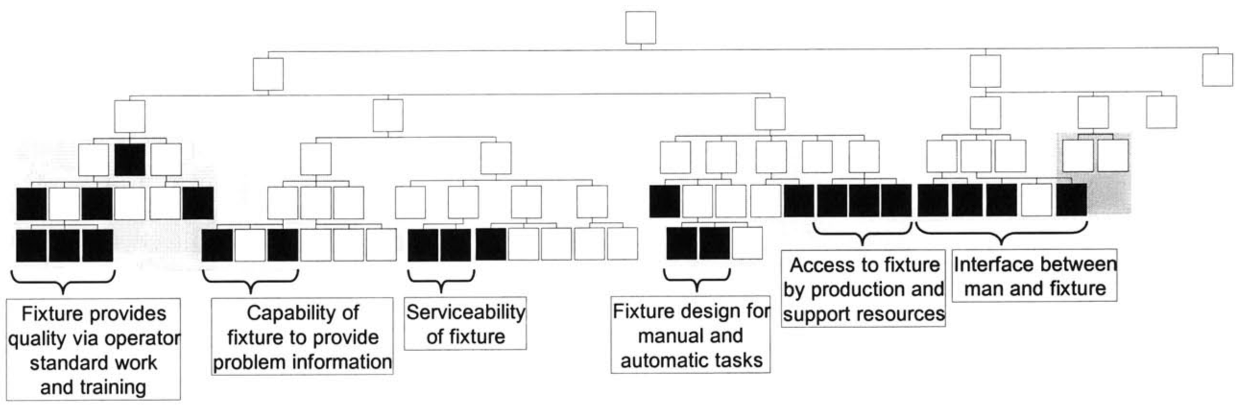


Figure 5.71 FRs/DPs selected from the MSDD to create the workholding view.

Problem information from the workholding device should help operators and support personnel find the nature of the problem. The serviceability of the workholding device depends on its accessibility by support personnel with specific service information. The accessibility of the workholding device in this view corresponds to how easily operators can load and unload easily parts. Accessibility for service personnel means access to functional components for removal without the need for extensive machine tear-down (i.e. to reach fastening bolts or electrical/hydraulic corrections). The last aspect of the workholding view is that it establishes the requirements for man-machine interaction during part handling. Ease of load/unload, tactile feedback, visibility during load, both visual and audio indicates proper orientations, etc.

5.4.4.4 Tooling View

Tooling plays a complementary role to that of workholding in that a tool modifies the part whereas the workholding device simply holds it while the tool performs its function. One characteristic of this relationship is that tooling generally has a shorter operating life than does a workholding device and hence needs more frequent replacement and maintenance. Thus accessibility of tooling is more critical than for workholding. An operator interacts with a tool to either operate it or to replace it whereas a workholding device is just a passive device for the operator to place a part into. However, despite this contextual difference, the same three criteria apply to creating the view, namely process, operator, machine. Chapter 6 provides a tool design example that uses the view to examine two types of tooling systems and how they meet MSDD FRs.

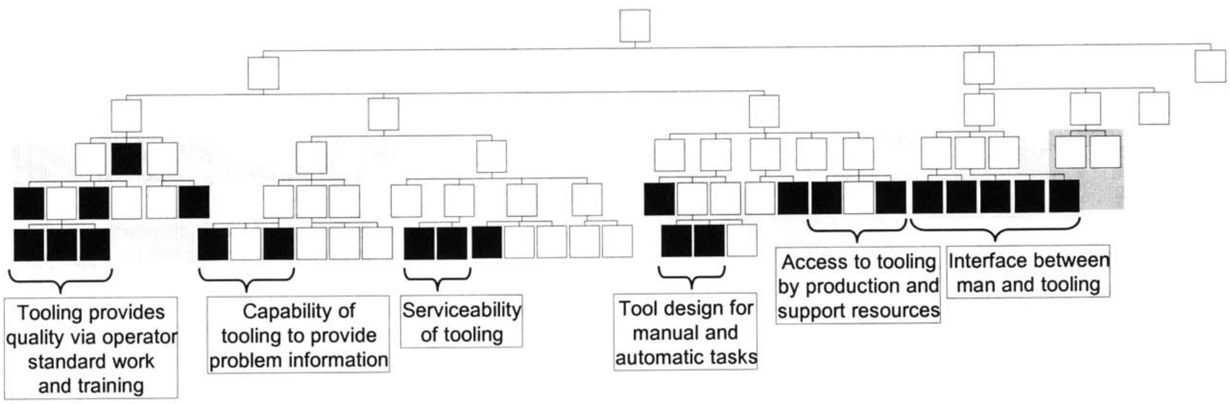


Figure 5.72 FRs/DPs selected from the MSDD to create the tooling view.

5.4.4.5 Operator Interface View

Design of the interface between the operator and a piece of equipment must consider simultaneously process, quality, maintenance, and production control requirements. The operator interface may be defined as the set of parameters through which an operator is aware of the equipment's status and has the capability to change the set to effect a desired response. The parameters may be physically presented to the operator in many different forms: audibly, tactually, or visually. The physical presentation of these parameters is design of the operator interface. The operator interface has to be designed depending on the level and amount of interaction that the operator will have with equipment.

The operator interface view (Figure 5.73) consists of requirements from four main branches of the MSDD: quality, problem resolution, predicatable output, and direct labor. The operator interface should be designed to provide task knowledge (FR-Q121), task supervision (FR-Q122), and to prevent translation of human errors into defects (FR-Q123). The problem resolution branch contains requirements that specify the presentation of information to the operator. Requirements such as FR-R111 to FR-R121 involve the recognition and communication of disruptions to operators. Therefore, the interface must organize problem information so that the operator can immediately assess the situation and take steps to solve the problem (FR-R13).

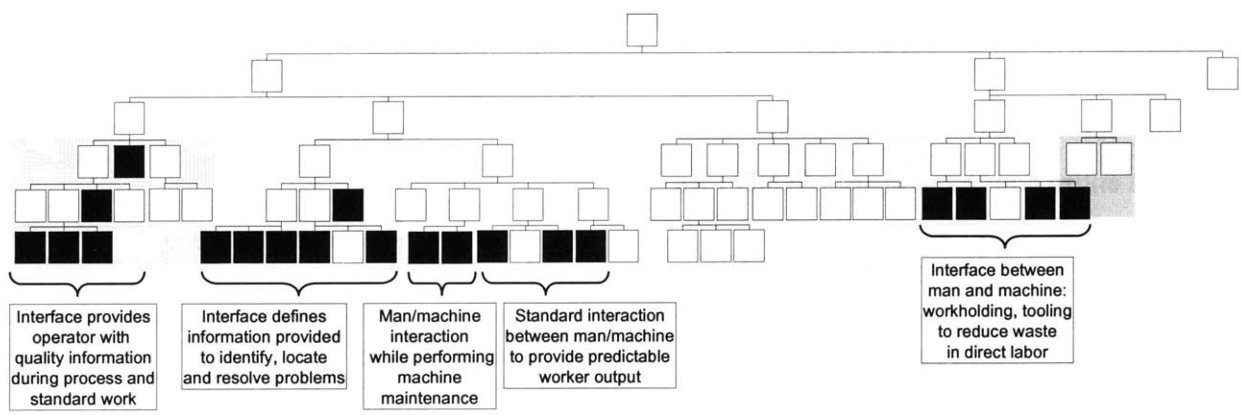


Figure 5.73 FRs/DPs selected from the MSDD to create the operator interface view.

Predictable output FRs specify the design of the operator interface for minimal variation in equipment, operator, and material variability. Though equipment components have to be designed for high reliability, the components should also be designed so that the operator is able to easily service the components. An example of FR-P121 is to make coolant levels easy to read for performing regular preventative maintenance (DP-P121).

The fourth branch of the MSDD that supplies FRs for operator interface view is that of direct labor. Direct labor has the highest frequency of contact with equipment in the context of process and production control. MSDD requirements also specify the design of the operator interface for varying levels of operator interaction. For example, FR-D11 describes the design of manual tasks at a station so that non-value added tasks are reduced and eliminated. Also organizational design of operator controls in workholding, tooling, and general equipment functions are specified by FR-D12, FR-D22, FR-D23.

5.4.5 Step 3 - Analysis of Requirements

The result of the application of Oliver's taxonomy in Section 4.7 to classify MSDD requirements showed that 97% of the FRs were stated in a non-verifiable form. A non-verifiable form of an FR is an objective that as stated can never be measured. For example, all goal-like statements such as "maximize/minimize" represent ideal states that designers "should" strive to attain. However, in the absence of a defined and specific quantitative value, the FR can not be verified to determine if it has been attained or not[24]. To make these FRs more verifiable, the entire set of MSDD FRs were recast in a form that specifies measurable parameters that can be used to verify attainment of the FR. Also, the FRs were restated to explicitly distinguish a requirement from a goal by use of the phrase "the manufacturing system shall do X...", where X is an attribute that the system must have and can be measured and therefore verified. Figure 5.74 shows an excerpt from the entire converted set of MSDD FRs.

FR ID	MSDD FR	Converted requirement statement
FR1	Maximize long-term return on investment	The manufacturing system shall provide a ROI of X over a time period of Y.
FR11	Maximize sales revenue	The manufacturing system shall generate $X of sales revenue over the period of Y.
FR111	Deliver no defects	The manufacturing system shall deliver X products to the customer with PPM quality less than Y.
FR112	Deliver products on time	The manufacturing system shall have a TPT variance less than X.
FR113	Meet customer expected lead time	The manufacturing system shall have a TPT less than the customer lead time.
FR12	Minimize production costs	The manufacturing system shall have production costs < $X over the period of Y.
FR121	Reduce waste in direct labor	The total amount of direct labor shall decrease according to the waste-reduction profile(t)
FR122	Reduce waste in indirect labor	The total amount of indirect labor shall decrease according to the waste-reduction profile(t)
FR123	Minimize facilities cost	The manufacturing system shall have a facilities cost < $X over a period Y.
FR13	Minimize investment over production system lifecycle	The manufacturing system shall have an investment (profile) of $X over a period Y.
FR-D1	Eliminate operators waiting on machines	Operators shall not wait for machine cycles to finish. Or... The operator time shall be greater than the machine cycle time.
FR-D12	Enable worker to operate more than one machine / station	Operators shall have the capability to operate greater than X machines.
FR-D2	Eliminate wasted motion of operators	Operators shall not make wasteful motions (deviate from work plan).
FR-D21	Minimize wasted motion of operators between stations	Operators shall not make wasteful motions between machines (deviate from work plan).
FR-D22	Minimize wasted motion in operators' work preparation	Operators shall not make wasteful motions during work preparation (deviate from work plan).
FR-D23	Minimize wasted motion in operators' work tasks	Operators shall not make wasteful motions during work tasks (deviate from work plan).
FR-I2	Eliminate information disruptions	The manufacturing system shall have < X information disruptions
FR-P1	Minimize production disruptions	The manufacturing system shall have availability of X.
FR-P11	Ensure availability of relevant production information	Production information shall be provided ...
FR-P12	Ensure predictable equipment output	Equipment shall have an availability of X.
FR-P13	Ensure predictable worker output	Worker output shall be predictable
FR-P131	Reduce variability of task completion time	Variability of task completion time shall be < X
FR-P132	Ensure availability of workers	Worker availability shall be X.

Figure 5.74 Sample of MSDD FRs converted into a verifiable and quantitative requirement form.

[24] A possible solution (a subject of current research) is to use performance measures that have been developed for each FR in the statement of the FR.

5.4.6 Step 4 - Equipment Design - Examples

The fourth step of the design approach is the actual design of equipment to meet the manufacturing system design requirements that were identified earlier and transformed in the first three steps. Since there are many design approaches and methods in existence, the equipment designer is free to choose the method that is appropriate for concept and detailed engineering design. In this compressor project, equipment suppliers followed their own design methods to achieve MSDD FRs/DPs. Therefore the design examples result from using a variety of design methods ranging from ad-hoc experience-based methods, design review meetings, to simulation programs. However, a parallel investigation of the use of Axiomatic Design was conducted and specific design decomposition examples (Section 5.4.6.5) were generated in the development of the Equipment Design Approach.

5.4.6.1 Cell View Example

The cell design view contains the requirements for production control and operation, layout and organization, and integration with other cells and subsystems. The examples developed from the cell view are taken from the operation of the cell, namely its design to meet customer takt time. Specifically, the distribution of automatic and manual tasks at each station or machine in a cell must be determined at the subsystem level so that takt time requirements are achieved. FR/DP pairs T22 decompose into the requirements for automatic and manual work content (cell design view given partially in Figure 5.75). The requirements FR-T221 and FR-T222 then give the conditions for design of station work content and overall work-loops.

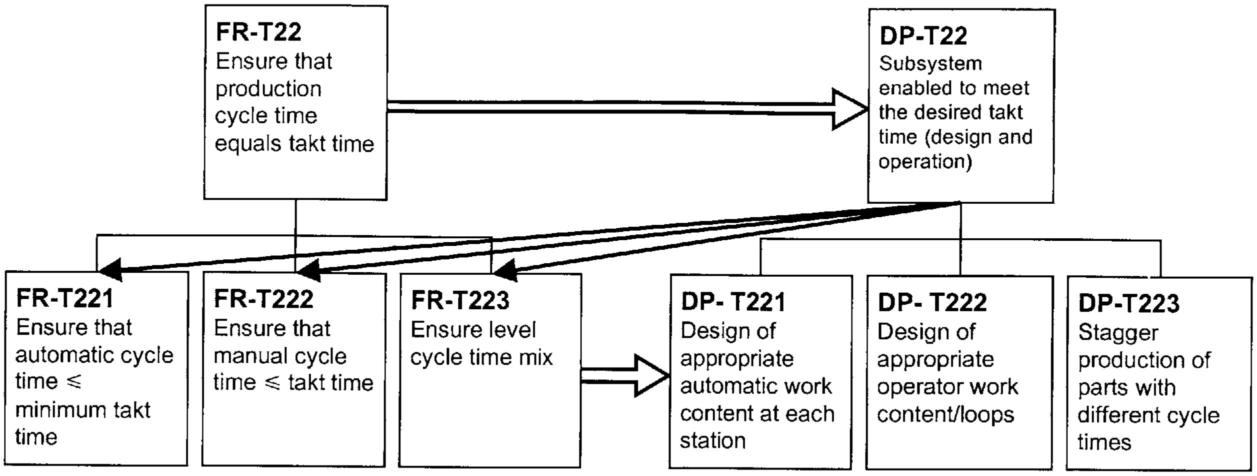


Figure 5.75 Decomposition of subsystem (cell) design meet takt time.

Specifically, FR-T221 provides the minimal condition so that the automatic cycle time is less than the takt time at every station in the cell. DP-T221 then specifies the design activity to develop automatic work content at each station. In the machining cells, work content at each machine was designed to be less than 108 seconds (Figure 5.76). However, the machining cells were designed solely to meet this takt time and studies at higher demand volumes (i.e. 54 seconds, and 27 seconds) revealed that operations 10a, 30a, 30c, 40c, 50c, 90c, 100c, 50d, 20e, 10f, 20f, 30f, and 50f would require redesign of the automatic work content to satisfy FR-T221.

Redesign of the work content in the cell can be done in one of two ways. The first is to simply expand the cell and duplicate the machine so that parallel machines can provide the needed capacity. However introducing secondary and even tertiary process streams increase the difficulty for rapidly identifying and resolving problems (i.e. satisfying FR-R111 to FR-R123). For example, the requirement FR-R112 - *Identify disruptions where they occur* becomes difficult to achieve as the number of material flow paths increases. The second way to redesign work is to redistribute the work onto an additional machine such that a primary process stream is maintained while providing the necessary capacity. This second approach was considered to avoid parallel machines, however, the product datums and associated tolerances in the operations described in the previous paragraph constrained such work content redistribution for a 54 second takt time.

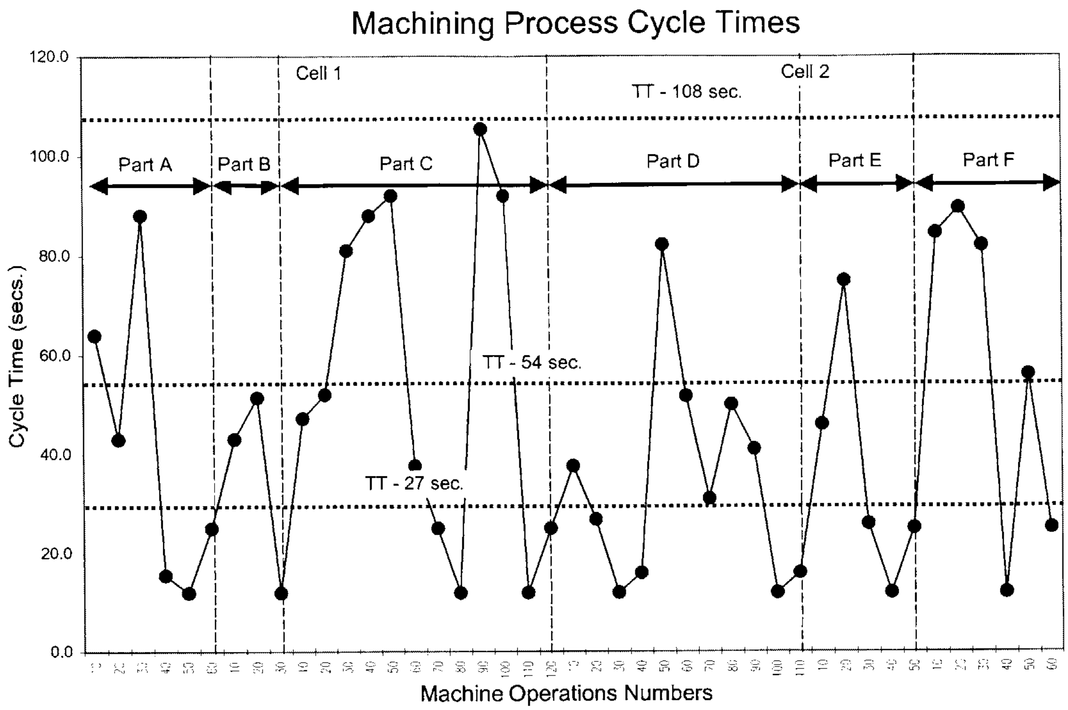


Figure 5.76 Machining operation cycle times for the six parts in the two cells.

An example of FR-T222 – *Ensure that manual cycle time <= takt time* is better illustrated by assembly cell design where the ratio of manual to automatic work content is higher. In the cell design view, it is DP-T222 that represents layout design to enable workers to operate more than one station. To meet this FR/DP pair all equipment in the assembly cell was designed with a narrow station width so that operators could run adjacent as well as opposing stations. Furthermore, varying numbers of operators and work-loops were designed for different takt times. These work-loops along with standardized work routines provided the operational plan to satisfy FR-T222. However, Figure 5.77 shows that as the number of workers in the cell was increased, it became harder to balance the cycle-times for the various work loop configurations. Thus, it is difficult to provide the operators with sufficient work to match takt time and the level of worker under-utilization increases. Figure 5.78 shows the operator workloop time as a function of the number of operators in the cell.

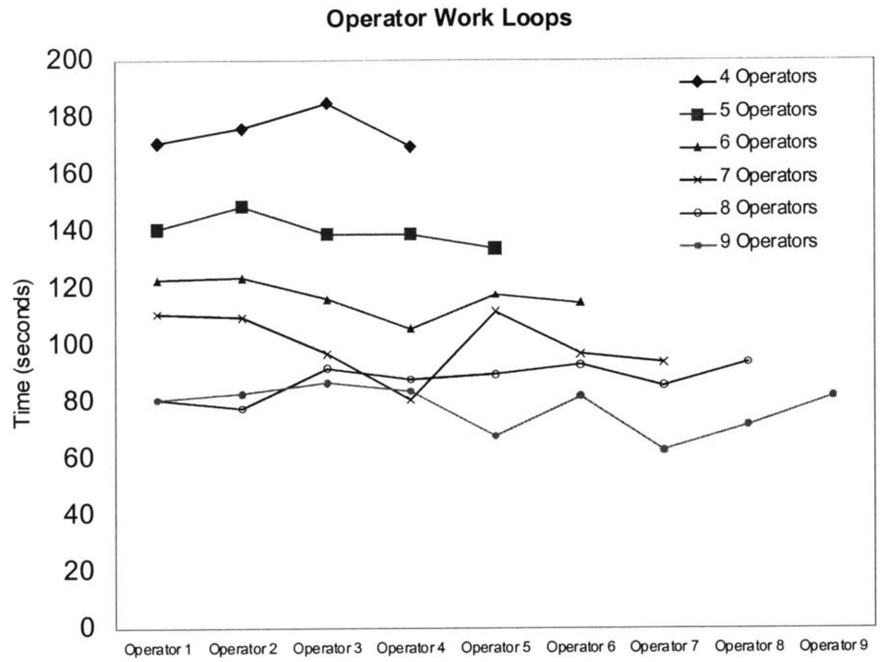


Figure 5.77 Planned cycle-times for each cell operator under different work-loop configurations (Collins, 1999)

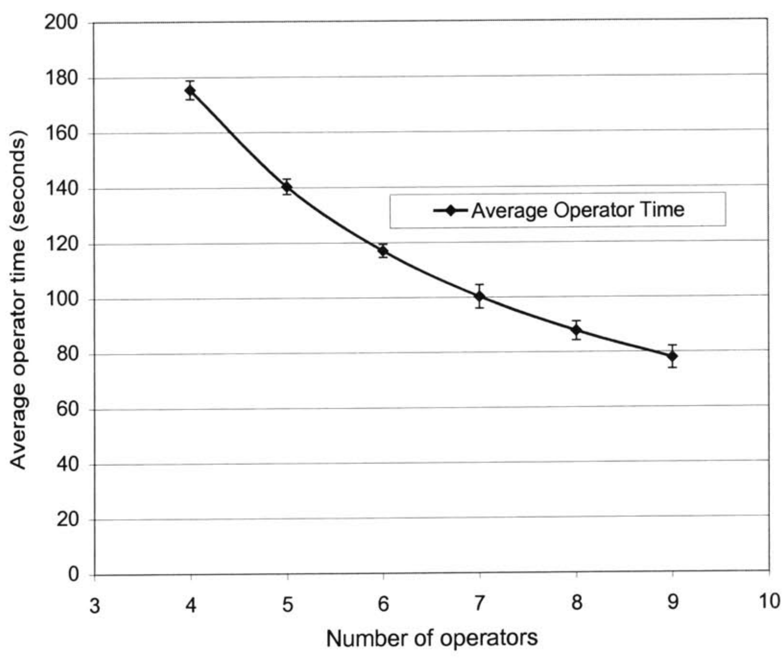


Figure 5.78 Average operator time versus number of operators.

One approach is to develop work tasks that are easily subdivided or increase the flexibility by which tasks may be moved from one station to the next. Alternatively, during operation, it is possible to partially redistribute the work tasks to different stations (depending on the stations) and thus balance the work-loop cycle times more effectively. This second approach was used since it was easier to allocate work amongst operator work-loops than to design highly divisible discrete tasks. These work-loops (five and six operator workloop designs shown in Figure 5.79) provide the operators with numerous standard work routines, that when followed result in different production rates.

