The Consequences of the Enterprise not Engaging the Manufacturing System Design

by

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ABSTRACT

Currently much of the conventional focus on system design has been directed exclusively upon the system's physical structures and behaviors. Various approaches have been developed to describe, understand and prescribe, in great detail, how systems should be structurally designed and physically operated. However, in a number of cases, these approaches only result in transitory improvement and a reversion back to prior practices. The rational notion of 'changing the behaviors by working on the behaviors' results in disappointment, and systems that have achieved enduring success seem contradictory to logic and paradoxical in nature. However, these design methodologies often do not explicitly and coherently map the physical system design approach with a systems thinking. For systems that include both technical *and* human interactions, one must first recognize that the thinking creates the structure that results in the behavior of the system.

The thesis presented herein provides an introduction into the development of an ideal systems engineering model based upon the thinking-structure-behavior model, and proposal of the unification of two powerful design approaches—axiomatic design and system dynamics. In order to rationalize the seemingly paradoxical trap of behavior-focus, the "Chasm of Paradox" model is developed. The "chasm" model relates the notion of paradoxes and paradigm shifts to the thinking-structure-behavior model.

The "Chasm of Paradox" model is applied in an application-based case study in the automotive components business. The case studies strongly support the notion that the same thinking that resulted in prior poor system performance will reincarnate itself in another unstable system design that produces poor results—even in light of the opportunity for 'green field' design. The hypothesis is that the enterprise must change its thinking before local changes to the manufacturing system design (i.e. the structure) and its performance (i.e. the behavior) can be successful. Only when the enterprise recognizes that 'they are *part* of the system, and they *are* the system' will paradigms shift and the apparent chasm be crossable. The thesis submits that the unified approach of axiomatic design and system dynamics is the bridge that enables a successful crossing.

Thesis Supervisor: David S. Cochran, Associate Professor of Mechanical Engineering

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Not only does this thesis mark the conclusion of a considerable academic endeavor (nearly twenty-one years of formal education), but it also represents a personal success that could not have been realized without the support of many individuals along the way. The thanks and gratitude I offer to these individuals is authentic and well-deserved.

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List of Acronyms

BOM	Bill Of Materials
C	Constraints
CA	Customer Attributes
CLD	Causal Loop Diagram
CT	Cycle Time
DM	Design Matrix
DP	Design Parameter
DSM	Design Structure Matrix
e.g.	Exempli Gratia (for example)
FR	Functional Requirement
i.e.	Id Est (that is)
MECE	Mutually Exclusive and Collectively Exhuastive
MRP	Material Requirements Planning
MSDD	Manufacturing System Design Decomposition
PSDD	Production System Design and Deployment
R	Requirement
ROI	Return On Investment
S	Solution
SWIP	Standard Work In Process
TPS	Toyota Production System
TSSC	Toyota Supplier Support Center
VSM	Value Stream Mapping
WIP	Work In Process

Chapter 1 Introduction

1.1 Thesis Motivation

Design approaches can be categorized into two broad, yet distinct, categories—design by philosophy and systems engineering [Duda, 2000]. Philosophy-based design is founded on a general high-level thinking that is understood and communicated—explicitly or implicitly—with the goal of achieving a holistic impact on all phases of design. A classic illustration is that of a rules-based approach to design. Rules-based approaches are intended to communicate the essence of one's thinking in a manner that helps simplifies the direction of design. In contrast, a systems engineering approach is characterized as a more rigorous treatment of the design process. Systems engineering focuses on designing systems in light of lifecycles of design, interdisciplinary complexity, defining requirements, and the hierarchical nature of designs [Blanchard, Fabrycky, 1998].

While a powerful as an approach to design, philosophy-based design requires a deep understanding of the underlying requirements and means to achieve them. By nature, philosophy-based design approaches do not necessarily reflect the concept of designing systems based on system requirements [Shukla, 2001]. The implicit nature of the thinking behind the philosophy-based design approaches, such as rules-of-thumb or maxims, calls for a lengthy, inductive learning process [Won, Cochran, Johnson, 2001]. Recall the difficulties in understanding someone's implicit thinking when questions are answered with "it depends" or the mysterious requests of Mr. Miyagi (