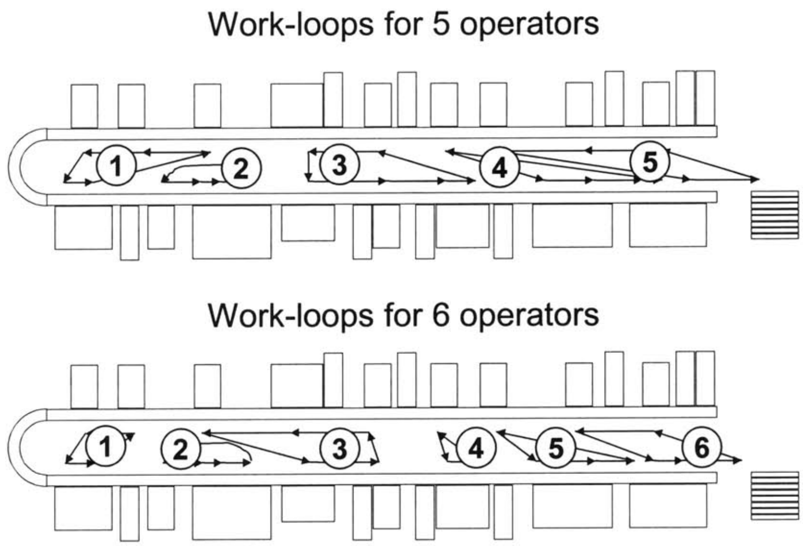


Figure 5.79 Representative work-loop design for 5 and 6 operator cell configuration, adapted from (Collins, 1999).

5.4.6.2 Equipment Structure View Example

The equipment structure view contains various FRs/DPs that specify how the structure should be designed for quality, serviceability, accessability, part processing, and man-machine interaction. The example described here shows how compressor machining equipment was designed to improve accessability for both production personnel (operators and team leaders) as well as support personnel that have to maintain or keep equipment supplied with parts.

The design example taken from the Equipment Structure View illustrates structural designs of machines that lead to reductions in systematic operational delays. Systematic operational delays such as routine maintenance that cause interruptions degrade the capability of the system to be responsive to customer demand. Systematic delays to the production flow include performing routine maintenance, removing by-products of the manufacturing process (coolant, oil, chips), supplying material to the sub-system or individual station/machine.

Disruptions to production can occur when the path of parts or cell operators intersects the path of maintenance or support personnel. Production personnel control material flow (i.e. movement of parts) along a predetermined path at a specified takt time. Since the configuration of the equipment structure is the primary determinant of material and personnel flow, FR-T51, T52, T53 are included in the design view.

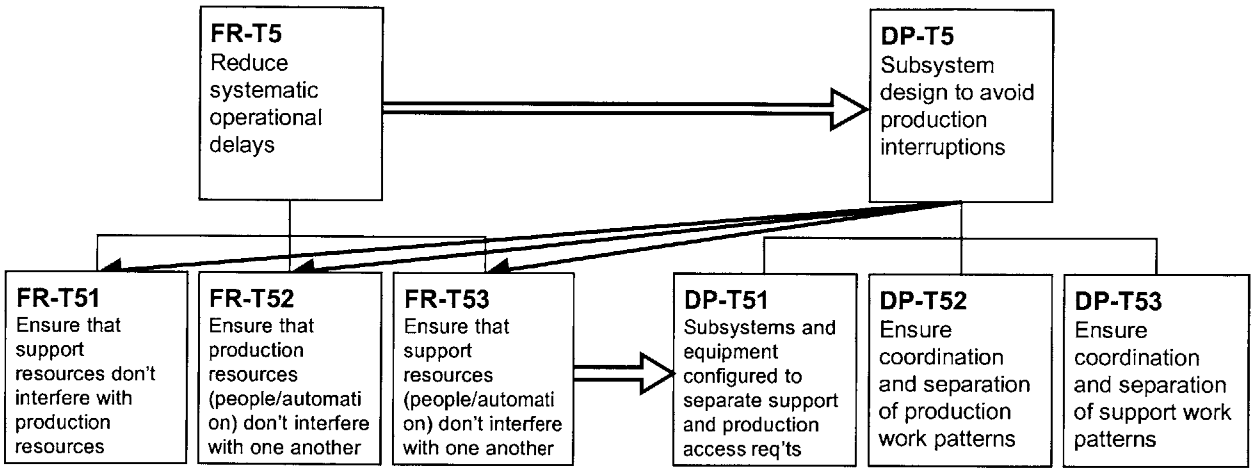


Figure 5.80 View Level 6 Decomposition of "FR - Eliminate Common Cause Disruptions to the Production Flow."

Figure 5.81 shows how equipment from machining satisfies FR-T51. The structure has been designed so that production personnel can easily load and unload parts from the front of the machine while support personnel can remove chips and monitor status of subsystems from the rear. With such separate, rear access points to equipment, costly downtime movements are reduced.

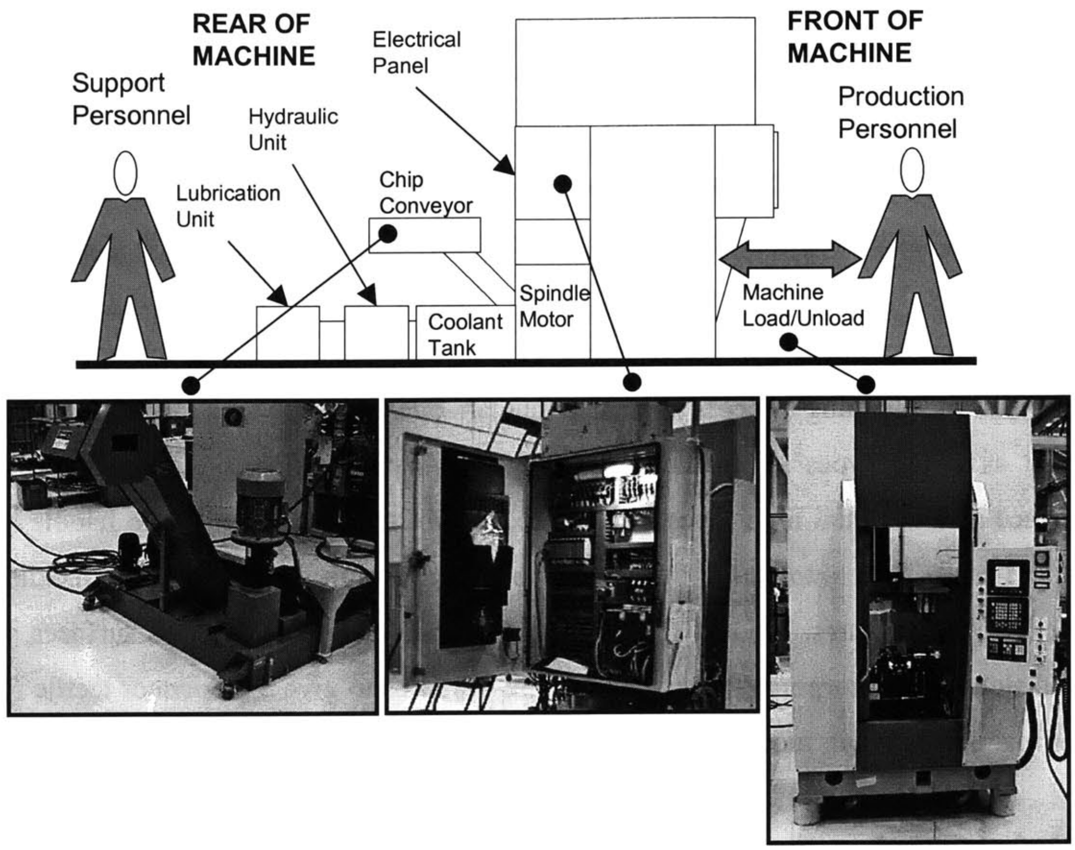


Figure 5.81 Side view of vertical lathe showing systems access from front and rear of machine.

5.4.6.3 Workholding View Example

The workholding view captures MSDD requirements that specify the grasping of the part by the operator and machine. The achievement of FR-D1 is an example of a MSDD requirement that depends on proper workholding design. FR-D1 requires that the operator not wait for the machine since the operator is capable of performing other value adding activities while a machine is carrying out completely automatic cycles. Thus, the man has to be separated from the machine during automatic operations to eliminate the need for the operator to wait for machines (DP-D1). Though DP-D1 states that the man is separated from the machine, the man is not separated from the part at all times. Therefore, separating the man from the machine leads to workholding requirements (sub-FRs) for material handling to and from machines as well as between machines.

The loading of parts to and from workholding devices is a material handling activity that significantly affects high-level manufacturing costs (FR12). When the loading is performed manually by operators, then the greatest effect on FR12 is in the cost of direct labor. In particular, complex workholding and related material handling devices carry high maintenance costs. To reduce costs, workholding in both machining cells was designed to make use of the operator's ability to cost-effectively load parts directly to the workholding device. After completion of the automatic cycle a simple device or mechanism unloads the part. The design reasoning for this loading process is that a human operator can load parts as quickly and accurately as many types of material handling automation without the need for ongoing maintenance and an initial high investment. Also, the ability of the operator to handle different parts is less costly than automation that has to be designed with the flexibility to handle a wide variety of product features. Product features such as outer diameters, stepped surfaces, locating holes and slots were incorporated into workholding surfaces to give the operator tactile feedback and thus make the loading process easier and more reliable.

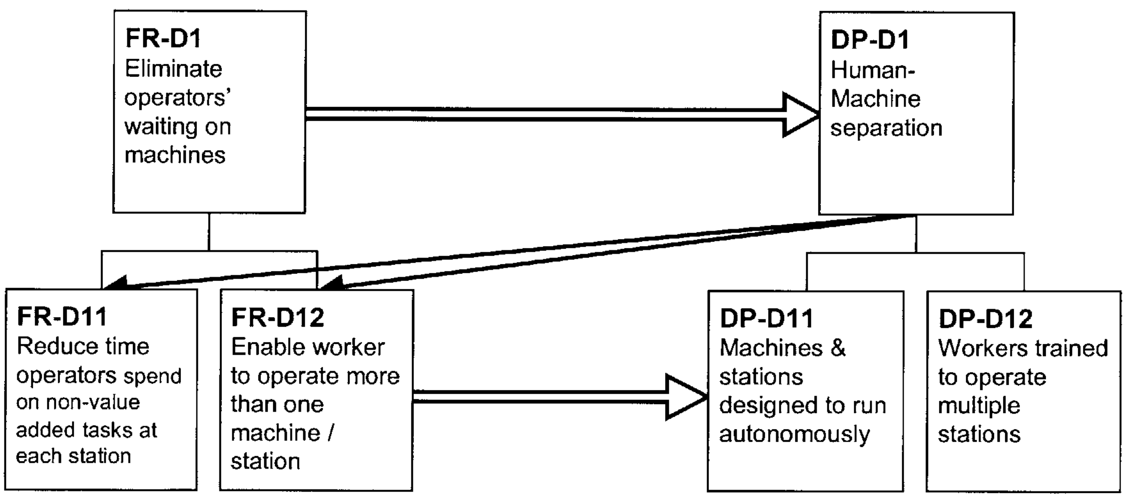


Figure 5.82 Workholding requirements for achieving human-machine separation.

Two examples are given in Figure 5.83 and Figure 5.84 that show how workholding devices were designed to meet FR-D11 and FR-D12. Both workholding devices were designed to incorporate product features to improve loading as described above. For unloading of the part, the non-value added task has been eliminated in Figure 5.83 by the use of a rotary actuator. After the part has been machined, a robot gripper (i.e. a type of workholding device) takes the part from the chuck and the actuator moves the part to the vertical orientation for presentation to the operator. The chuck is now clear and is ready to be manually loaded. Similarly in Figure 5.84, the part is unloaded by another rotary actuator, however, the difference here is that the gripper unloads it to a mechanism that in turn unloads it at a specific angular rotation. The angular rotation of the part in the nest makes it easy for the operator to grasp the part by the end of the shaft. In both cases the DP-D12 that is used is consistent unload orientations that permit the operator to be uniformly trained to run multiple machines. Figure 5.83 shows a part presence sensor that in conjunction with an activation switch[25] verification allows the machine to begin cycling automatically upon removal of the part (DP-D11). Similar sensors that exist in the workholding device of Figure 5.84 are not visible in the figure.

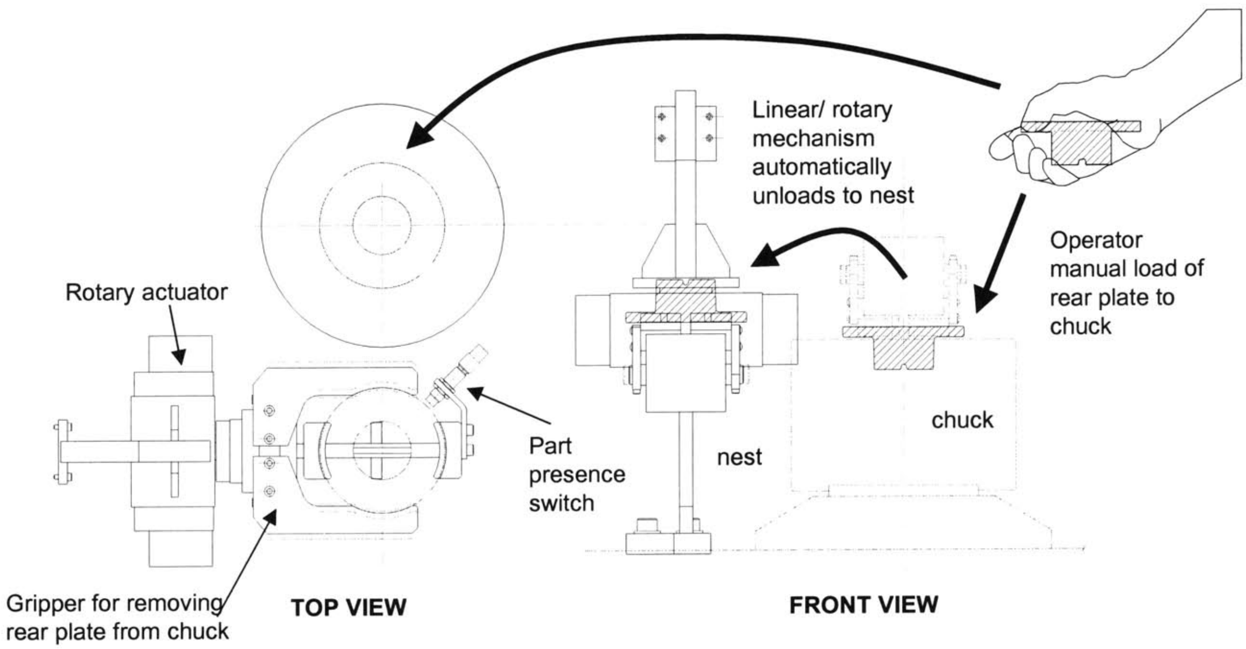


Figure 5.83 Workholding view example for operator loading part to a chuck (CAD courtesy of Royal Engineering).

With the workholding devices designed as shown in Figure 5.83 and Figure 5.84 the material handling sequence at each machine in the cells follows the following steps:

1. The operator approaches a machine with a part from the previous operation and loads the part directly into the empty workholding device. The placement of the part in the device activates a part presence sensor in the machine control.

2. The operator then removes the previously processed part from the auto-unload part holder/nest[26]. The operator then stands clear of machine so that the light curtain (or similar safety sensor) recognizes that the operator is safely away from the machine.

[25] Also known as a walk-away switch.
[26] The holder or nest may be inside or outside of the machine.

3. The operator then activates a walk-away switch that initiates automatic part clamping and the start of the machine cycle. The operator now proceeds to the next machine with part in hand.

Steps 2 and 3 may vary slightly depending on where the part is unloaded. If the part is unloaded inside the machine, the logic must check for both conditions, part removed and no person inside machine.

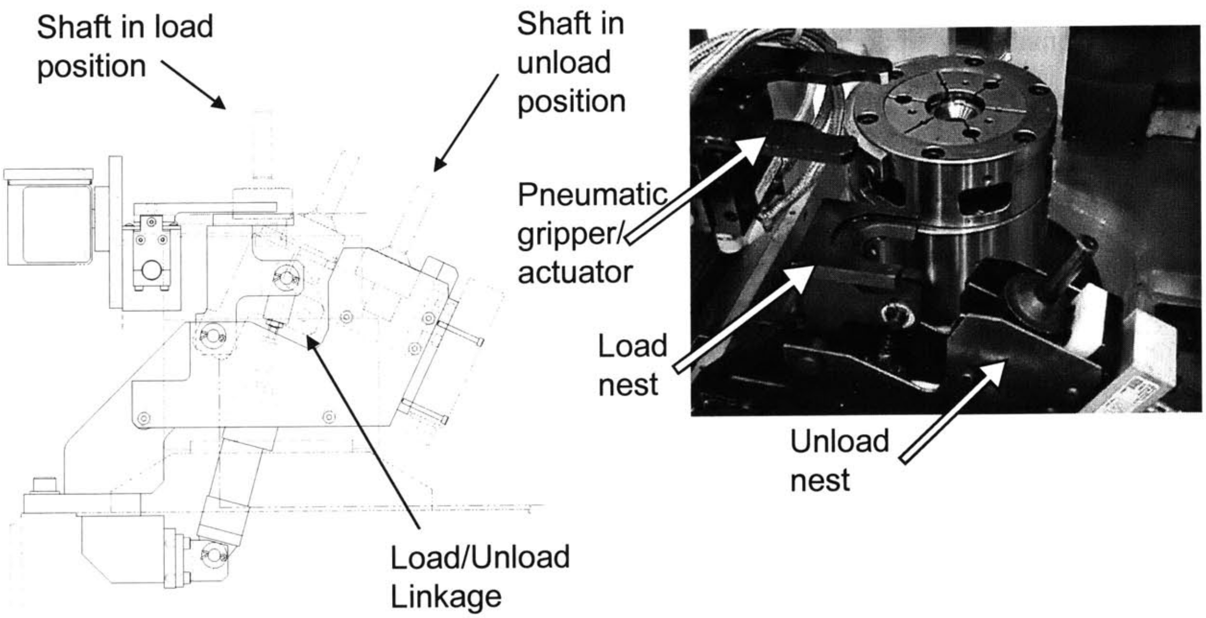


Figure 5.84 Workholding view example where loading is to a robotic gripper instead of directly to the chuck (CAD courtesy of Royal Engineering).

Finally, note that since material handling is being done by the operator, ergonomic requirements must also be considered in the design of workholding devices. Designs should incorporate standard ergonomic principles such as proper load heights, minimal transport and reach distances, and good line of sight for manual tasks. These requirements are described in greater detail in the next section with examples from the operator interface view.

5.4.6.4 Operator Interface View Example

Examples from the operator interface view are taken from the high-level FR-D2. FR-D2 is the requirement to reduce waste in the motion of the operator, while at a station, between stations, or away from a station. The operator interface requirements result from decomposition of FR-D2 (Figure 5.85) into the improvement of motion for each of these cases. Physical location of controls, displays, and other interface elements define the range of motions required by the operator. Therefore, design of the operator interface to meet FR-D2 involves specifying the placement of such elements so as to reduce wasteful motion.

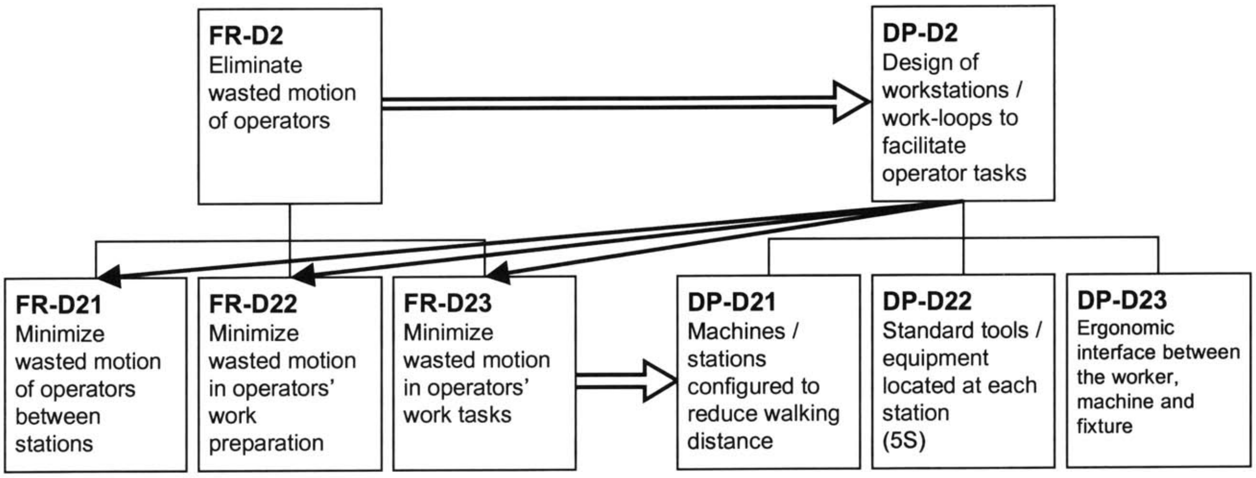


Figure 5.85 Decomposition of motion requirements for operator interface view.

For example, design of the operator interfaces in the assembly cell improved motion by ensuring all necessary objects were within reach whether for production or offline tasks. In the machining cells, not only were subsystems placed at the rear of the machine for ease of maintenance access, no side access was provided so that equipment could be placed side by side. Figure 5.86 shows an illustration of the placement of machines to minimize wasted motion of operators between stations (FR-D21).

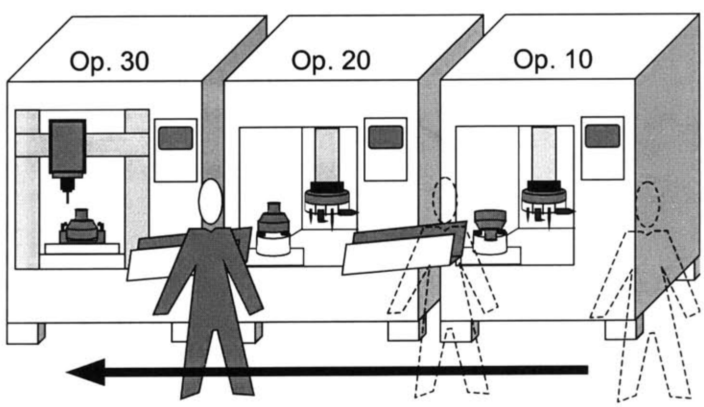


Figure 5.86 Example of reducing walking distances between equipment.

Operator interfaces were also developed concurrently with the manufacturing process plan and consider the orientation of the part as it is clamped in the workholding device at each operation. The orientation of the part as it leaves one operation was designed not to require reorientation by the operator to load it into the next station. This sequence gives a consistent transfer that the operator can readily learn (DP-D12). Furthermore, the sequence enhances the ability of the operator to be aware of other process states and thus not have to focus on non-value adding motions. Figure 5.87 shows the design of the process orientation and the unload orientation for one of the six parts. By reducing manipulations of the part from station to station,

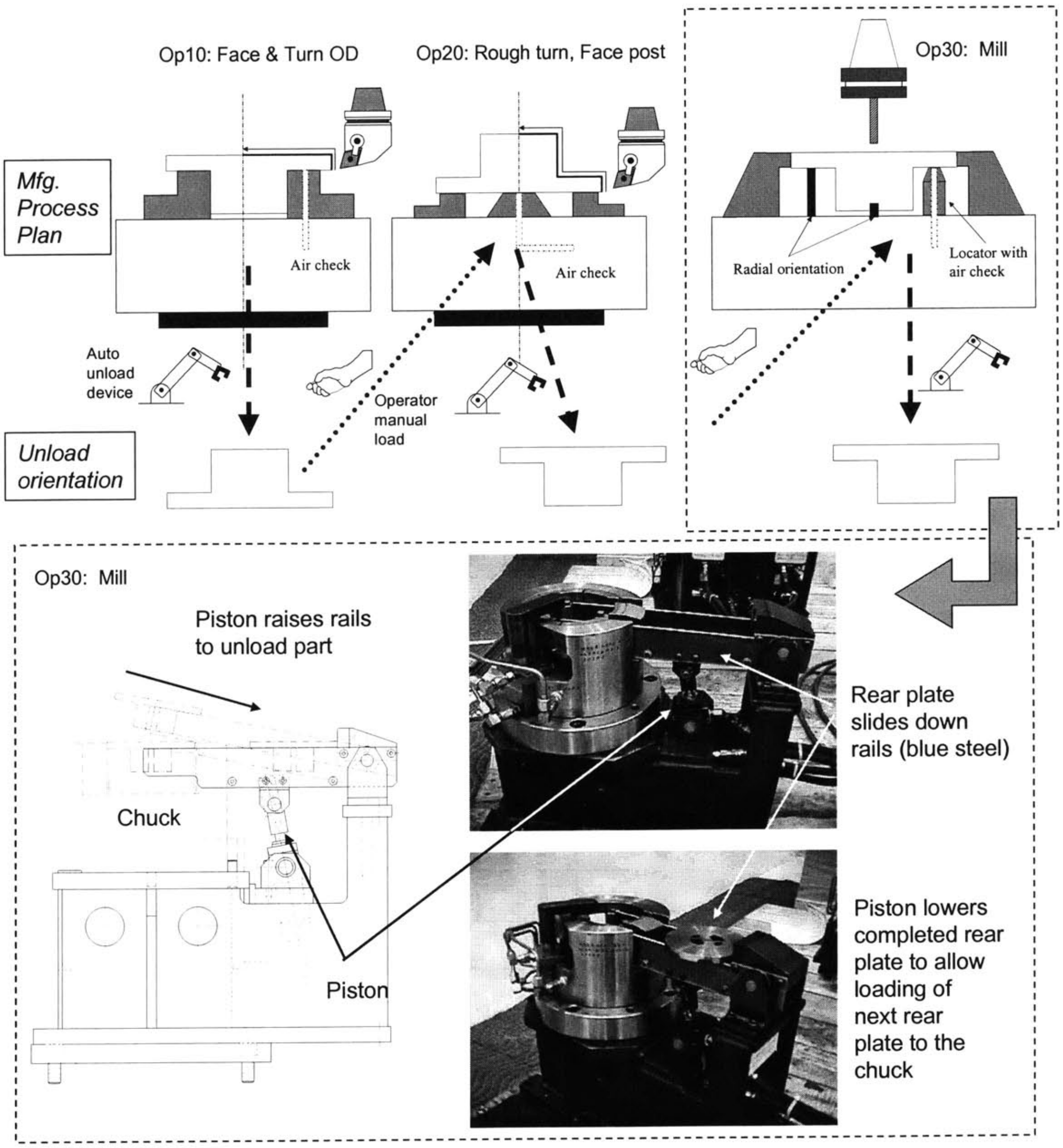


Figure 5.87 Interface between operator and workholding to achieve cost effective loading.

symmetrical features were used to help the operator quickly distinguish when handling the part. The lower half of Figure 5.87 shows the design details for the automatic unloading of the part by means of a simple gravity slide.

In the compressor assembly stations, the position of both in-feed and out-feed slides is part of the definition of the operator interface. All the stations were designed with in-feed slides to present the part within an operator's ergonomic work envelope shown in Figure 5.88. The out-feed slide used to return empty bins was placed at the upper limit of an operator's reach because the movement is made with relatively low frequency. The position of the material feed slides was designed to be adjustable to provide a means to vary the operator interface according to the ergonomic needs of individual operators. The slides were connected to the equipment structure's base aluminum extrusions with fasteners that are quickly loosened and tightened by hand (DP-D22).

As with equipment in the machining cells, a standard work-height was fixed across every station that was based on the requirements of the local workforce. This height was measured from the floor to the middle of the compressor resting on a pallet. Thus the pallet position in the operator interface is a constant height across all stations. A consistent pallet position is also important in reach distances for offline tasks present in the assembly cell. The reach distance in offline tasks was minimized to reduce the exertion required of the operator when lifting the compressor on and off the conveyor (DP-D23).

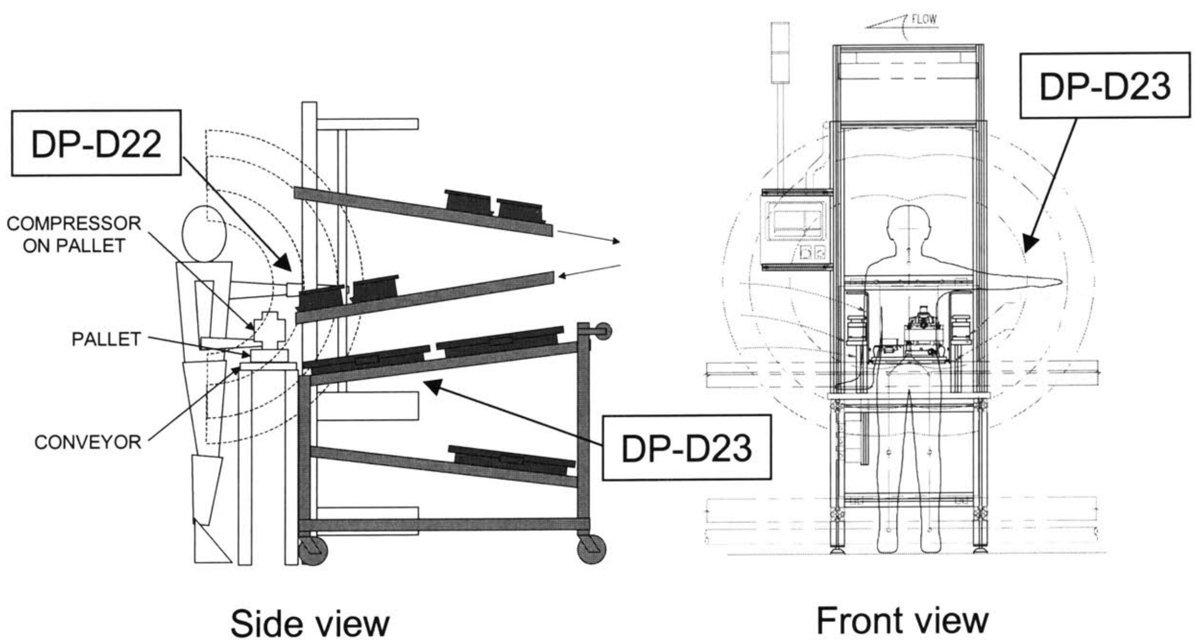


Figure 5.88 Standard tools and ergonomic interface in assembly stations (Collins, 1999) (CAD courtesy Advanced Assembly Automation).

5.5 Evaluation of Design Decisions

After having designed the compressor equipment, the overall manufacturing system design was evaluated using classifications derived from the MSDD. Since the EDA prescribes a method to use the MSDD to design equipment, further analysis is required prior to system launch and operation. Figure 5.89 shows the division of the MSDD into sets of FR/DP pairs for evaluation in three broad classifications: system configuration and management, equipment design, and design for human operators. Within each classification, the FR/DP pairs were further subdivided into categories, each category represents different aspects of the design. The three main classifications reflect high and low levels of detail in manufacturing system design. Furthermore, using these three broad classifications from the decomposition allows designers of the manufacturing system to determine whether failing to satisfy requirements in one category may also affect those in another category. Thus designers of detailed subsystems can better assess the effect of their design decisions.

Once the FR/DP pairs were subdivided into classifications and categories, the manufacturing system design elements that were appropriate for each classification were "ranked" on how well each FR was satisfied. This part of the mapping process drew on relatively subjective rankings, but it is a method that is frequently used in product design theory to evaluate a number of competing design solutions (Pugh, 1991; Eppinger, 1995). In such methods, designs are compared against functional requirements generated through voice-of-the-customer practices or other design constraints. The performance of each design solution within the ranking system is used to make decisions on how to move forward in the product development process (Eppinger, 1995).

A five-point discrete scale shown in Figure 5.90 was used to assess how well a DP was implemented to satisfy the corresponding functional requirement. Any ranking less than a '+2' represents a design that can be improved either through improvement activities or in future system design iterations.

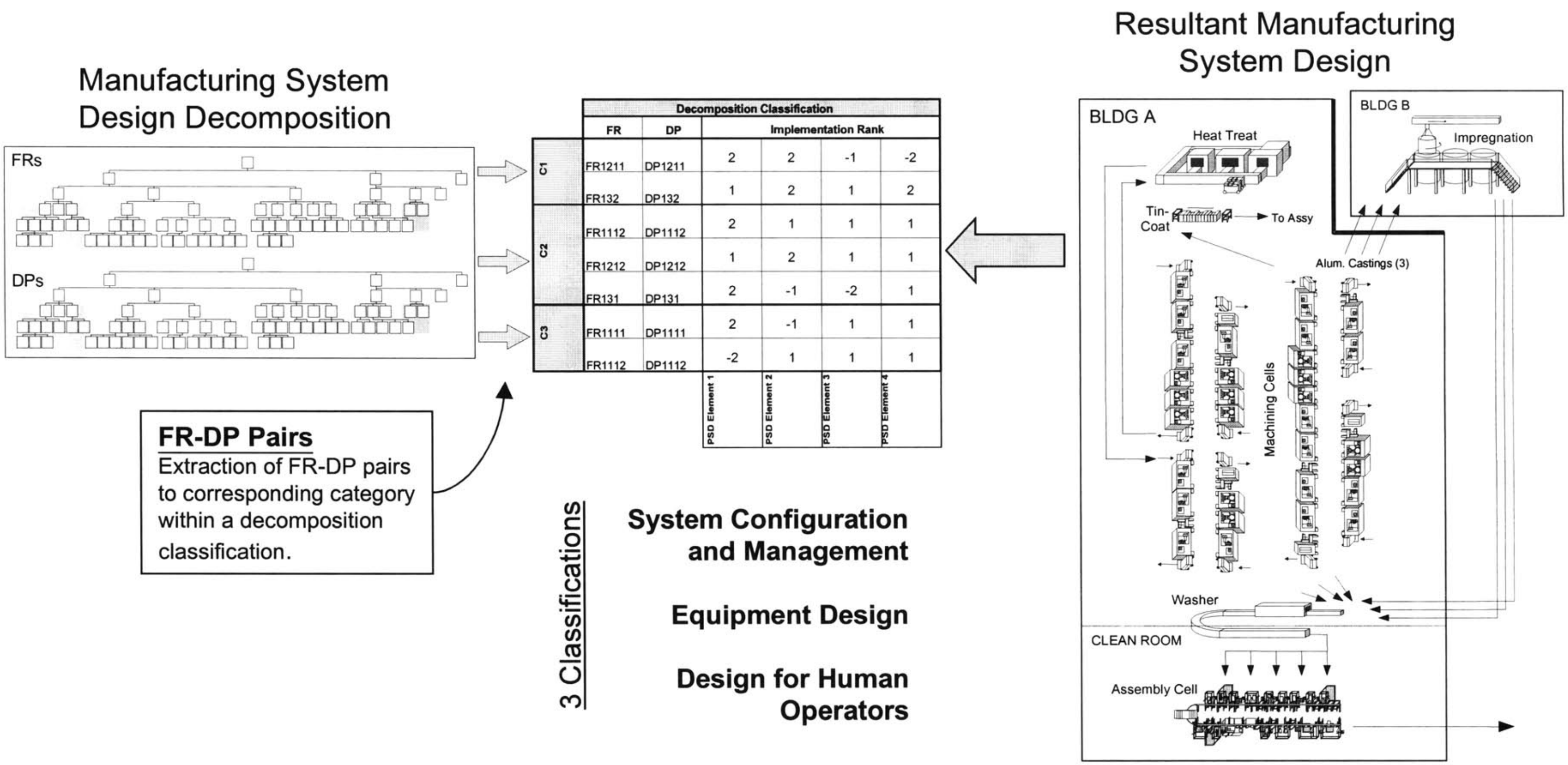


Figure 5.89 Overview of the use of three classifications derived from the MSDD to evaluate the system and equipment design.

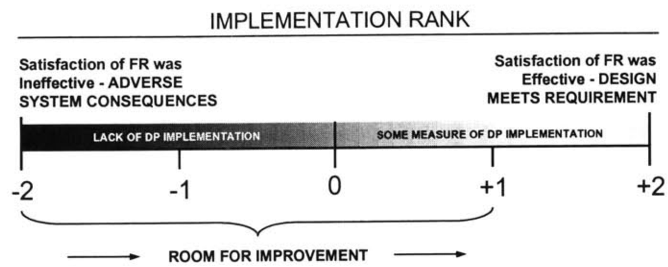


Figure 5.90 Ranking system used in evaluating compressor manufacturing system (Collins, 1999).

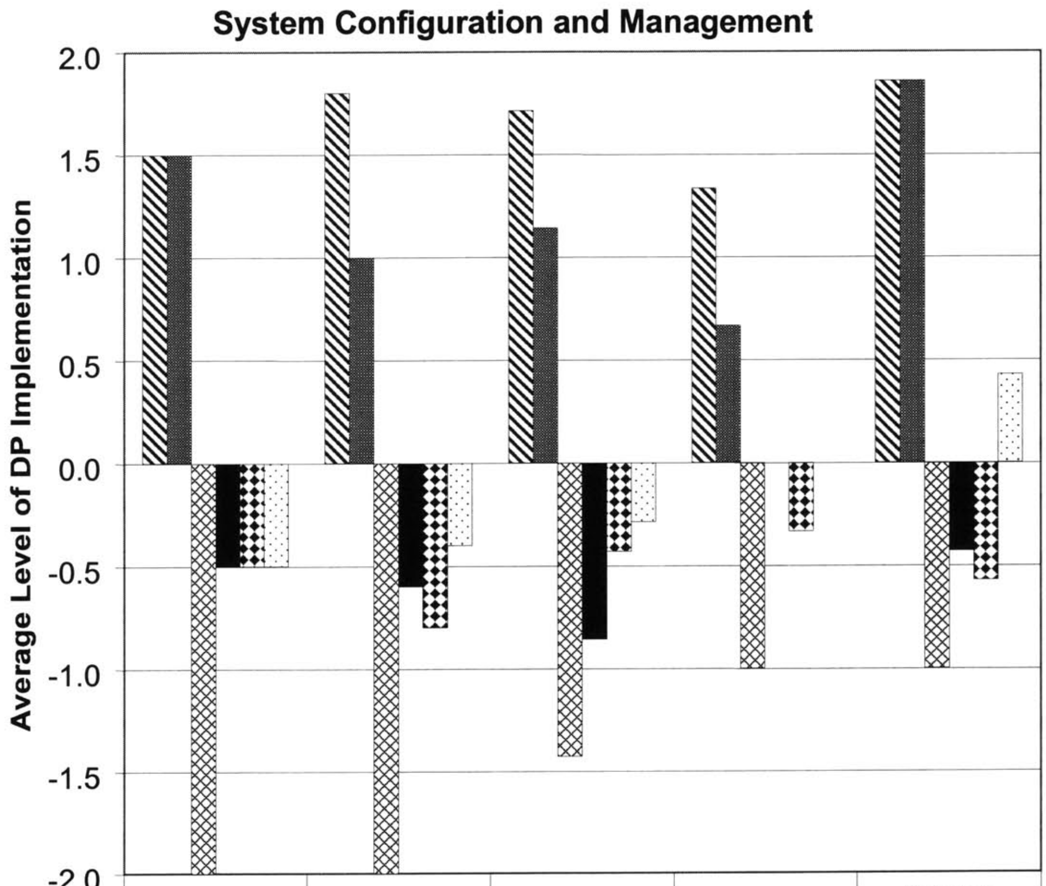
5.5.1 System Configuration and Management Results

The configuration and management of the system was analyzed by examining how well each of the major subsystem designs (i.e. Assembly, Machining Impregnation, Washer, Heat Treat, and Tin Coat) scored in five categories of FR/DP pairs: information flow, layout, material flow, rate, and resource management against the different subsystems in the actual system design.

The information flow category reflects how well individual subsystems transfer manufacturing data from one to another (i.e. signals to produce for pull manufacturing) and whether problems may be resolved quickly across the entire system by visual control methods within each subsystem. Within the layout category, FR/DP pairs are grouped according to the ability of subsystems to be configured to meet overall system requirements such as minimal transport distances and volume flexibility. Subsystem layout must be able to change to meet such requirements. Material flow, though closely related to layout, is different because of the focus on part paths through subsystems whereas layout measures the ability of the entire subsystem to be reconfigured.

Customers along with their demand cycle times must be considered at a subsystem design level for the entire system to be balanced. The rate category therefore measures whether a subsystem's manufacturing rate is balanced to the takt time. The resource management category also reflects whether subsystems are designed to achieve effective utilization of their resources, namely people and equipment. For example, can a subsystem be reconfigured to ensure effective utilization of its operators by altering machine arrangements to improve worker motion.

The results of the system configuration and management design ranking in Figure 5.91 showed significant differences between continuous and batch processes. In all five system categories, the machining and assembly cells received positive scores whereas the batch processes scores were negative (with the slight exception of the tin coating process in one category). The impregnation process received the poorest ranking of –2.0 because of its location in an adjacent building and the lack of flexibility in relocating it to reduce material transport distances. The other batch processes scored poorly (-0.5) because of the tendency to isolate workers from other processes where they can be cross utilized (a layout disadvantage of batch processes).



	Information Flow	Layout	Material Flow	Rate	Resource Management
Assembly Cell	1.5	1.8	1.7	1.3	1.9
Machining Cell	1.5	1.0	1.1	0.7	1.9
Impregnation	-2.0	-2.0	-1.4	-1.0	-1.0
Washer	-0.5	-0.6	-0.9	0.0	-0.4
Heat Treat	-0.5	-0.8	-0.4	-0.3	-0.6
Tin Coat	-0.5	-0.4	-0.3	0.0	0.4

Figure 5.91 Design Ranking: System Configuration and Management.

By comparison, the machining and assembly cells had a higher score of (1.0 and 1.8 respectively) in the layout and material flow categories because cells may be reconfigured to improve resource management. For example, work loops may be more easily redesigned because the flexibility exists to reconfigure a cell to improve the effectiveness of operators work content. Note that the assembly cell scored higher than the machining cells mostly due to smaller, lighter duty stations which are inherently easier to move. Machining and assembly cells also have a high level of DP implementation in the information flow category because if a production problem occurs the entire line is shut down immediately. Thus, attention may be drawn to the problem leading to more rapid and effective problem resolution. For the rate category, the assembly cell scored highest (1.3) compared to the batch processes (-1.0 and -0.3). The assembly cell (and the machining cells to a lesser extent with a score of 0.7) can be more easily redesigned for alternate production rates than can fixed cycle time batch processes.

5.5.2 Equipment Design Results

The individual machine and station designs (e.g. Arbor Press Stations, Turning Machines, Batch Washer, etc.) were scored against appropriate FR/DPs that addressed the design of equipment in the manufacturing system. These pairs were broken down into three main categories that correspond to views discussed in Section 5.4.4: equipment structure, process, and workholding/tooling. Equipment structure is the basis for standardized equipment and determines the ease by which improvements and modifications may be made by plant personnel. Equipment structure includes overall size of structure, location of components on the structure, and connection with other equipment or subsystems. Equipment structure design decisions are especially important because of their broad impact on system requirements such as layout, material flow, and resource management as well as detailed subsystem requirements.

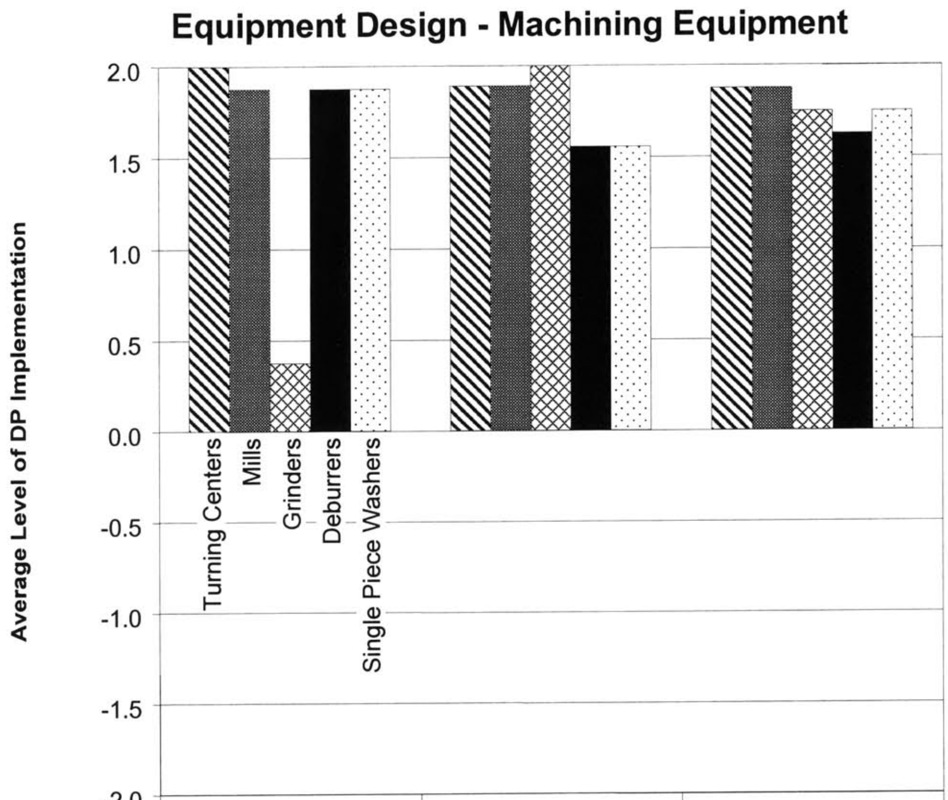
The process category has a different interpretation depending on the type of equipment being considered. For assembly equipment, process refers to the entire assembly sequence as well as work steps at each station. Similarly with machining equipment, process is the sequence of part orientations to complete a part along with the material removal steps for specific machines. For batch sub-systems, the definition of process is equivalent to that of assembly and machining, However, there is less flexibility in designing a batch process because with fewer processing steps there is less opportunity to select alternative sequences or to modify equipment work content.

Workholding/tooling FRs/DPs refer to any specific device which directly changes the part or supports/locates/moves the part while it is being processed. In machining this clearly means cutting tools and workholding devices (i.e. chucks). In assembly, tools refer to devices such as bolt runners, and fixturing includes pallets and station assembly fixtures. For the batch subsystems a more general interpretation was used for workholding/tooling. For example, with the impregnation batch process, though there is no tooling, workholding may be thought of as the wire baskets which hold the parts during impregnation and that also serve as material handling containers.

5.5.2.1 Machining

In the equipment structure category (Figure 5.92), machining has a high level of DP implementation. DPs such as chip removal and control access from the rear were incorporated into the structural design of the milling and turning machines which received scores of 1.9 and 2.0 respectively. Furthermore, these machines can be easily moved since the structure does not require a special foundation. The process category yielded equally favorable rankings for all machines because of single-piece-flow throughout the cells. Washers and deburr machines have no inherent method to detect whether a part has been properly washed or is free of burrs – therefore inspection has to be performed by the operator. Washers and deburr machines received high scores (1.9 in both cases) since they do not require special foundations and can be easily moved. In comparison, grinding machines received the lowest score (0.4) since the machines require special foundations because of sensitivity to vibrations that can affect the ability to meet tight part tolerances.

For the workholding/tooling category, all machines once again received high rankings (with an average of 1.8) because DPs, such as error prevention of manual operator loading, were emphasized during design. In addition to error prevention of the part loading, the ergonomics of the man-machine interface was greatly considered. Auto unload devices were widely used on various machines to improve worker effectiveness (see Section 5.4.6.3 for examples). In some cases, simplicity of workholding designs (i.e. deburr machines) allowed for purely manual load and unload.



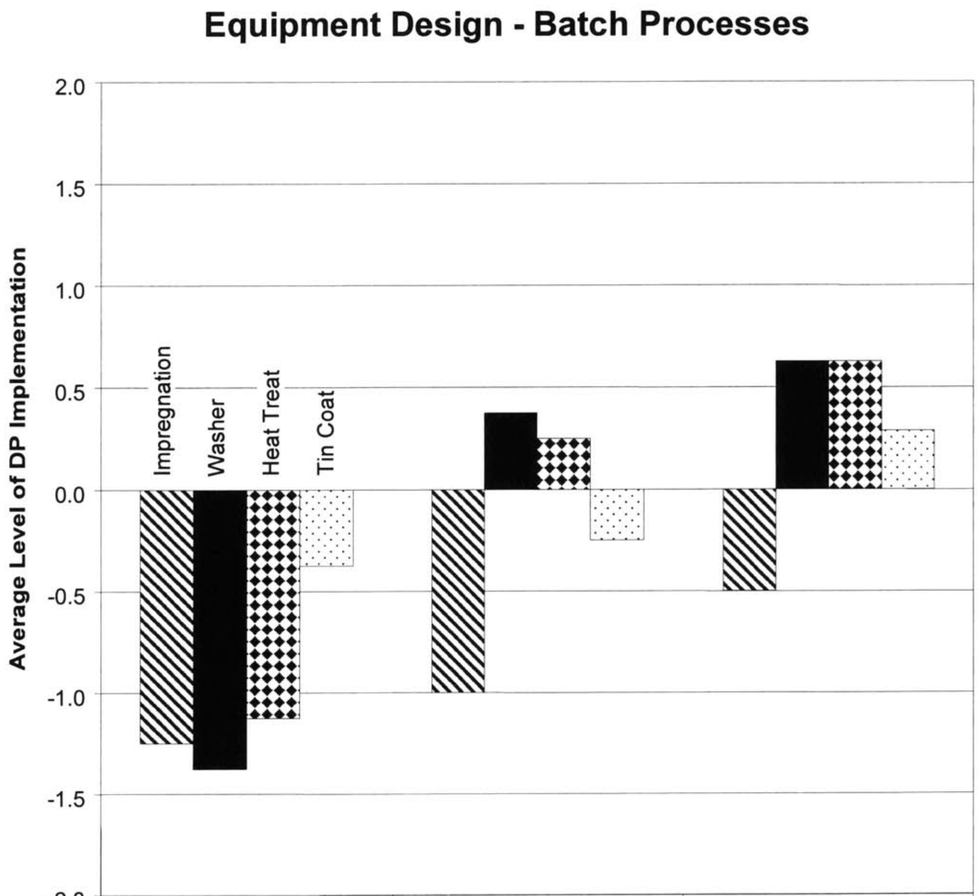
	Architecture	Process	Workholding
Turning Centers	2.0	1.9	1.9
Mills	1.9	1.9	1.9
Grinders	0.4	2.0	1.8
Deburrers	1.9	1.6	1.6
Single Piece Washers	1.9	1.6	1.8

Figure 5.92 Design Ranking: Equipment – Machining.

5.5.2.2 Batch Processes

For the equipment structure category (Figure 5.93), all batch processes had low rankings (average of -1.05) because equipment size is large and thus the walking distances associated with this equipment also tends to be large. The size also effects how well the equipment can be moved. Furthermore, both the impregnation system and the washer do not place materials at point of use. Consequently, both pieces of equipment require double handling of material trays and thus receive low scores of -1.3 and -1.4. The tin coat process performs relatively well compared to the other batch processes due to the fact that it is a small piece of equipment, simple in design and easily relocated.

In the process category, all batch processes were penalized because they do not produce according to single-piece flow. Therefore, the ability to instantly detect defects is greatly diminished. Impregnation (-1.0) cannot run autonomously (except when cycling) and defects can only be caught in assembly. This detection is very late in the material flow stream and results in the potential for a large amount of defects. The tin coat process (0.3) with further design modifications can have auto unload capability, however, the current design requires a dedicated operator to ensure parts are not over-etched.



	Architecture	Process	Workholding
Impregnation	-1.3	-1.0	-0.5
Washer	-1.4	0.4	0.6
Heat Treat	-1.1	0.3	0.6
Tin Coat	-0.4	-0.3	0.3

Figure 5.93 Design Ranking: Equipment - Batch Subsystems.

In the workholding/tooling category, impregnation ranks low (-0.5) because of the wire frame baskets that hold the parts during impregnation. These special baskets introduce double handling and furthermore, there is no guarantee that parts are loaded in the correct orientation for proper impregnation. The same tray loading mistakes can occur in heat treatment and with the flow washer, thus these processes are penalized (0.6 in both cases) because they do not have successive checks to prevent such mistakes from occurring.

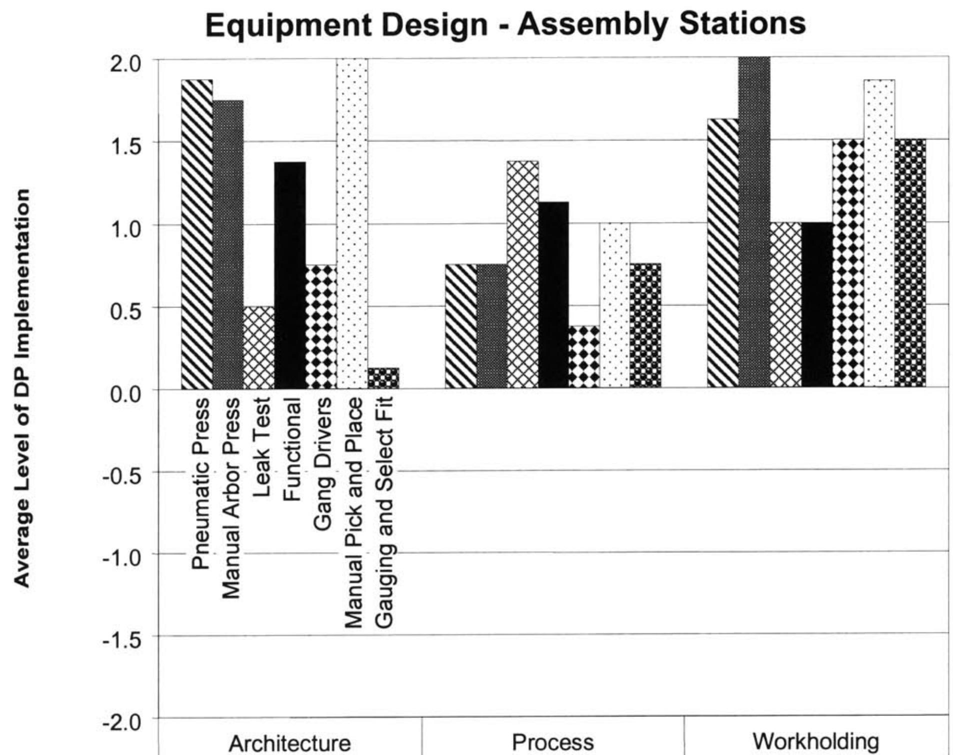
5.5.2.3 Assembly

In Figure 5.94, the equipment structure of the pneumatic/manual presses reflects a high level of DP implementation because of their inherent simplicity and flexibility in design. Manual pick and place stations were also well designed because material could be fed from the rear of the station and most importantly location of tools and supply bins could be easily modified by the operators (Figure 5.88). Guaging/select fit stations scored poorly (0.1) mainly because of design complexity and the repositioning difficulty (large size of select fit receptacles).

In the process category, gang drivers received a score of 0.4 because there is no means to separate the man from the machine. Separation was prevented by a plant design constraint requiring palm buttons with a dedicated operator throughout the machine cycle. The leak test station[27] was well integrated into the cell and cycling was automated yet it still allowed man-machine separation. Process fittings in the leak test station were also designed to accommodate a number of port configurations.

For the workholding category, much design effort was placed on implementing preventative and successive checks at each station. Manual stations such as arbor presses were well designed against operator errors (score of 2.0). Workholding devices at these stations were designed to ensure correct location and orientation of the sub-assembly. Also, successive checks were employed to ensure that defects were not passed onto subsequent stations. The leak test station was an exception as it scored relatively lower (1.0) in this category because of the difficulty in disconnecting process fittings from the compressor on the pallet. Process-fittings for connection to test chambers that have to be made between the compressor and the station.

[27] The leak test station design was outsourced by assembly cell supplier.



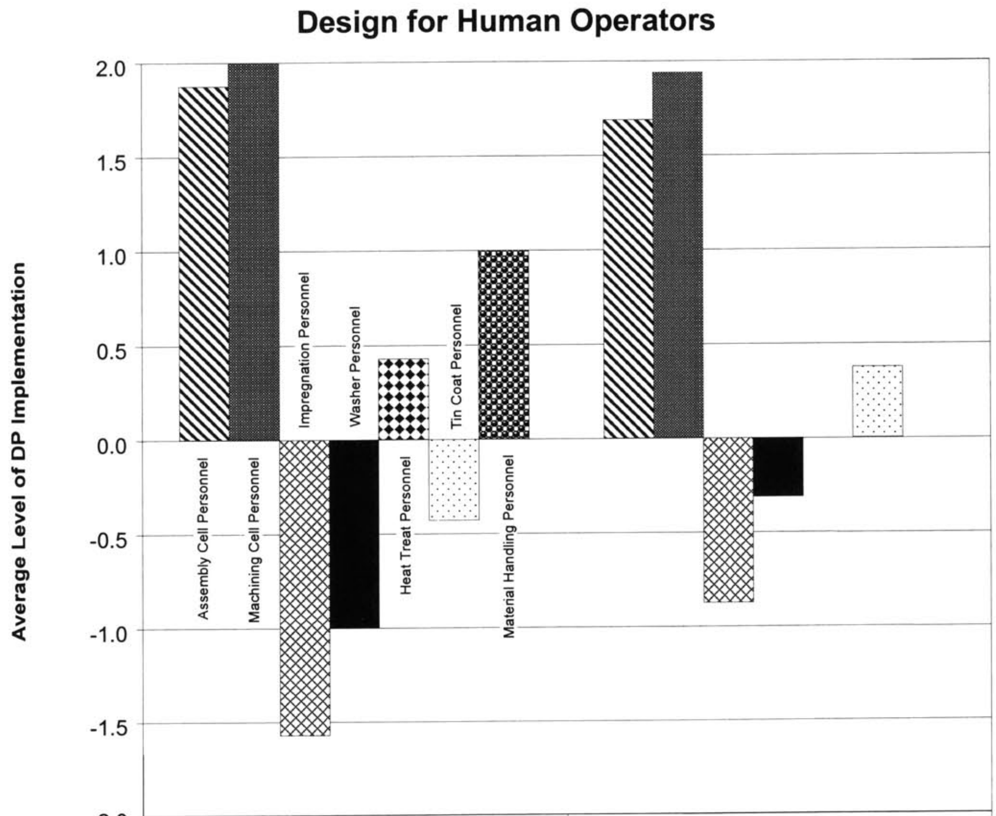
	Architecture	Process	Workholding
Pneumatic Press	1.9	0.8	1.6
Manual Arbor Press	1.8	0.8	2.0
Leak Test	0.5	1.4	1.0
Functional	1.4	1.1	1.0
Gang Drivers	0.8	0.4	1.5
Manual Pick and Place	2.0	1.0	1.9
Gauging and Select Fit	0.1	0.8	1.5

Figure 5.94 Design Ranking: Equipment – Assembly.

5.5.3 Design for Human Operators Results

The third classification of FR/DP pairs was derived by using the operator interface view (Section 5.4.4.5). This view contains FRs/DPs that affect the design of the work content of the human operator and the work environment. The environment of the human operator comprises the area where production work is carried out. For example, in the assembly and machining cells this area corresponds to the walking space inside the cells. Designing work content involves specifying work steps to be performed at a given machine or station and also includes distributing overall work amongst a team of operators. To rank the designs, the work content of the personnel that operates each of the manufacturing subsystems was considered. Therefore, included in the ranking are material handling personnel along with personnel for assembly, machining, heat treat, impregnation, tin coat, and washer operation.

The machining and assembly cells in Figure 5.95 ranked well (2.0 and 1.9 respectively) in the work environment category due mainly to workspace efficiencies associated with cellular layouts. Some of these efficiencies include reduced walking distances between machines, ergonomic and uniform human-machine interfaces, and reduced disruptions to the production operators from routine maintenance and material support activities. The batch processes suffer in the work environment category (-1.6, -1.0, and –0.4) due to their large size and the resulting



	Environment	Work Content
Assembly Cell Personnel	1.9	1.7
Machining Cell Personnel	2.0	1.9
Impregnation Personnel	-1.6	-0.9
Washer Personnel	-1.0	-0.3
Heat Treat Personnel	0.4	0.0
Tin Coat Personnel	-0.4	0.4
Material Handling Personnel	1.0	0.0

Figure 5.95 Design Ranking: Design for Human Operators.

physical isolation that workers have when operating these processes. Material handling performed reasonably well in this design category (1.0) since support personnel have good access to remove and replenish stock. Material handlers have increased transportation from double-handling of parts. Also, there is added travel distance associated with large batch processes, particularly with the remotely located impregnation system.

The work content category showed better relative performance by the machining and assembly cells in comparison to the batch processes. The work inside the cells is standardized and defined to takt time. The work of the operator is aided by standardized work procedures as well as error prevention devices. Further, the ability to plan the number of multi-skilled operators in a cell at varying standard operating patterns provides flexibility in terms of volume and mix. Work content definition is poor in batch processes (-0.9 for impregnation) since the equipment does not operate at takt time. The personnel who operate the batch processes are physically isolated and are forced to perform more monotonous activity. This isolation inhibits taking full advantage of a human's ability to perform a variety of tasks, and in turn, limits the system's overall flexibility.

5.6 Chapter Summary

This chapter described the use of the MSDD as a design aid for a new automotive compressor manufacturing system. Since existing knowledge of manufacturing systems and equipment was from high production volume environments neither internal manufacturing engineers nor suppliers could rely on prior experience to design low volume equipment. A result of this project was the application of the EDA with the use of equipment design guidelines to compensate for the limited low volume production knowledge.

The first three steps of the Equipment Design Approach (EDA) were developed and integrated with the company's existing equipment procurement process. Also, the design of the actual manufacturing system was given along with examples of the specific subsystems and equipment that resulted from the views of the second step of the EDA. These examples from the views illustrated how machine and process designs were selected during the design phase of machining and assembly equipment.

Also, the equipment in this chapter was evaluated based on the use of views derived from the MSDD. The evaluation consists of categorizing MSDD design parameters and elements of a design against the parameters. The MSDD was divided into sets of FR/DP pairs in three broad classifications: system configuration and management, equipment design, and design for human operators. Each classification was further subdivided into categories representing different aspects of the manufacturing system design. Also, these three broad classifications from the decomposition show designers whether failing to satisfy requirements in one category may also affect those in another category. A matrix-based ranking method was employed that evaluated the level of MSDD design parameter implementation in the actual system design. Finally, this chapter showed the EDA in a case where the fourth step of the EDA came from the equipment supplier's own design approach, the next chapter shows tool design linked directly to the MSDD FR.

Chapter 6 Equipment Design for Setup Reduction

6.1 Introduction

The conventional manufacturing system approach to dealing with the setup difficulties in equipment is to use inventory models to determine appropriate lot sizes that will minimize cost. In contrast, equipment designers seek to modify the attributes of the machine (whether through hardware or software) that cause excessively long setup times. An improved solution to the setup reduction problem can be obtained if the respective models and methods can be integrated. The use of the EDA to provide the integrating steps between these two types of approaches was presented in Chapter 4.

This chapter describes equipment design work at United Electric Controls to meet setup reduction objectives arising from its manufacturing system requirements. This case provides an illustration of the second and fourth step of the EDA by the detailed design of a tooling system for quick changeover. First, an overview is given of United Electric's manufacturing system design and corresponding system objectives for improved changeover capability. Since United Electric is a small company, it does not have as structured and as rigorous an equipment procurement process as the company described in the previous chapter, however, it does have the capability to design and build equipment that meets the majority of its needs. This capability is discussed in the context of designing and selecting a quick-change tooling system. Finally, this chapter provides the details how equipment design was done at United Electric and the resulting improvements in setup times.

6.2 United Electric Controls

United Electric Controls (UE) is a small, family owned manufacturer of electromechanical temperature and pressure controllers located in a single facility in Watertown, Massachusetts. It was founded in 1931 (Ryckebusch, 1996) and experienced modest growth and success following the second world war from the 50's to 80's. UE's products while not very complex or sophisticated, are robust and this high durability has to led to its success in industries such as the nuclear, oil, mining, and submarine building industries where failures of any degree are intolerable.

6.2.1 Overview of United Electric's Manufacturing System Design

UE from the early 1950's occupied two buildings in which design engineering and production were carried out (in addition to all of the other company functions such as sales, marketing, accounting, etc.). Then in the early 1980's UE went through a downturn in which demand declined for many of its products and it was forced to reduce its labor force from a high of around 500 employees to approximately 180 where it stands today. Part of UE's ability to survive this downturn can be attributed to its adoption of various manufacturing improvement methods most notably the implementation of the Toyota Production System (TPS). Over a period of more than ten years UE slowly and steadily applied specific elements of TPS that led to the redesign of its manufacturing system and its return to a competitive position in the controller and sensor market.

Perhaps the most influential of these TPS elements has been the pursuit of "single-piece-flow"[28] to reduce manufacturing lead time from order point to shipment. Other manufacturing improvements at UE that are associated with TPS (kaizen, SMED, poka-yoke) have been instrumental if not vital to support the single-piece-flow mode of production. UE has implemented single-piece-flow wherever possible by identifying batch production processes and physically relocating them next to each other to avoid excess transportation and then reducing batch sizes. One area where single-piece-flow was first introduced is in final assembly.

Assembly cells were designed to integrate many operations that were previously done by batch production. Inside the assembly cells (Figure 6.96), controllers and sensors are made one at a time with mainly manual operations and little automation (i.e. torque drivers). These manual operations are performed by people trained in the many possible combinations of controller and sensor configurations that may be custom ordered. An assembly whether for a temperature or pressure controller consists of mating a housing containing switch components to a sensor subassembly. Once these two subassemblies are fastened together, the product is then calibrated and tested before finally being packaged. In addition to assembly cells, UE has a machining department that supplies many of the components that go into the various temperature and pressure controls. The machining department provides components to not just a single final assembly cell, but also to various sub-assembly areas.

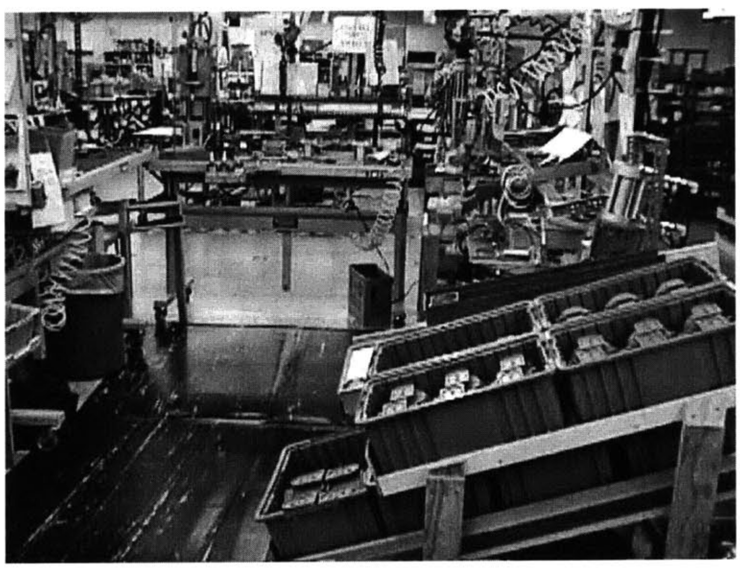


Figure 6.96 One of United Electric's final assembly cells (courtesy of United Electric).

6.2.2 Motivation for Improving Machining and Assembly Link

In UE's manufacturing system design it is quite apparent that two different production approaches are operating simultaneously. Final assembly is arranged according to cells dedicated to product families. In contrast, machining is arranged in a departmental layout and supplies batches of parts to final assembly. The result of these dual approaches is an imbalance in production flow between machining and assembly. In this sense, the machining department produces to the aggregate demand of assembly because many parts are used in more than one type of control. This commonality of parts while good from a product design point of view,

[28] The production of parts one at a time with no batch processes.

prevents the machining department from being balanced to the actual product demand from final assembly.

The imbalance between machining and assembly is illustrated in Figure 6.97. The figure depicts a pressure control consisting of upper and lower plates and fasteners being made on four different machines with different lot sizes. This problem is further complicated by the fact that these four sub-components are not produced concurrently, instead they are made whenever the corresponding machine becomes available. As a result, production is never balanced and can never be synchronized to the actual demand of assembly. This indicates that despite attempts to arrange machining in cells according to product families, the machining department still must operate as a job shop because of high product variety and low volumes.

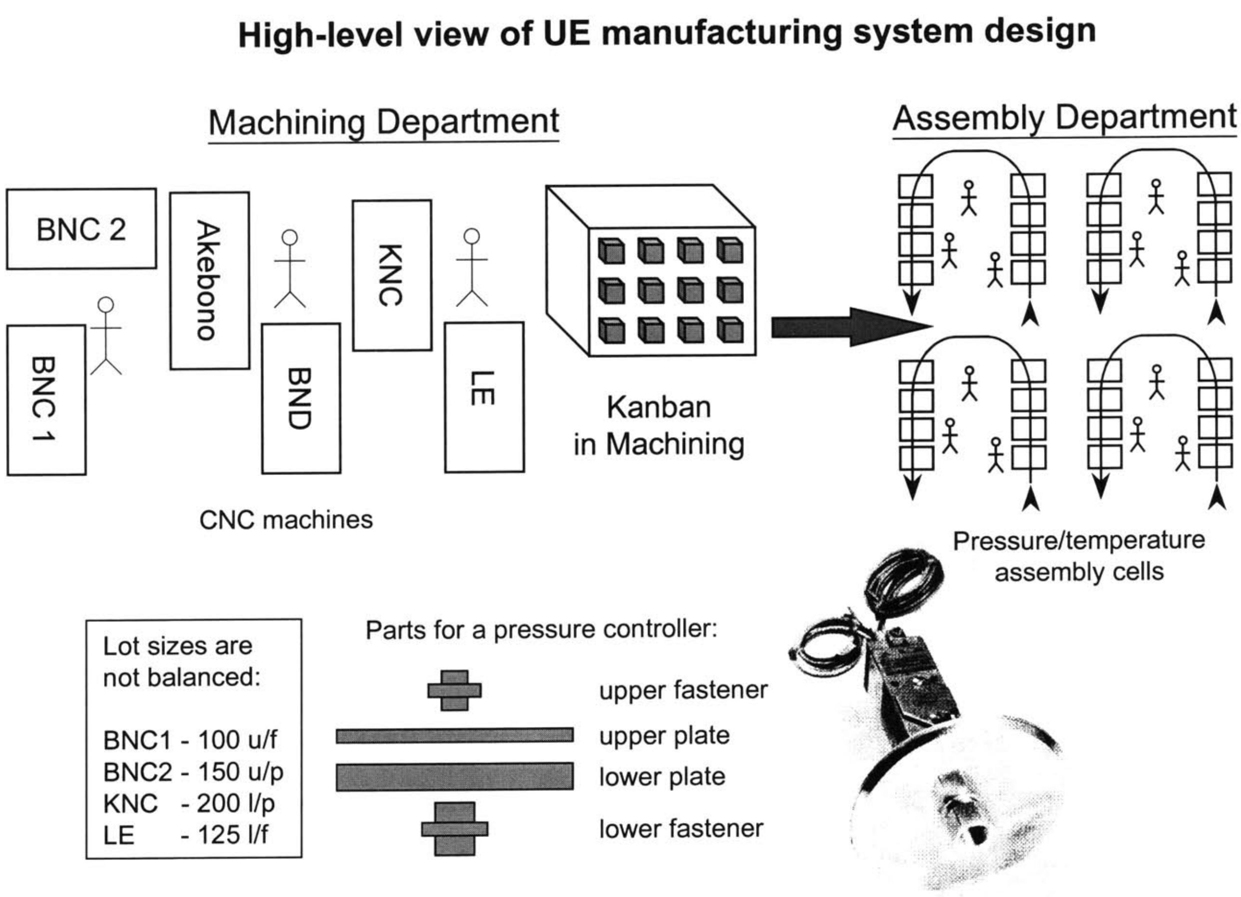


Figure 6.97 UE Manufacturing System Design showing production imbalance for an example pressure controller product and its four machined components.

Thus, given UE's manufacturing system design, the main system objective in this project was to improve the balance between assembly and machining. The MSDD provides the context and FRs in Figure 6.98 for this objective namely FR-T1 *Reduce run size delay*. Since UE must produce such a variable mix of products in final assembly, FR-T1 describes this high-level mix requirement. However, DP-T1 is implemented in final assembly, but it is not implemented in machining since machining cannot supply the desired mix in each demand interval. Therefore, in machining two requirements must be necessarily satisfied: FR-T11, and FR-T12. For FR-T11, a visual kanban system that dynamically updates lot sizes was developed for DP-T11 (Arinez et al., 1997). For FR-T12, the equipment design setup capabilities in the machining department were examined for quick changeover. The next sections describe the implementation of DP-T12.

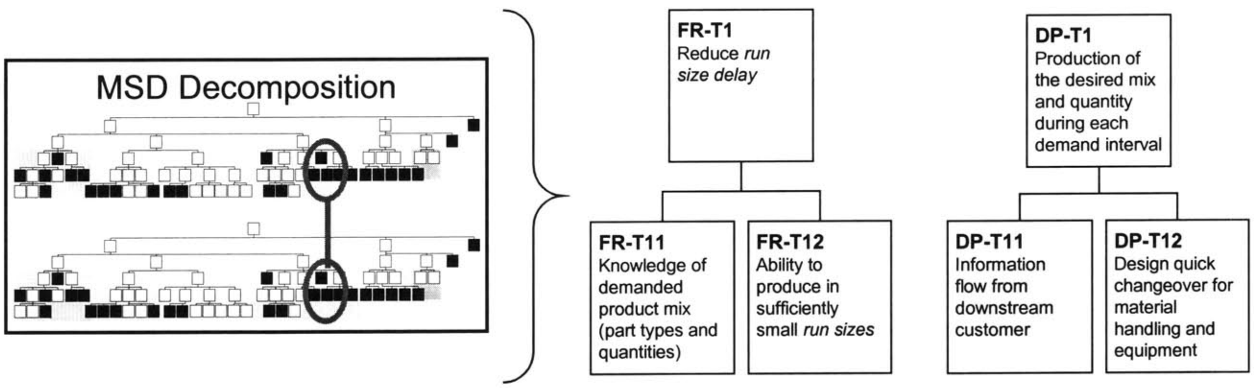


Figure 6.98 MSDD requirements FR/DP-T12 specifying quick changeover capability in equipment.

6.3 In-house Equipment Design Capabilities

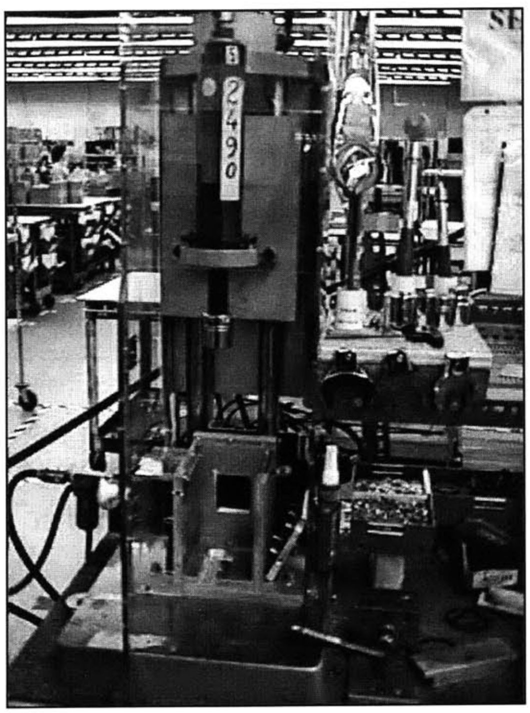
Before discussing equipment design in machining to meet FR-T12, UE's design capabilities are first reviewed. UE's equipment design ability provides the context for the selection and implementation of the tooling system described in the next section.

UE's initial attempts at reducing lead time through final assembly were modest efforts of simply placing all of the assembly operations as close together as possible on work benches[29]. These work benches and the specialized manually operated tools on each bench are the reflection of UE's approach to equipment design. Though there are many commercial components that are the building blocks of the various handheld tools and fixtures, the majority of tools are modified to meet the needs of the operator performing a given manual task or the requirements of the

[29] Previously, various assembly steps were done in isolated parts of the building and then transported to the location of the following step.

assembly process steps. Since these tools are not highly complex, they are easily modified yet sufficient for the manual assembly requirements.

The majority of UE's assembly equipment is designed and modified in-house by its model shop (Figure 6.99). This model shop in addition to designing equipment also builds engineering prototypes for product engineering. Thus, the skilled tradespeople in the shop are able to communicate suggestions to product design engineers to improve manufacturability (Plant, 1996). Also, with its model shop capability UE does not frequently purchase externally designed fixtures so as to avoid paying for later modifications resulting from efforts to improve manual operations. UE also does this because it recognizes that a small company has relatively less leverage in obtaining such design modifications in a timely manner compared to larger companies.



In-house designed and built automatic torque driver station

Light duty assembly fixture for internal assembly housing operations

Figure 6.99 Examples of in-house equipment design at United Electric (courtesy United Electric).

Another element of UE's equipment design capability is its strategic focus on simplicity in its equipment designs. The simplicity here is revealed in two characteristic properties: size and construction materials. The focus on size is evident in the location where fixtures are placed – on a small work bench (table dimensions of 48" x 72"). Since there may be as many as two or three operators at a given bench, work space is at a premium and the designs of tool locations and fixtures reflect this requirement. Utilities (air, electricity) are provided from one side of the bench to occupy less space. This space requirement is an example where in-house equipment design capability is effective since otherwise UE would have to accept an equipment vendor's standard fixture/equipment dimensions. Such a standard does not give UE as much flexibility for designing a fixture to meet the work space volume.

The second characteristic property is the selection of simple construction materials used by the model shop to build fixtures and stations. UE makes liberal use of cardboard and wood as equipment construction materials. The use of such basic materials makes equipment modifications easier and quicker since it is easier to work with wood than metal. Power hand tools can quickly make an equipment modification right on the production floor. Metallic structural elements require machining offline and lead to production downtime.

In summary, UE's equipment design capability allows it to make design modifications to tools and stations. This capability provides the skills for the retooling of equipment in the machining department described in the next sections.

6.4 Setup in Context of Equipment Design

To meet the manufacturing system requirement FR-T12 means that equipment should be designed with quick-changeover capability for short setup times, DP-T12. The task of preparing a machine for changeover involves adjustment of machine parameters to desired settings such that a part is produced within the design tolerance. Some of these parameters may be physical settings, others may be software-based. However, in all cases the objective is to perform this adjustment task in the shortest possible time since this represents unproductive time for the machine and operator.

Systematic setup reduction techniques first introduced by Shingo (1989) distinguish between internal and external setup actions. Internal setup procedures are those that require the machine to be stopped while being changed over. External setup procedures can be performed while the machine is running and are thus preferable since no downtime is incurred. This section reviews the largest contribution to setup time in UE's machining department, namely the need for internal adjustment procedures that require equipment to be stopped.

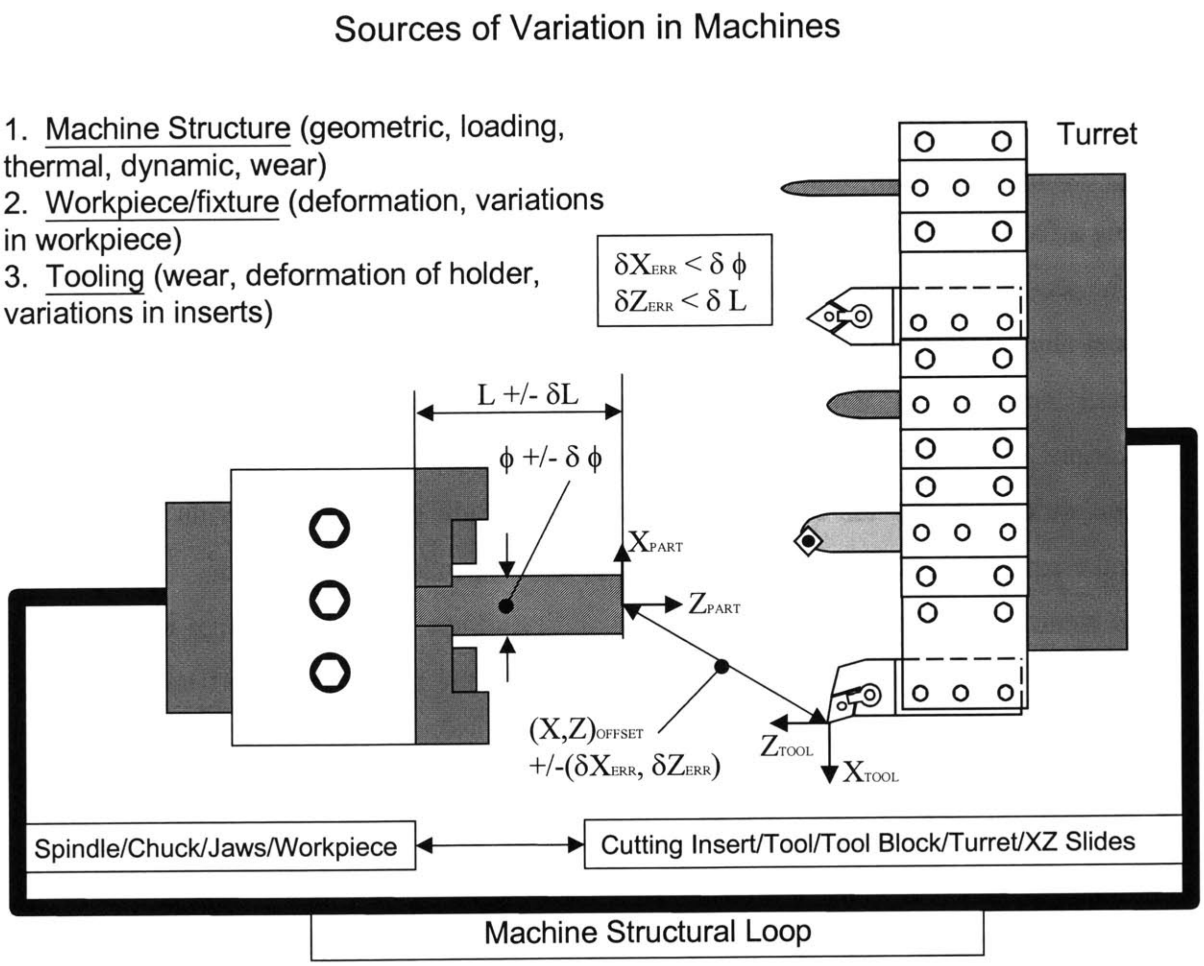


Figure 6.100 Areas of machines that contribute to variation.

Adjustment is required because of uncertainty in machine settings reflected in highly variable part dimensions. Therefore, understanding the adjustment process is critical to minimizing the setup time of a machine. Cochran (1991) has proposed an error model that describes the source of errors leading to increased adjustment. This model distinguishes between static and dynamic accuracy requirements. Static requirements are relatively easy to deal with since parts may be measured and machine offsets quickly calculated. In situations where dynamic compensation is required[30] the parameters of such an error model can be used to control the cutting process online. Uncertainty in machine settings originates from various sources common to all machining applications. These sources include thermal, position, dynamic, and static errors (shown in Figure 6.100 above). To reduce adjustment, hence setup time, these errors must be compensated for and controlled. The conventional way to compensate for errors is to touch off tools prior to every setup (Brown, 1990).

The general adjustment process required in all types of setups consists of the following steps:

1. Touch off the tool at a known dimension with a shim of a known dimension
2. Make a specific depth of cut
3. Measure the resultant machined dimension
4. Calculate the required machine geometrical offset to compensate for the tooling error

Thus, given the above sources of variation in Figure 6.100, the goal of setup time reduction is to control these sources so that (δX_{ERR}, δZ_{ERR}) that appear between the tool and part are less than the design tolerance so that the process yields the nominal dimensions.

6.5 Application of the EDA to Tool Design

All of the tooling on UE's CNC equipment in the machining department must undergo the adjustment process described in the previous section. This section first applies the second step of the EDA to examine the initial state of UE's tools to meet MSDD requirement FR-T1. Given this review, a new tooling system is then presented that meets a greater number of requirements in the MSDD tooling view. Also, the new tooling system is decomposed according to the fourth step of the EDA and analysis of coupling in both the initial and new tooling system is performed.

6.5.1 Step 2 - Use of Tooling View and MSDD Requirements

At UE all of the CNC machines are equipped with conventional shank tooling (Yeo, 1996). Shank tooling was developed from the need to fasten a cutting tool to a single tool post on an engine lathe. However, the main disadvantage of this type of tool system is that there is no fixed reference point that can be used for a tool coordinate system. Figure 6.101 illustrates a conventional shank tool which has a variable position Z-tool with respect to the part. Each time the tool holder is changed, the adjustment process must be performed because tool position changes with respect to the machine home reference position, therefore Z-tool must be again established. This variation in position in addition to being a source of adjustment is also a source

[30] i.e. gear cutting machines require gear pairs to be meshed to adjust the machine offsets

of process variation since the tool stiffness is directly related to the amount of overhang. Therefore, dynamic cutting forces exerted by the tool will not be consistent if the Z position of the tool varies with respect to the tool holder.

The tooling view in Figure 6.102 includes requirements from the quality, problem resolution, throughput time, and labor branches of the MSDD. UE's current shank tooling may be examined using requirements from these branches. For example, when performing a setup for a new part, tools must often be manually relocated to alternative positions due to the need for different tools or for clearance between the chuck, part and tools. With traditional shank tools, these additional movements involve time consuming tightening, repositioning of tools thereby prolonging the adjustment process. These movements make the serviceability of tooling (FR-P121, FR-P122) more difficult since repeated repositioning wears out the tool/holder interface.

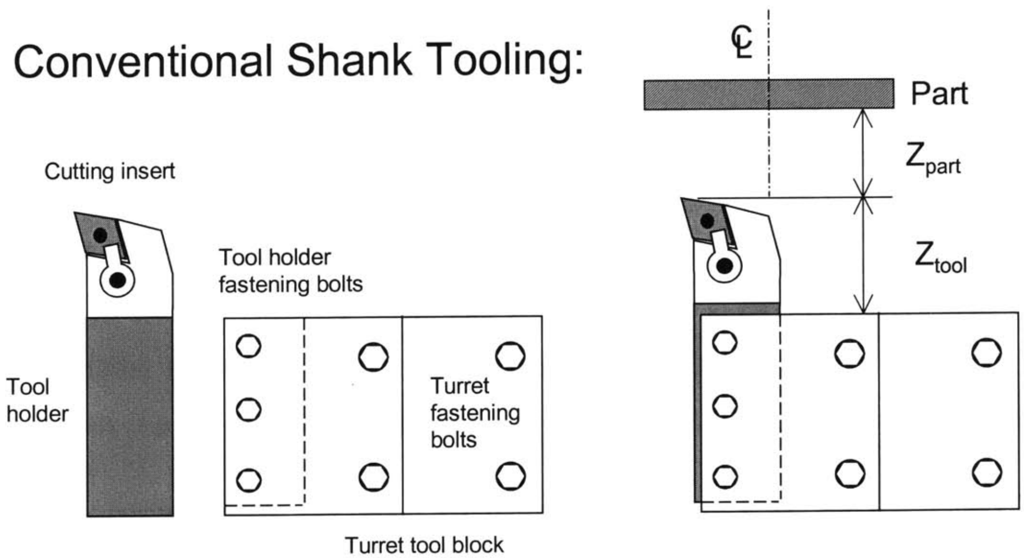


Figure 6.101 Conventional shank tooling.

Furthermore, at UE the interface between machine operators and the shank tooling is variable since the torque applied by each operator is different leading to much wear of tool fasteners. Excessive wear leads to difficulty in positioning the toolholder in the tool block and thus FR-D22 *Minimize wasted motion in operator's work preparation* is difficult to achieve.

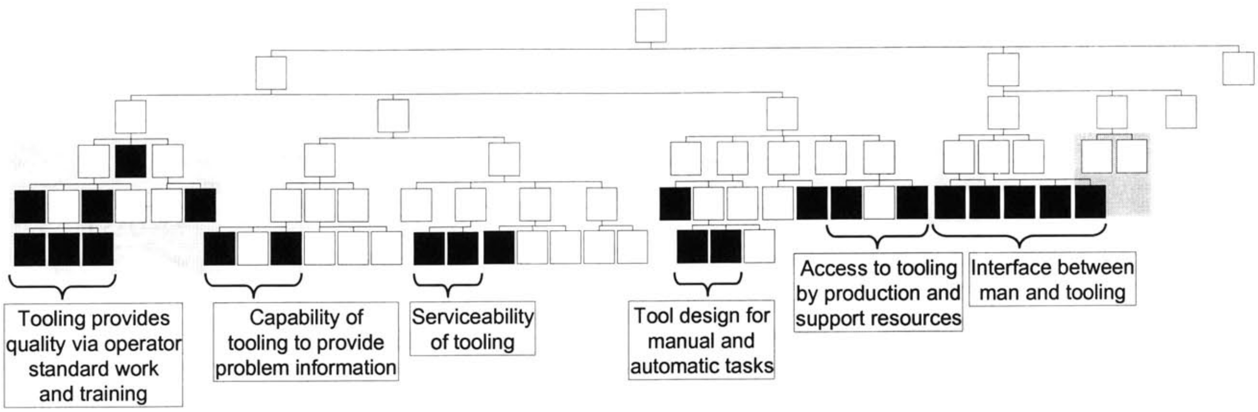


Figure 6.102 The tooling view from which the MSDD requirements are decomposed into the equipment design decomposition.

Thus, to overcome the shortcomings of UE's shank tooling to meet the requirements contained in the tooling view above, the use of an alternative tooling system was investigated. Tooling manufacturers (Lyle, 1987; Dahlqvist, 1987) have responded to the above limitations by developing standardized tools that can greatly reduce (though not completely eliminate) the amount of adjustment required to produce a "good" first part in the setup process. Malachowski (1992) and Lyle (1986) both propose quick-change tooling concepts designed to simplify the machine-tool coupling. Standardizing the coupling permits greater repeatability in locating the tool with respect to the part in the machine (Wolf, 1984; Carleros, 1985). These couplings all are designed to establish a machine reference position which can be premeasured outside of the machine to reduce downtime. Brown (1995) discusses the need to understand the sources of error in CNC turning machines to improve machine utilization by premeasuring on an external presetter.

In contrast to shank tools, quick-change tooling systems (Figure 6.103) have repeatable locating reference surfaces that permit presetting offline. The offline presetting determines the Z-tool offset which is then referenced to known machine geometry for which errors can be compensated. The locating surfaces on quick-change tools are predominantly tapered couplings with either conical or polygonal profiles. Thus, the key advantage of quick-change tools is that the face of the clamping mechanism is consistent and eliminates the need to "touch off" the tool. The geometrical location of the tool is known with respect to the clamping mechanism coordinate frame which can in turn be related to the machine home position. It is desirable to decouple these two sources of error by adjusting the CNC code only once so that the presetting will only reflect insert variations.

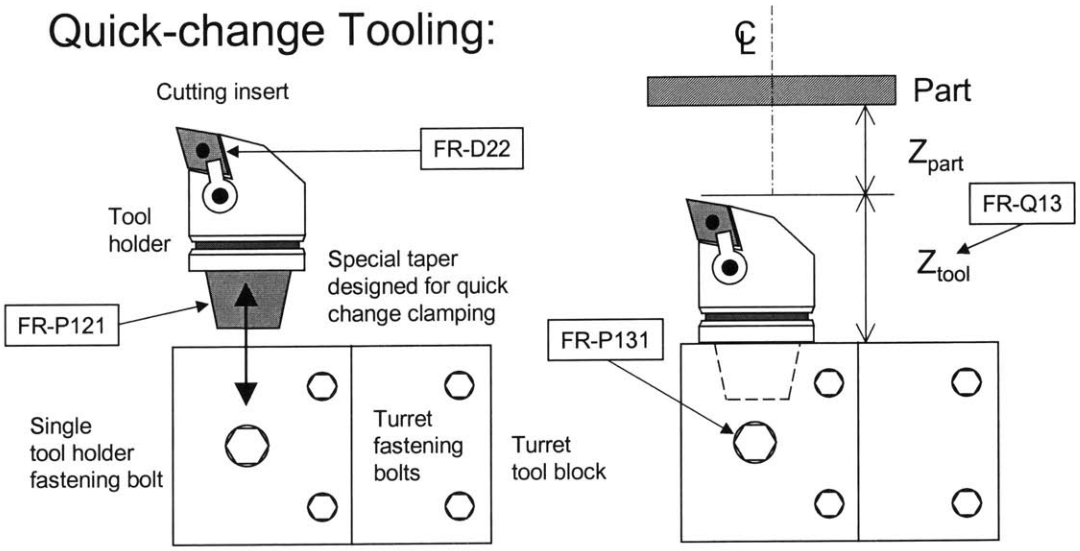


Figure 6.103 Quick-change tooling system.

Also these tools in addition to being modular have the added benefit that standardized work can be performed during setup as well as production. For example, with predictable tool configurations, tool positions remain constant from operator to operator and from setup to setup. Therefore, FR-P131 *Reduce variability of task completion time* is satisfied by the standard toolholder coupling. Other FRs from the tooling view are indicated above in Figure 6.103.

6.5.2 Step 4 - Design Decomposition for Quick-Change Tooling

The example of the fourth step of the EDA comes from the tool holding branch in the equipment decomposition from Section 4.8.2. The sub-FR that decomposes from DP-*Tool turret* specifies the maximum tool changeover time $t_i^{changeover}$ allowable for the setup so that the run size requirement from FR-T12 is satisfied. The DP corresponding to this FR (originating from the MSDD) is design[31] of the tool coupling $D_{coupling}^{tool}$. The tool-coupling design defines the tool-to-machine connect and disconnect time.

The position $\vec{R}_{xyz}^{toolholder}$ of the shank tool depends on the clamp force $\vec{F}_{xyz}^{clamps}$ applied and is a function of the operator and application position. Also, the cutting edge position can shift since over time plastic deformation of the holder and fasteners occurs. $\vec{R}_{xyz}^{toolholder}$ depends on the number of tools N_{turret} that the turret can hold because movement of tools is required to accommodate

[31] The D specifies that the DP is a geometrical design attribute of the object.

each tool configuration. Finally, $\vec{R}_{xyz}^{toolholder}$ also depends on the tool-coupling design. $\vec{F}_{xyz}^{toolholder}$ depends on the tool-coupling design since the geometry defines the stress distribution and the repeatability of the tool in the toolholder.

Contributions to setup time via adjustment were observed by the coupling present in the FRs: $\vec{R}_{xyz}^{toolholder}$, $\vec{F}_{xyz}^{toolholder}$, n_{tools}, and $t_i^{changeover}$ in Equation 6.1. The use of shank tooling results in a coupled design matrix since there are dependencies between $\vec{R}_{xyz}^{toolholder}$ and $\vec{F}_{xyz}^{toolholder}$ from $D_{coupling}^{tool}$. Quick-change tooling by comparison decouples the tool positioning from the clamping dependency. Tool position $\vec{R}_{xyz}^{toolholder}$ is independent of clamping $\vec{F}_{xyz}^{clamps}$ once the minimum clamp force is reached. Furthermore, with a standard coupling interface, inner or outer diameter tools fit in any turret position and therefore the turret magazine size N_{turret} does not influence the movements that occur with shank tooling.

To reduce the total setup time, new quick-change tooling was designed that eliminated coupling between $\vec{R}_{xyz}^{toolholder}$ and $\vec{F}_{xyz}^{toolholder}$ (tool holder position and clamping force – Equation 6.2). Therefore, with greater certainty in tool position, the need for adjustment of tools and workpiece was eliminated. The next section describes the results of implementing the latter decoupled design in UE's machining department.

$$\begin{Bmatrix} \vec{R}_{xyz}^{toolholder} \\ \vec{F}_{xyz}^{toolholder} \\ n_{tools} \\ t_i^{changeover} \\ Q_i^{coolant} \end{Bmatrix} = \begin{bmatrix} X & X & X & X & O \\ X & X & O & X & O \\ O & O & X & O & O \\ X & X & X & X & O \\ O & X & O & O & X \end{bmatrix} \begin{Bmatrix} \vec{R}_{xyz}^{locators} \\ \vec{F}_{xyz}^{clamps} \\ N_{turret} \\ D_{coupling}^{tool} \\ D_{path}^{flow} \end{Bmatrix} \quad (6.1)$$

Shank tooling design exhibiting coupling in the design matrix.

$$\begin{Bmatrix} \vec{R}_{xyz}^{toolholder} \\ \vec{F}_{xyz}^{toolholder} \\ n_{tools} \\ t_i^{changeover} \\ Q_i^{coolant} \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O \\ X & X & O & O & O \\ O & O & X & O & O \\ X & X & X & X & O \\ O & X & O & O & X \end{bmatrix} \begin{Bmatrix} \vec{R}_{xyz}^{locators} \\ \vec{F}_{xyz}^{clamps} \\ N_{turret} \\ D_{coupling}^{tool} \\ D_{path}^{flow} \end{Bmatrix} \quad (6.2)$$

Quick-change tooling design equation eliminates coupling between locating and clamping.

Table 6.4 Parameters in Tool Design Equations 6.1 and 6.2.

$\vec{R}_{xyz}^{toolholder}$	Position of the toolholder	$\vec{R}_{xyz}^{locators}$	Position of clamps for toolholder
$\vec{F}_{xyz}^{toolholder}$	Toolholder reaction force	$\vec{F}_{xyz}^{clamps}$	Clamping force on toolholder
n_{tools}	Number of tools required for part	N_{turret}	Turret design number of tools
$t_i^{changeover}$	Maximum tool changeover time	$D_{coupling}^{tool}$	Tool-coupling design
$Q_i^{coolant}$	Required coolant flow rate	D_{path}^{flow}	Coolant flow path design

6.6 Results

This section presents results from experimental data from work done in UE's machining department after conversion of two of its machines from shank tooling to quick-change tooling. Also the implementation of an offline tool presetting station is given. The tool presetter was implemented to premeasure tools that have variable dimensions such as drills and boring bars.

First, the premise of presetting tools is that a measurement system can reproduce the machine's axes. However, the extent to which this may be done depends on how well the sources of error in the presetter are accounted for. Analysis of tooling and fixturing by Hockenberger (1996) have found that repeatabilities are of the order (+/- 0.0001") which are often commercially quoted for a specific cutting holder in a specific cutting clamping unit. At UE, operator-to-operator reading errors of the optical comparator is between 0.001" to 0.003". To avoid these large variations one operator was dedicated so that the reading error was less than 0.0005". The tool presetting station is shown in Figure 6.104 with a schematic illustration above the photograph. The schematic shows the electronic transfer of a CNC header file to the machine controller.

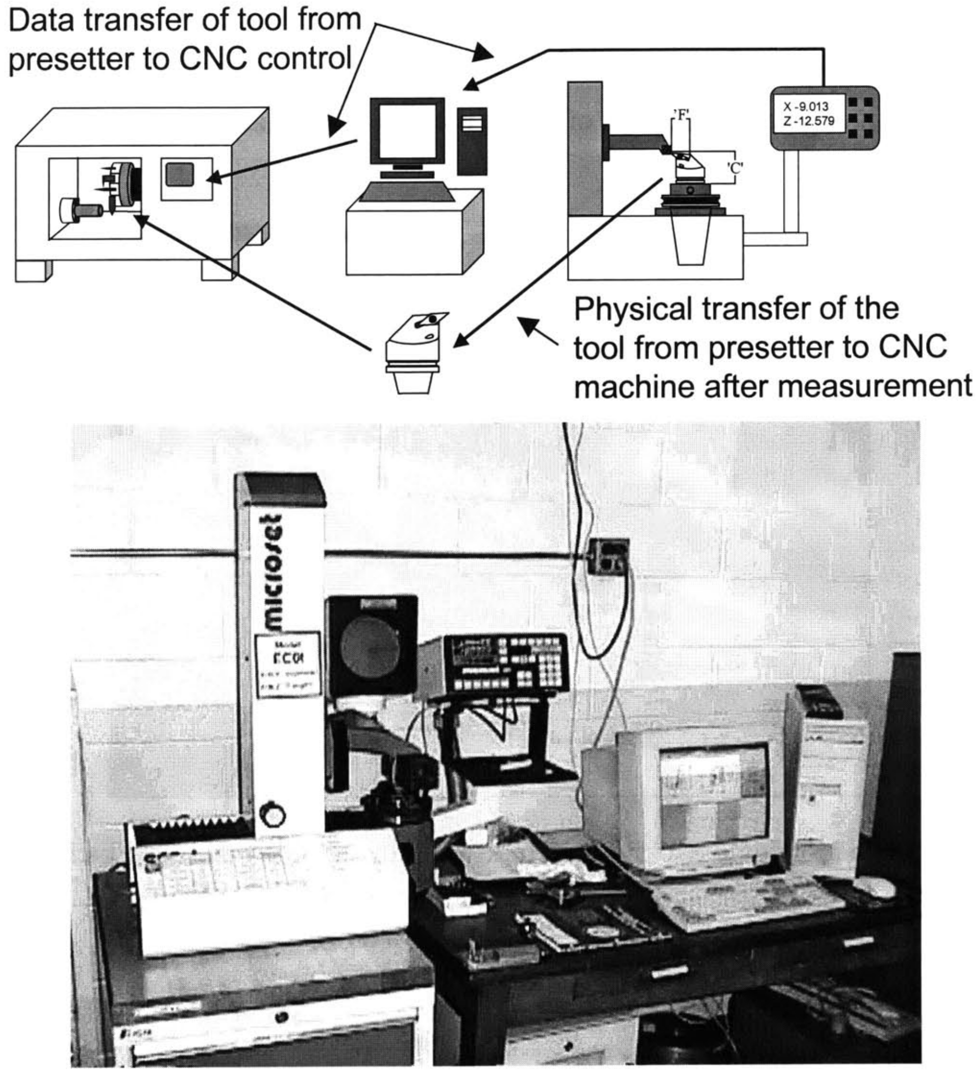


Figure 6.104 Tool presetter implemented to support quick-change tooling system (courtesy UE).

Along with the tool presetter above, a quick-change tooling system was implemented on two CNC turning machines. One machine is a single-spindle single-turret machine while the other has a twin-spindle and two-sided turret (Figure 6.105). A setup analysis of a frequently manufactured part was performed before the quick-change tools were installed and then again after the tools had been used for approximately one month. The result in the form of a Pareto chart in Figure 6.106 shows a reduction in the overall setup time from 49.4 to 15.9 minutes. In particular, quick-change tooling reduces adjustment and mounting time from 42.33 minutes to 1.17 mins. The elimination of tooling adjustment alone accounts for a reduction of 33 minutes.

The importance of this result is that once this tooling change has been made, the workholding adjustment becomes the next internal procedure that must be improved to reduce the setup time. The sources of error arising from workholding then must be evaluated to determine whether they can be eliminated or made external. Other quick-change technologies such as single-point-contact chuck jaws offer the ability to eliminate the turning of new jaws for every setup.

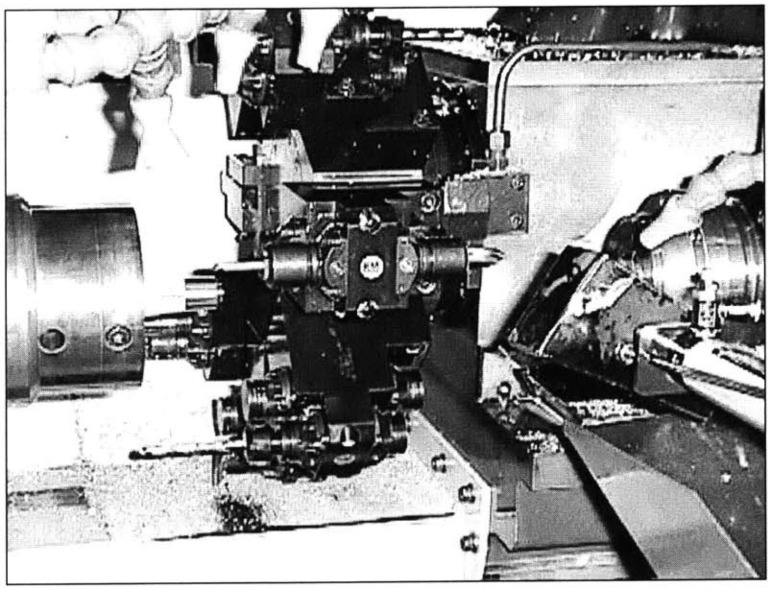


Figure 6.105 A twin-spindle two-sided turret CNC lathe retooled with quick-change tooling (courtesy of United Electic Controls).

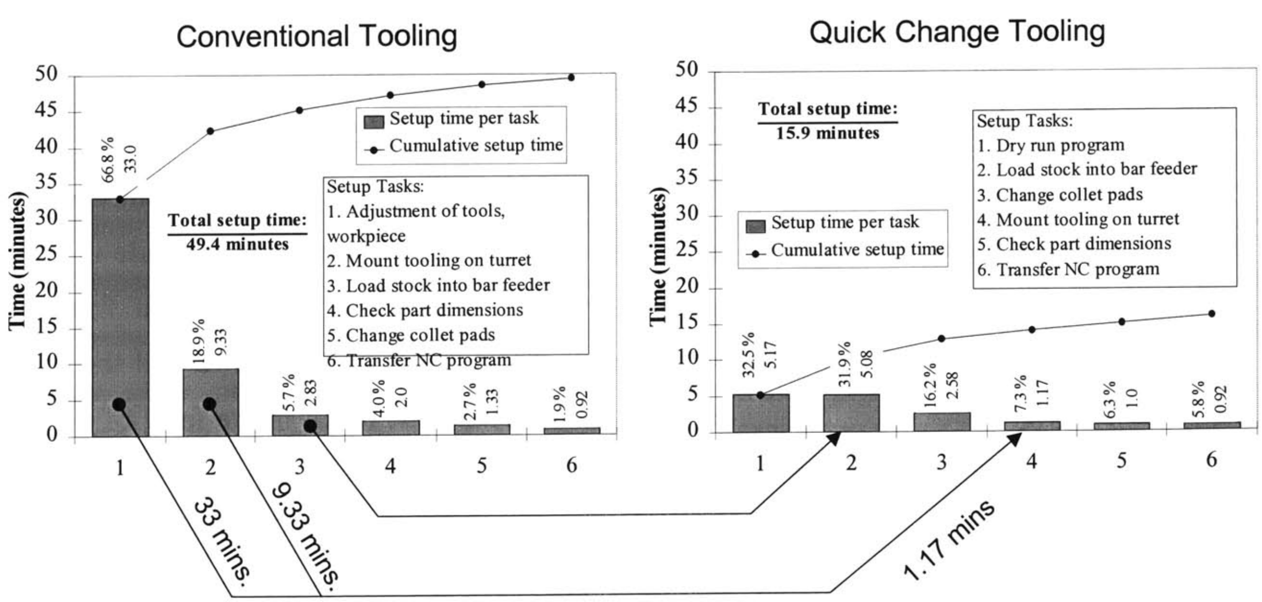


Figure 6.106 Pareto results from conversion from conventional shank tooling to a quick-change tooling system for a selected part studied before and after retooling.

Since the above results are for a single part and may not represent the entire population of parts, observations were made daily of all setups on the two machines selected for conversion. Figure 6.107 shows eight weeks of production over which 70 and 55 setups were performed on machines 1 and 2 respectively. The mean setup time for machine 1 was 1.307 and 1.497 hours for machine 2. In both cases the standard deviation was high representing approximately half of the mean setup time.

Figure 6.108 shows production after conversion to quick-change tooling. In this plot the means were reduced by 47% and 65% for the two machines (Table 6.5). The reductions in standard deviation are especially significant since all setups include all operators who run the machines. Figure 6.108 indicates that setups have become more standardized even when accounting for multiple operators running the machines studied and therefore the system has become more predicatable, FR-P131.

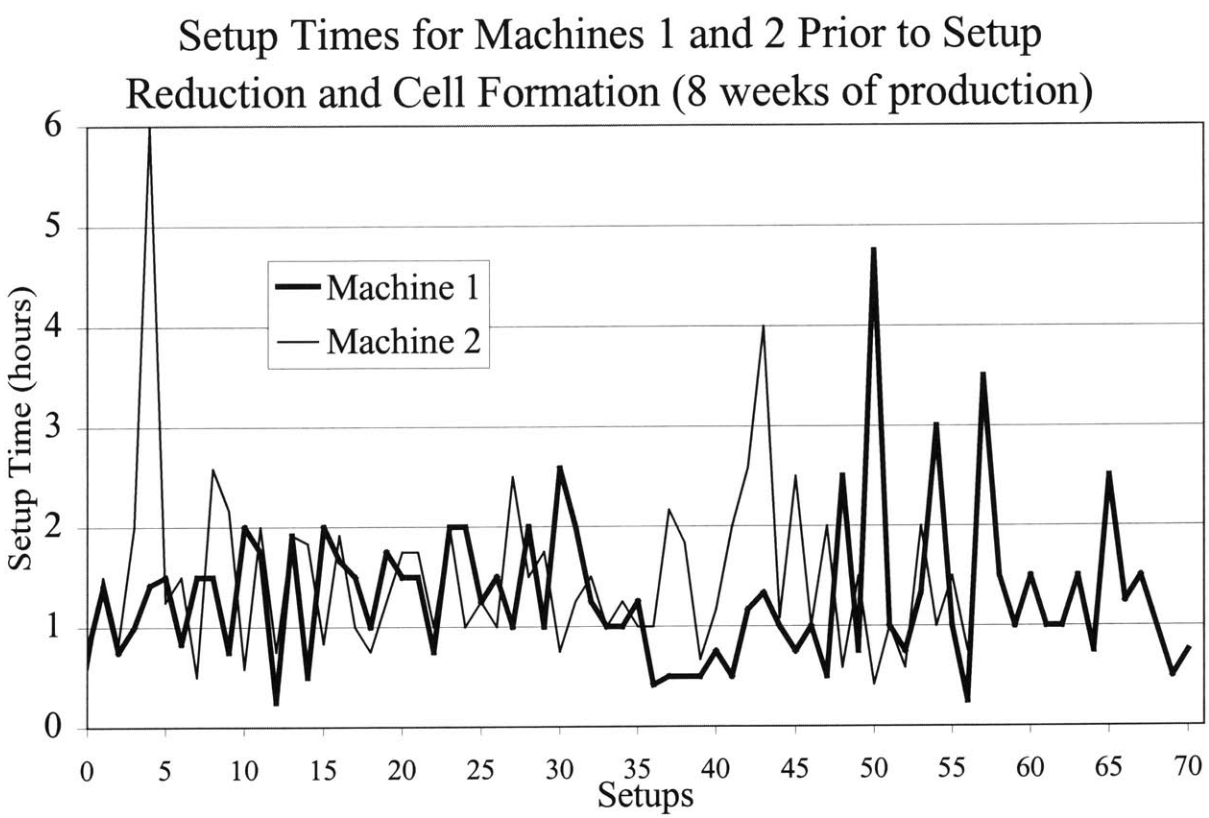


Figure 6.107 Setup variability prior to setup reduction.

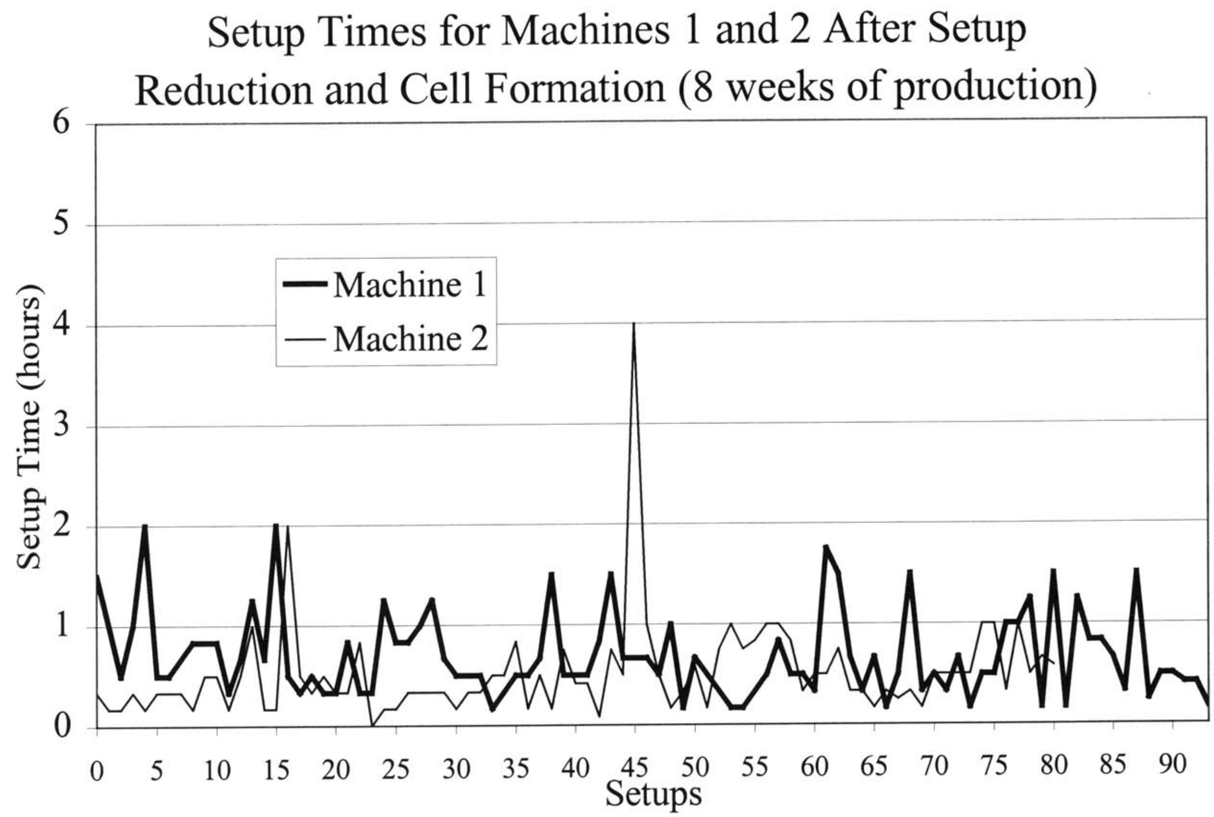


Figure 6.108 Setup variability after setup reduction.

Table 6.5 Change in mean and standard deviation setup times for Machines 1 and 2.

	Before		After		% Decrease	
	Machine 1	Machine 2	Machine 1	Machine 2	Machine 1	Machine 2
Mean (hrs.)	1.307	1.497	0.689	0.522	47.3	65.2
Std. Dev. (hrs.)	0.760	0.911	0.427	0.502	43.8	44.9

6.7 Chapter Summary

In summary, the requirement to achieve greater balance in production synchronization between the assembly and machining departments led to the investigation of the setup capabilities of equipment in the machining department. Initial analysis of the setup times for the CNC machines showed high variability that led to examinations of UE's existing shank tooling system. The second step of the EDA was used to contrast an alternative quick-change tooling system. Also, the fourth step of the EDA examined coupling in both tooling systems using design matrices.

UE's in-house equipment design capability described in this chapter provided tool modifications during the conversion to the quick-change tooling system. In-house knowledge was also beneficial while surveying potential tooling vendors. The conversion was further supported by machine operators with knowledge of MSDD requirements, namely FR-T11 and FR-T12.

In conclusion, the conversion of the two machines has shown that greater, longer term benefits lie in opportunities for process improvement (FR-Q23). Process improvements that have eliminated tooling adjustment can better control process variables such as feeds, speeds, cutting geometry and cutting materials. Better control leads to greater machine utilization and machining flexibility observed in decreased machining cycle times and improved quality.

Chapter 7 Conclusions and Future Work

7.1 Summary of Work

This dissertation has presented a design approach to communicate requirements between designers of manufacturing systems and designers of equipment. In particular, this work has examined how a design approach can not only communicate system requirements, but also provide understanding of the system to equipment designers. Providing a system perspective to equipment designers is especially important since designers have traditionally had only an operational focus. The perspective therefore must contain requirements that meet the goals of a multiplicity of operations and dependencies within the manufacturing system.

First, to develop a systems perspective for equipment designers, a source of manufacturing systems requirements is needed. The Manufacturing System Design Decomposition (MSDD) was therefore introduced and analyzed for its role as a source of requirements for equipment design. The MSDD contains a diverse set of requirements that integrate many of the elements of a manufacturing system. For example, in addition to equipment requirements, the MSDD also has requirements that determine the design of information and production control systems. These systems are not typically considered simultaneously with the design of equipment, however, the MSDD provides an integrated view to achieve the system design relationships.

Given that the MSDD is fundamentally a decomposition of requirements, additional guidance must be provided to equipment designers before the MSDD can be used as a source of requirements. The necessary additional guidance was developed in the form of an equipment design approach (EDA). The EDA consists of four steps that transform the MSDD requirements into alternative forms that improve the equipment designer's understanding of the system.

The first step of the EDA is the identification of the set of MSDD equipment requirements. Second, this initial set of requirements is then transformed into different views that correspond to major equipment subsystems. Views serve to abstract system goals thereby creating clear links between high-level objectives and low-level design solutions. The third step is requirements analysis to ensure that MSDD FRs are stated in a form that equipment designers can use in detailed engineering. Since the MSDD is meant for conceptual design, FRs must be expressed in a form that can be used to verify and validate equipment and system performance. The fourth step is the integrating step that links MSDD requirements to a specific equipment design process. This final step involves the actual design of the equipment to meet system requirements. Example equipment designs were taken from a compressor manufacturing system and setup reduction tool design to illustrate application of the fourth step of the approach.

7.2 Recommendations for Future Work

The EDA specifies a general design process for translating MSD requirements into equipment designs. The four steps of the EDA are a combination of requirements and design engineering methods that allow for this translation. These four steps were developed using a single machine model and demonstrated using manual requirements processing methods. However, for more complex manufacturing systems and larger sets of equipment requirements the introduction of automated tools and standardized methods can increase the ease and speed of applying the EDA. Furthermore, visualization tools can improve the communication of requirements. Therefore, recommended future work can be divided into three main lines of research. First, enhance the underlying MSDD relationships by developing and integrating models that consider equipment design. Second, standardizing the decomposition process from the MSDD to the equipment decomposition. Third, use of existing requirements management tools to reduce the chance for errors and thereby free the manufacturing systems engineer to better understand and communicate the objectives of the system.

The first line of research to pursue is to further develop the design matrices in the MSDD. These matrices reflect the influences and dependencies between FRs and DPs. The current version of the MSDD (PSD Lab, 2000) needs the addition of quantitative models and relationships that can be integrated with external design tools. For example, an automated workloop designer can use the influence relation in the pair FR/DP-D3 to generate workloops that are balanced and eliminate operators waiting on other operators. For equipment design, process planning tools can be integrated with FR/DP-T221 when designing automatic work content. Process planners can use FR-T221 that the automatic cycle time must be less than the takt time as a design requirement. Furthermore, setup models for process plans can be used as part of the MSDD to quantitatively check for coupling in the FR/DP-T22 design matrix.

Another example of an area in the MSDD that can be enhanced with quantitative relationships and links to design tools is the throughput time reduction branch. Here, queuing theory models and discrete event simulations can use the FRs and DPs from T1 to T5 as modeling parameters to test for coupling in the design matrix.

The second area for further work is the need to standardize the MSDD and equipment decomposition process. The analysis in Chapter 3 of the main DP nouns showed that there is a great deal of variety in the statement of DPs. Whitney (2000) has observed that the lack of structure reflects the elasticity of some of the nouns. For example, DP-P122 *Regular Preventative Maintenance Program* (classified as a "program") can be also expressed as a Preventative Maintenance System. Also, an FR such as *Eliminate material assignable causes* can be easily converted to the DP *Elimination of material assignable causes.* Thus, a potential solution is to develop clearly defined design dictionaries that standardize the formulation and statement of the FRs and DPs. This reference library of terms can greatly reduce the time spent in searching for appropriate terms. Also, using such a reference library leads to greater rigor since any additional word that is desired to be used must first be clearly defined in meaning as well as application.

The third line of research considers the use of requirements management tools. Currently there exist many requirements management tools (Owre, 1995; Dutertre, 1997; Pinheiro, 1996) to automate requirements processing and improve the flow of requirements between manufacturing systems engineers. The first three steps of the EDA were developed in a general manner and do not require any specific skills that can vary with the skills and size of the company. One area where the EDA can better enhance communication and understanding is the ability to improve flow of requirements through the structure of the four steps. Thus the extension to already developed requirements management tools can improve the communication. For example, better use of interfaces for view creation and superposition of views is possible with such tools (Structured Software Systems, Cradle; Vitech Corporation, CORE). These tools contain editors that allow operation on requirement hierarchies such as the MSDD set of FR/DP pairs. Since there are FRs that overlap in some views, these tools can also provide links that apply to different subsystems of a piece of equipment in different contexts.

Guidelines developed from the EDA provided context but more is needed particularly at the quoting phase of equipment design and procurement. Context is any description that helps explain a requirement or multiple requirements. Also, context is needed to avoid repetitive explanations that apply to a similar set of requirements and thereby improve clarity. Context may exist in the form of tables, figures, videos, etc. For example, videos of cells provided context for the manufacturing systems engineers in the compressor project. The videos provided explanations of operator interactions with machines. The more conceptual requirements are, the more context is needed and therefore since MSDD requirements are general stated, tools (such as those above) that provide context development is an important area for further investigation.

Operational descriptions of subsystems such as cells are multi-layered with integration given by the DP-hierarchy of the MSDD. As such, their requirements are not easily communicated as simple requirement statements. Therefore additional visualization and verification tools can be helpful. Formal requirements engineering methods by Easterbrook (1998) can be implemented with the MSDD to validate and verify the detailed design phases of the MSDD. Since the EDA uses input requirements from product design, verification of requirements for cross interactions during concurrent development is needed. Also, automated verification tools can be used to complement the requirements from the MSDD and those that originate from legacy systems. Some requirement analysis tools such as Prototype Verification System (PVS) (Dutertre, 1997) can provide complex reasoning functionality.

Figure 7.109 below shows potential data flow interfaces between the MSDD, product design, EDA, equipment design and a suite of Requirements Management Tools (RMT). The functional and physical domains of the MSDD and PD provide the source of requirements for the corresponding models in the RMT. The use of simulation in the MSDD is currently being investigated and requirements flow from a simulation package could be also linked to the RMT. Also shown in the figure is the link between the four steps of the EDA and the publication, scheduling and risk management tools in the RMT. Publication tools are important since currently the MSDD with annotated FR/DP pairs is the primary publication mechanism. Other automated view generations can be also published. Planning tools and risk management were beyond the initial scope of the EDA but should be included to provide analysis for the risk of failure to meet requirements.

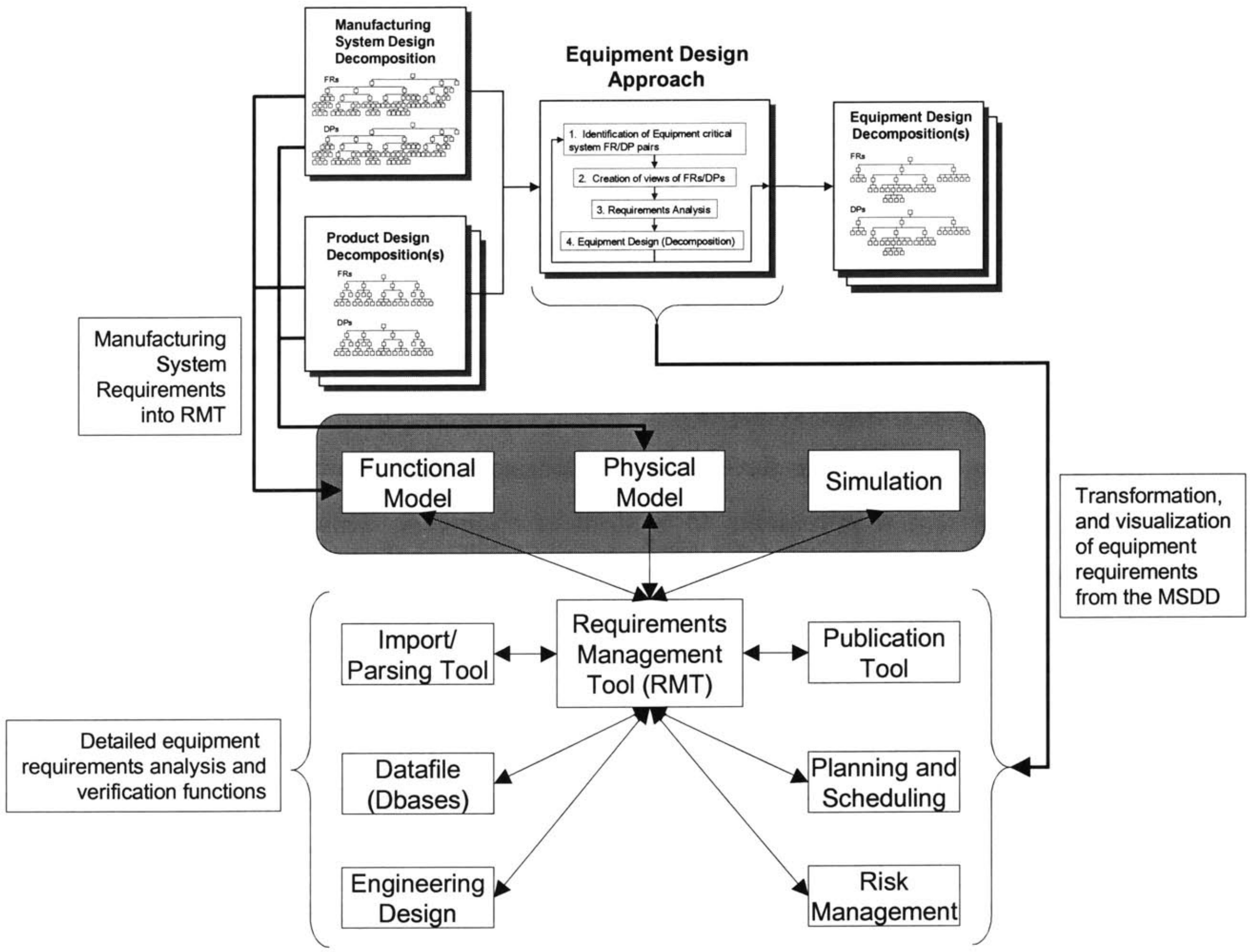


Figure 7.109 The Equipment Design Approach augmented by Requirements Management Tools. (Jones et al., 1997)

7.3 Conclusions

The design of equipment to operate effectively in a manufacturing system involves consideration of a wide diversity of requirements. At the concept design phase, structured design methods are important to organize and communicate system objectives and goals to equipment designers. The manufacturing system decomposition presented provides such a structure and improved understanding to designers because detailed requirements are decomposed from these high-level system objectives. The EDA that was developed can then be used to express system objectives as equipment requirements.

The design of equipment is an activity that must always be undertaken in the context of meeting manufacturing system requirements. Since equipment builders provide a wide variety of machine design options to customers, different approaches are necessary to handle these cases while satisfying the requirements of the system. Two design cases based on the MSDD were presented that address the different categories of equipment customization and concurrent design. The compressor case illustrated most turnkey forms of manufacturing system design, where a more integrated approach is needed at high levels of equipment customization. The setup reduction tooling design case offers better understanding of interdependencies (to facilitate concurrency) amongst equipment and system requirements because a common design methodology (Axiomatic Design) is employed.

In conclusion, the EDA was developed for communicating knowledge and understanding of manufacturing system requirements to equipment engineers. This disseration studied the applicability of the Manufacturing System Design Decomposition (MSDD) to design equipment in two different ways. First, by analysis of the structure of the DP hierarchy, and second by application of requirements analysis theory to FRs. The EDA also demonstrated a process for decomposition between the MSDD and equipment decompositions. In this process, a novel use of system engineering tools (Interaction matrices, Requirements Taxonomies, Views) was applied to Axiomatic Design. Finally, the EDA was applied and concurrently developed in examples from equipment that was actually designed and built for a compressor manufacturing system as well as for tooling design.

References

AL-AHMARI, A M A. RIDGWAY, K. (1999), "An Integrated Modelling Method to Support Manufacturing Systems Analysis and Design," Computers in Industry. 38(3): 225-238.

ALTING, L. (1994), *Manufacturing Engineering Processes*, Marcel Dekker.

ARINEZ, J. MOREIRA, D., (1997) "Implementation of a Kanban Control System to Support CNC Setup Reduction," M.I.T. Course Report in 2.812.

ARINEZ, J.F., COCHRAN, D.S., (2000) "An Equipment Design Approach to achieve Production System Requirements," *Proceedings of the 33rd CIRP International Seminar on Manufacturing Systems*, Stockholm, Sweden.

ASKIN, R.G. (1993), *Modeling and Analysis of Manufacturing Systems*, John Wiley and Sons.

BABIC, B. (1999), "Axiomatic design of flexible manufacturing systems," *International Journal of Production Research*, Vol. 37, No. 5, pp.1159-1173.

BASCARAN, E., TELLEZ, C. (1994), "The Use of the Independence Design Axiom as an enhancement to QFD," *ASME Design Theory and Methodology*, DE-Vol. 68, pp. 63-69.

BLACK, J T. (1991), *The Design of the Factory with a Future*, McGraw-Hill.

BLANCHARD, B.S., FABRYCKY, W.J. (1998), *Systems Engineering and Analysis*, Prentice-Hall, 3rd Ed.

BOTHE, D. R. (1997), *Measuring Process Capability*, McGraw-Hill.

BRAVOCO, RALPH R. YADAV, SURYA B. (1985c), "A Methodology to Model the Information Structure of an Organization," *Journal of Systems & Software*, 5(1): 59-71.

BRAVOCO, RALPH R. YADAV, SURYA B. (1985c), "Requirement Definition Architecture - An Overview," *Computers in Industry*, 6(4): 237-251.

BRAVOCO, RALPH R. YADAV, SURYA B. (1985a), "A Methodology to Model the Functional Structure of an Organization," *Computers in Industry*, 6(5): 345-361.

BROWN, C.R. (1990), "Machine Utilization Strategy," *Technical Paper MR90-252*, Society of Manufacturing Engineers.

BROWN, C.R. (1995), "Machine and Cutting Tool Automation," *Technical Paper MR95-177*, Society of Manufacturing Engineers.

BUZACOTT, J.A. (1993), *Stochastic Models of Manufacturing Systems*, Prentice Hall.

CARLEROS, M. (1985), "Toolholding Methods", *Technical Paper MR85-516*, Society of Manufacturing Engineers.

CHARLES, M. D. (1997), *The Impact of Machine and Cell Design on Volume Flexibility and Capacity Planning*, Masters Thesis in Department of Mechanical Engineering, Massachusetts Institute of Technology.

CHARLES, M. D., COCHRAN, D. S., DOBBS, D. C. (1999), "Design of Manufacturing Systems to Support Volume Flexibility," SAE IAM 99 Conference.

CHASE, K.W., PARKINSON, A.R. (1991), "A Survey of Research in the Application of Tolerance Analysis to the Design of Mechanical Assemblies," *Research in Engineering Design*, Vol. 3, pp.23-37.

CHRYSSOLOURIS, G. (1992), *Manufacturing Systems: Theory and Practice*, Springer-Verlag.

CLAUSING, D. (1989), "Quality Function Deployment: Applied Systems Engineering," *Quality and Productivity Research Conference*, University of Waterloo.

COCHRAN, D. S. (1991), "The Total Source Error of Adjustment Model: A Methodology for the Elimination of Setup and Process Adjustment," *The International Journal of Production Research*, July, Vol.29, No. 7.

COCHRAN, D. S. (1994), *The Design and Control of Manufacturing Systems*, Ph.D. Thesis, Auburn University.

DAHLQVIST, S., (1987), "Manual and Automated Block Tooling Systems for CNC Lathes," *Technical Paper MR87-430*, Society of Manufacturing Engineers.

DEWITTE, P.S. POURTEAU, C. (1997), "Inside the process," *Manufacturing Systems*, 15(3): 70-75. 1997.

DIMAROGONAS,A.D. (1993), "On the Axiomatic Foundation of Design," *ASME Design Theory and Methodology*, DE-Vol. 53, pp. 253-255.

DOUMEINGTS, G., VALLESPIR, B., DARRICAU, D., ROBOAM, M. (1987), "Design Methodology for Advanced Manufacturing Systems," *Computers in Industry*, Vol.9, No.4, pp. 271-296.

DUDA, J.W., (2000) *A Decomposition-Based Approach to Linking Strategy, Performance Measurement, and Manufacturing System Design,* Ph.D. Thesis, Massachusetts Institute of Technology.

DUTERTRE, B.; STAVRIDOU, V. (1997), "Formal Requirements Analysis of an Avionics Control System", *IEEE Transactions on Software Engineering*, Vol. 23, No. 5, pp. 267 –278.

EASTERBROOK, S., LUTZ, ROBYN, L., COVINGTON, R., KELLY, J., AMPO, Y., HAMILTON, D. (1998), "Experiences Using Lightweight Formal Methods for Requirements Modeling," *IEEE Transactions on Software Engineering*, Vol. 24, No. 1.

EL-GIZAWY, A.S., HO, Y., ABU-HAMDAN, M.G., AND WOOD, R.A. (1993), "Concurrent Engineering With Quality Approach for Manufacturing Industry," *ASME Design for Manufacturability*, DE-Vol. 52, pp. 143-149.

EL-HAIK, B., YANG, K. (1999), "The Relationship Between Axiomatic Design and Tolerance Design," *Journal of Engineering Design and Automation.*

EPPINGER, S.D., ULRICH, K.T. (1995), Product design and development, McGraw-Hill.

FENG, C., KUSIAK, A. (1997), "Robust Tolerance Design With the Integer Programming Approach", Journal of Manufacturing Science and Engineering, Vol. 119, pp. 603-610.

FINE, C.H., WHITNEY, D.E. (1996), "Is the make-buy decision process a core competence?" MIT Center for Technology, Policy, and Industrial Development, Working Paper.

GERSHWIN, S.B. (1994), *Manufacturing Systems Engineering*, Prentice Hall.

GOUVINHAS, R.P., CORBETT, J. (1999), "The Use of Design Methods Within Production Machinery companies", *Proceedings Institution of Mechanical Engineers*, Vol. 213, Part B, pp. 285-293.

GREENWOOD, W.H., CHASE, K.W. (1988), "Worst Case Tolerance Analysis with Nonlinear Problems", *Journal of Engineering for Industry*, Vol. 110, Aug. 1988, pp. 232-235.

GRIGELY, L.J., AND BILLATOS, S.B. (1993), "Case Based Reasoning Approach to Concurrent Engineering", DE-Vol. 66, Intelligent Concurrent Design: Fundamentals, Methodology, Modeling and Practice, pp. 83-95.

HARDING, J.A., YU, B., POPPLEWELL, K. (1999), "Information modellng: an integration of views of a manufacturing enterprise," *International Journal of Production Research*, Vol. 37, No. 12, pp. 2777-2792.

HATAMURA, Y. (1999), *The Practice of Machine Design*, Oxford University Press, 1999.

HAYES, R.H., ABERNATHY, W.J. (1980), "Managing Our Way to Economic Decline", *Harvard Business Review*, July-August.

HAYES, R.H., CLARK, K.B. (1986), "Why Some Factories Are More Productive Than Others", *Harvard Business Review*, September-October.

HAYES, R.H., GARVIN, D.A. (1982), "Managing as if Tomorrow Mattered", *Harvard Business Review*, May-June.

HAYES, R.H., WHEELWRIGHT, S.C. (1984), *Restoring Our Competitive Edge - Competing Through Manufacturing*, John Wiley & Sons.

HILL, T. (1994), *Manufacturing Strategy*, 2nd Ed., McGraw-Hill.

HITOMI, K. (1996), *Manufacturing Systems Engineering*, Taylor and Francis.

HOCKENBERGER, M.J., DE METER, E.C. (1996), "The Application of Meta Functions to the Quasi-Static Analysis of Workpiece Displacement Within a Machining Fixture," *Journal of Manufacturing Science and Engineering*, Vol. 118, pp. 325-331.

HOOKS, I. (1993), "Writing Good Requirements (A Requirements Working Group Information Report)," *Proceedings of the Third International Symposium of the INCOSE*, Volume 2.

HOPP, W.J., SPEARMAN, M.L. (1996), *Factory Physics: Foundations of Manufacturing Management*, Irwin/McGraw Hill.

HOUNSHELL, D.A. (1984), From the American System to Mass Production, 1800-1932, *The John Hopkins University Press.*

ICAD (2000), *First International Conference on Axiomatic Design*, June 21-23, Cambridge, MA USA.

ICAM (1981), *ICAM Architecture Part II-Volume IV - Function Modeling Manual (IDEF0)*, AFWAL-TR-81-4023, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base.

IMAI, M. (1986), *KAIZEN: The Key to Japan's Competitive Success*, McGraw-Hill.

INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING, SAN FRANCISCO BAY AREA CHAPTER (1998), *Systems Engineering Handbook: A "How To" Guide For All Engineers*, Release 1.0, http://www.incose.org/.

JONES, D.A., HOLLENBACH, F., KAR, P.C., BELL, M.,VAN GRAASBEEK, J.R., ELLINGER, R.S. (1997), "Interfacing Requirements Management Tools in the Requirements Management

Process - A First Look," *Proceedings of the Seventh International Symposium of the INCOSE*, Volume II, August, http://www.incose.org.

KALPAKJIAN, S. (1995), *Manufacturing Engineering and Technology*, Third Edition, Addison-Wesley Publishing Company, 1995.

KAPLAN, R.S. (1984), "Yesterday's Accounting Undermines Production," *Harvard Business Review*, July-August.

KRISHNASWAMI, M., MAYNE, R. (1994), "Optimizing Tolerance Allocation Based on Manufacturing Cost and Quality Loss", *ASME Advances in Design Automation*, DE-Vol.69-1, New York, pp. 211-217.

LARSON, M. (1998), "Five days to a better process - Are You Ready For Kaizen?", *Quality Magazine*, June.

LEAN AEROSPACE INITIATIVE (1999), *Final Draft: Transition-To-Lean in Production Operations Team*, Massachusetts Institute of Technology, December 4.

LYLE, C.S. (1986), "A Complete Tooling System for the Multifunction Flexible Turning Machine", Technical Paper MR86-127, Society of Manufacturing Engineers.

LYLE, C.S. (1987), "A Quick-Change Tooling Concept for Turning", Technical Paper MR87-432, Society of Manufacturing Engineers.

MALACHOWSKI, R.B. (1992), "Modular Quick-Change Tooling for Turning Centers and Machining Centers", Technical Paper MR92-379, Society of Manufacturing Engineers.

MERRIAM-WEBSTER (1993), *Merriam-Webster's Collegiate Dictionary.*

MONDEN, Y. (1993), *Toyota Production System*, Industrial Engineering and Management Press, 2nd Ed.

MONTGOMERY, D.C. (1985), *Introduction to Statistical Quality Control*, John Wiley and Sons.

NEVINS, J.L., WHITNEY, D.E. (1989), *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing*, McGraw-Hill.

OHNO, T. (1988), *Toyota Production System : Beyond Large-scale Production*, Productivity Press.

OLIVER, D.W., KELLIHER, T.P., KEEGAN, J.G. (1997), *Engineering Complex Systems with Models and Objects*, McGraw-Hill.

OWRE, S.; RUSHBY, J.; SHANKAR, N.; VON HENKE, F. (1995), "Formal Verification for Fault-Tolerant Architectures: Prolegomena to the Design of PVS," *IEEE Transactions on Software Engineering*, Vol. 21, No. 2, Feb., pp. 107-125.

PAHL, G., BEITZ, W. (1984), *Engineering Design*, Springer-Verlag.

PARKER, G., (1998), *Contracting for Employee and Supplier Capability Development*, Ph.D. Thesis, Massachusetts Institute of Technology, Sloan School of Management.

PARNABY, J. (1979), "Concept of a Manufacturing System", *International Journal of Production Research*, Vol. 17, No. 2, pp.123-135.

PHADKE, M.S. (1989), *Quality Engineering Using Robust Design*, Prentice Hall.

PINHEIRO, F.A.C.; GOGUEN, J.A. (1996), "An Object-Oriented Tool for Tracing Requirements", *Proceedings of the Second International Conference on Requirements Engineering*, pg. 219.

PLAIA, A., CARRIE, A. (1995), "Application and assessment of IDEF3 - Process flow description capture method," *International Journal of Operations & Production Management*, 15(1): 63-73.

PLANT, P., Personal Conversation, Manager, United Electric Controls Model Shop, 1996.

PSD LAB (2000), *The MSDD*, Internal Document, Version 5.1, April.

PUGH, S. (1991), *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley.

RAO, H.A., GU, P. (1997), "Design methodology and integrated approach for design of manufacturing systems," *Integrated Manufacturing Systems*, Vol. 8, No. 3, pp. 159-172.

REYNAL, V. A., COCHRAN, D. S. (1997), "Axiomatic Design of Manufacturing Systems," *The Second World Congress of Intelligent Manufacturing Processes and Systems*, Budapest, Hungary, June 10-13.

REYNAL, VICENTE A. (1998), "Production System Design and Implementation in the Automative and Aircraft Industry", Masters Thesis in Department of Mechanical Engineering, M.I.T., June.

ROSS, E.T. (1977), "Structured Analysis for Requirement Definition", *IEEE Transactions on Software Engineering*, Vol. SE-3, No. 1, January.

RUDOLPH, S. (1996), "Upper and Lower Limits for "The Principles of Design", *Research in Engineering Design*, Vol. 8, No. 4, 1996, pp. 207-216.

RYCKEBUSCH, S. (1996), "United Electric Controls", Harvard Business School Case, 9-697-006, December 1996.

SAATY, T.L. (1980), *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, McGraw-Hill, 1980.

SAGE, A.P. (1992), *Systems Engineering*, John Wiley & Sons, 1992.

SARKIS, JOSEPH. LILES, DONALD H. (1995), "Using IDEF and QFD to develop an organizational decision support methodology for the strategic justification of computer-integrated technologies," *International Journal of Project Management*, 13(3): 177-185.

SHIBA, S., GRAHAM, A., WALDEN, D. (1993), *A New American TQM: Four Practical Revolutions in Management*, Productivity Press.

SHIGLEY, J.E. (1983), *Mechanical Engineering Design*, McGraw-Hill, 4th Ed.

SHINGO, S. (1985), *A Revolution in Manufacturing : The SMED System*, Productivity Press.

SHINGO, S. (1989), *A Study of the Toyota Production System from an Industrial Engineering Viewpoint*, Productivity Press.

SLOCUM, A.H. (1992), *Precision Machine Design*, Prentice Hall.

SOHLENIUS, G. (1992), "Concurrent Engineering," *Annals of the CIRP*, Vol. 41, No. 2, pp. 645-655.

SPEAR, S., BOWEN, H.K. (1999), "Decoding the DNA of the Toyota Production System", *Harvard Business Review*, September-October.

STRUCTURED SOFTWARE SYSTEMS, Cradle, http://www.3sl.co.uk

SUH, N. P. (1990), *The Principles of Design*, Oxford University Press.

SUH, N.P. (1995), "Designing-in of Quality Through Axiomatic Design", *IEEE Transactions on Reliability*, Vol. 44, No. 2, June, pp. 256-264.

SUH, N.P. (2000), *Advances in Axiomatic Design*, forthcoming.

SUH, N.P., BELL, A.C., GOSSARD, D.C. (1978), "On an Axiomatic Approach to Manufacturing and Manufacturing Systems", *Journal of Engineering for Industry*, Vol. 100, pp. 127-130.

SUH, N.P., COCHRAN, D.S., LIMA, P.C. (1998), "Manufacturing System Design," *48th General Assembly of CIRP*, Annals of the CIRP, Vol.47/2, pp. 627-639.

SUH, N.P., KIM, S.H. (1987), "Mathematical Foundations for Manufacturing", *Journal of Engineering for Industry*, Vol. 109, pp.213-218, August.

TAGUCHI, G. (1989), *Quality Engineering in Production Systems*, McGraw-Hill, 1989.

TAYLOR, F.W. (1911), *The Principles of Scientific Management*, Harper & Brothers, 1911.

TROTT, A.R. (1989), *Refrigeration and Air-Conditioning*, Butterworth & Co, 1989.

ULLMAN, D.G. (1992), *The Mechanical Design Process*, McGraw-Hill, 1992.

UPTON, D.M. (1994), "The Management of Manufacturing Flexibility," *California Management Review*, Winter, pp.72-89.

VALLHAGEN, J. (1994), "Aspects on Process Planning Issues in Axiomatic Design", *ASME Advances in Design Automation*, DE-Vol. 69-2, Vol.2, pp. 373-381.

VAN RENSBURG, A., ZWEMSTRA, N. (1995), "Implementing IDEF Techniques as Simulation Modelling Specifications," *Computers & Industrial Engineering*, 29(1-4): 467-471.

VITECH CORPORATION, CORE, http://www.vtcorp.com

WASSERMAN, A.I. (1996), "Toward a Discipline of Software Engineering", *IEEE Software*, Vol. 13, No. 6., Nov. pp. 23-31.

WEMMERLOV, U., JOHNSON, D.J. (1997) "Cellular manufacturing at 46 user plants: implementation experiences and performance improvements," *International Journal of Production Research*, Vol. 35, No. 1.

WHITNEY, D.E. (1993), "Nippondenso Co. Ltd: A Case Study of Strategic Product Design.", *Research in Engineering Design-Theory Applications & Concurrent Engineering*, Vol.5, No.1, pp.1-20.

WHITNEY, D.E. (2000), Personal communication.

WOLF, W., MAGADANZ, P., (1984), "Block Tool System Fulfills the Tooling Requirement for Unattended Turning", Technical Paper MS84-235, Society of Manufacturing Engineers.

WOMACK, J.P., ROOS, D., JONES, D. (1990), *The Machine that Changed the World*, Rawson Associates.

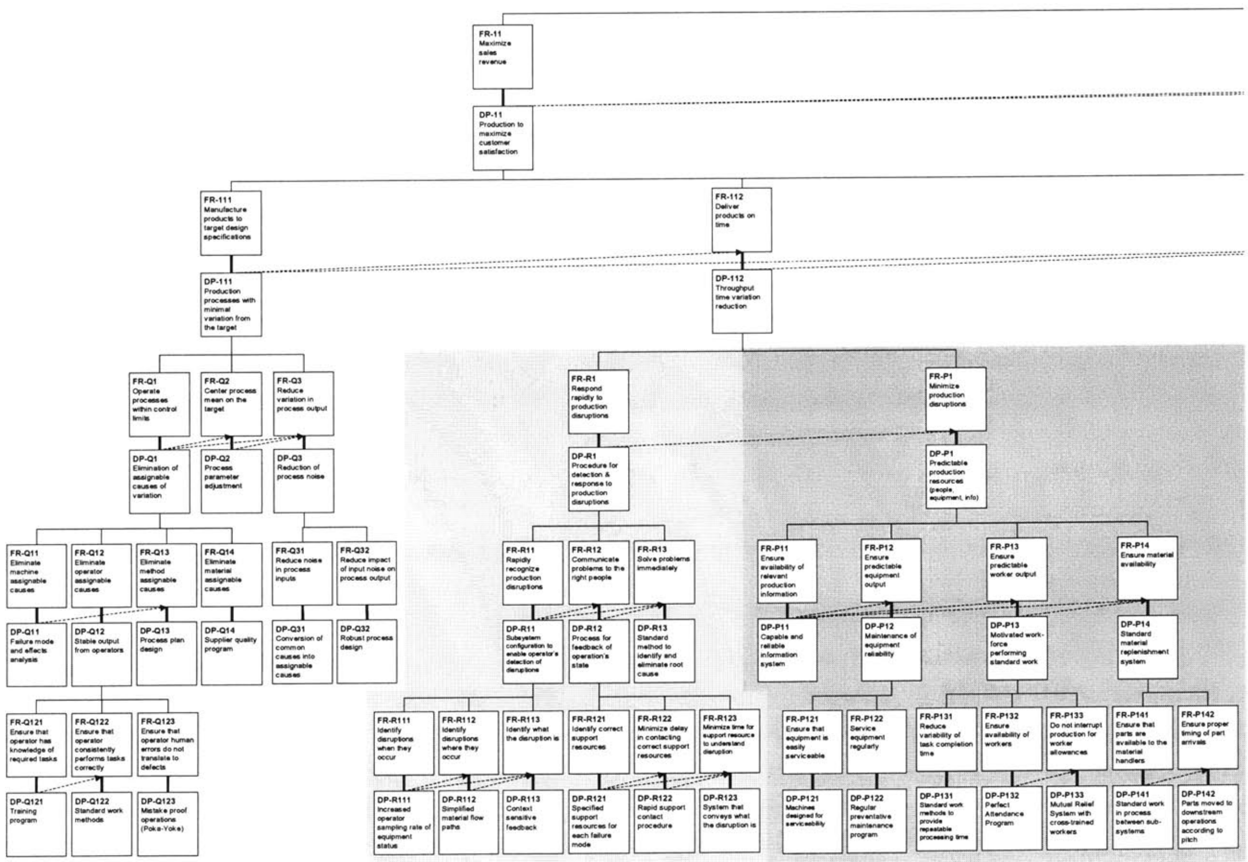
WU, B. (1995), "Object-Oriented Systems Analysis and Definition of Manufacturing Operations," *International Journal of Production Research*, Vol. 33, No. 4, pp. 955-974.

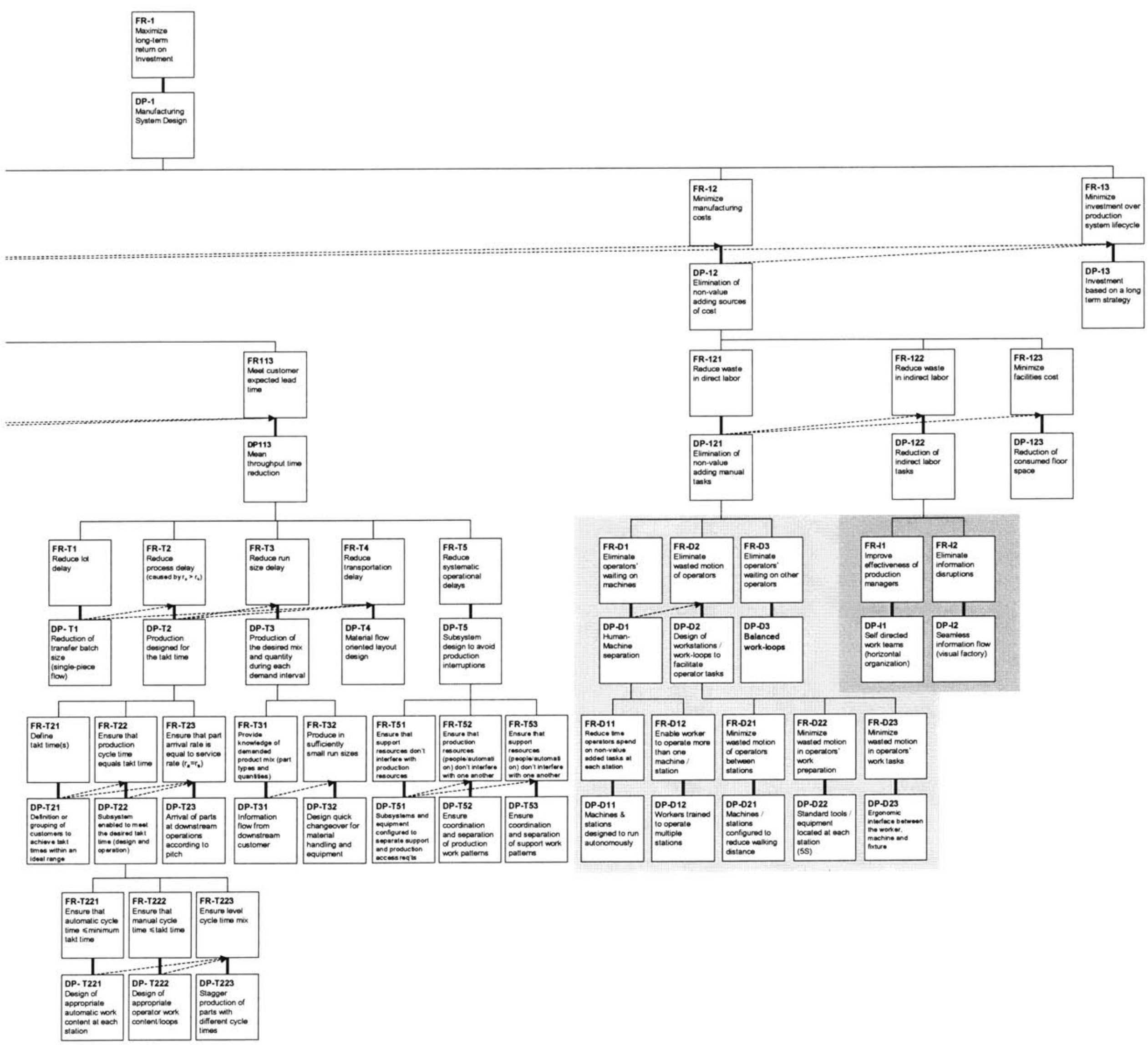
WU, B. (1992), *Manufacturing Systems Design and Analysis*, Chapman and Hall.

YANG, K., TREWN, J. (1998), "Relationship Between System Functions, Reliability and Dependent Failures", *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, 1998, pp. 4722-4727.

YEO, S.H., RAHMAN, M., (1996), "Performance evaluation of shank-type tooling and modular tooling for lathes", *Journal of Materials Processing Technology*, Vol. 62, pp. 335-340.

Appendix A - The Manufacturing System Design Decomposition (MSDD)





FR-1 Maximize long-term return on investment
DP-1 Manufacturing System Design
FR-12 Minimize manufacturing costs
FR-13 Minimize investment over production system lifecycle
DP-12 Elimination of non-value adding sources of cost
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
FR-122 Reduce waste in indirect labor
FR-123 Minimize facilities cost
DP-121 Elimination of non-value adding manual tasks
DP-122 Reduction of indirect labor tasks
DP-123 Reduction of consumed floor space
FR-T1 Reduce lot delay
FR-T2 Reduce process delay
FR-T3 Reduce run size delay
FR-T4 Reduce transportation delay
FR-T5 Reduce systematic operational delays
DP-T1 Reduction of transfer batch size (single-piece flow)
DP-T2 Production designed for the takt time
DP-T3 Production of the desired mix and quantity during each demand interval
DP-T4 Material flow oriented layout design
DP-T5 Subsystem design to avoid production interruptions
FR-D1 Eliminate operators' waiting on machines
FR-D2 Eliminate wasted motion of operators
FR-D3 Eliminate operators' waiting on other operators
DP-D1 Human-Machine separation
DP-D2 Design of workstations / work-loops to facilitate operator tasks
DP-D3 Balanced work-loops
FR-I1 Improve effectiveness of production managers
FR-I2 Eliminate information disruptions
DP-I1 Self directed work teams (horizontal organization)
DP-I2 Seamless information flow (visual factory)
FR-T21 Define takt time(s)
FR-T22 Ensure that production cycle time equals takt time
FR-T23 Ensure that part arrival rate is equal to service rate ($r_a=r_s$)
FR-T31 Provide knowledge of demanded product mix (part types and quantities)
FR-T32 Produce in sufficiently small run sizes
FR-T51 Ensure that support resources don't interfere with production resources
FR-T52 Ensure that production resources (people/automation) don't interfere with one another
FR-T53 Ensure that support resources (people/automation) don't interfere with one another
FR-D11 Reduce time operators spend on non-value added tasks at each station
FR-D12 Enable worker to operate more than one machine / station
FR-D21 Minimize wasted motion of operators between stations
FR-D22 Minimize wasted motion in operators' work preparation
FR-D23 Minimize wasted motion in operators' work tasks
DP-T21 Definition or grouping of customers to achieve takt times within an ideal range
DP-T22 Subsystem enabled to meet the desired takt time (design and operation)
DP-T23 Arrival of parts at downstream operations according to pitch
DP-T31 Information flow from downstream customer
DP-T32 Design quick changeover for material handling and equipment
DP-T51 Subsystems and equipment configured to separate support and production access req'ts
DP-T52 Ensure coordination and separation of production work patterns
DP-T53 Ensure coordination and separation of support work patterns
DP-D11 Machines & stations designed to run autonomously
DP-D12 Workers trained to operate multiple stations
DP-D21 Machines / stations configured to reduce walking distance
DP-D22 Standard tools / equipment located at each station (5S)
DP-D23 Ergonomic interface between the worker, machine and fixture
FR-T221 Ensure that automatic cycle time ≤ minimum takt time
FR-T222 Ensure that manual cycle time ≤ takt time
FR-T223 Ensure level cycle time mix
DP-T221 Design of appropriate automatic work content at each station
DP-T222 Design of appropriate operator work content/loops
DP-T223 Stagger production of parts with different cycle times

Appendix B - Glossary of Key Terms

Abstraction: alternative presentation of information so as to emphasize a particular aspect while simultaneously obscuring information that is unimportant.

Balanced: Having the same production rate. Two manufacturing operations are said to be *balanced* if they produce parts at the same pace (Duda, 2000).

Conceptual System: are comprised of components that exist in the form of ideas, plans, procedures. (Blanchard and Fabrycky, 1998)

Cycle time: The time it takes to perform a manufacturing operation. (Lean Aerospace Initiative, 1999)

Design: A design in its most fundamental form is a simply a description of the product that meets the needs of its intended customer. A description can exist in many different forms and with varying amounts of detail.

Flexibility: Flexibility is the ability to change or react with little penalty in time, effort, cost or performance (Upton, 1994)

Kaizen: Kaizen is a Japanese word for gradual, unending improvement. A continuous improvement strategy, typically achieved through incremental improvements and involving everyone from top management to supervisors and workers. A process that has its roots in the Toyota Production System. The underlying assumption is small improvements, continuously made to a process, will lead to significant positive change over time. (Lean Aerospace Initiative, 1999; Imai, 1986; Larson, 1998)

Manufacturing Process: refers to the transformation of the incoming state of materials and products into a changed outgoing state. Process reflects the input/output view of a manufacturing system whose purpose it is to transform incoming raw materials into finished/semi-finished products having a greater value than before. A generalized model of a manufacturing process considers material, energy, and information as inputs and outputs (Alting 1994).

Manufacturing System: the integration and organization of resources and processes for the purpose of manufacturing products. Resources are the elements that make up the infrastructure of the manufacturing system and perform some operation on the product, or they support other resources (eg. machines, people). A process refers to the transformation of the incoming state of materials and products into a changed outgoing state. Organization includes physical layout, arrangement, structure of the combination of resources and processes as well as specification of interactions (planning, control, etc.).

Manufacturing System Design: the specification of the attributes of the manufacturing system, namely the resources, processes, and its organization.

Manufacturing System Design Approach: A set of methods, models, and analysis tools that when used as prescribed lead to the development of a manufacturing system design.

Operation: A single step in a manufacturing process (e.g. machining one feature in a part (Duda, 2000).

Physical System: physical systems are made up of components that occupy space. (Blanchard and Fabrycky, 1992)

Requirement: states something that is necessary, verifiable, and attainable (Hooks, 1993).

Requirements Communication: The clear expression of needs between designers.

Requirements Management: defined as the process of ensuring that people are aware of requirements that they have and do not have (Jones et al., 1997).

Specification: A document that fully describes a physical element or its interfaces in terms of requirements (functional, performance, constraints and physical characteristics) and the qualification conditions and procedures for each requirement. (IEEE Std. 1220-1994).

Structure: The organization of the components that make up a system, including the number of each component, their arrangement, and their interrelations (Oliver, 1997; Duda, 2000).

System Architecture: The arrangement of elements and subsystems and the allocation of functions to them to meet system requirements (INCOSE, 1998).

System: An integrated set of elements to accomplish a defined objective. These include hardware, software, firmware, people, information, facilities, services and other support elements. (INCOSE, 1998)

Takt Time: Takt is the German word for the baton used by an orchestra conductor to regulate or pace the tempo or playing speed of the orchestra, i.e., to synchronize the orchestra. In conjunction with Lean concepts, it is a goal that must be reached to satisfy demand. Takt Time is the daily production number required to meet orders in hand divided into the number of working hours in the day. (Lean Aerospace Initiative, 1999).

Throughput time: The amount of time it takes an individual part to go through an entire manufacturing system, entering as a raw material and then leaving as a marketable product (Duda, 2000).

Traceability: the ability to review the path of previous design decisions so as to gain insight into the dependencies from a high to low level of abstraction.

View: a subset of requirements based on equipment design characteristics. It clarifies equipment design by extracting relevant information and can be augmented by explanations to provide designers with further systems understanding. A view in the EDA is a "look" at the MSDD to determine specific FRs/DPs that affect a physical element of the manufacturing system, i.e. equipment.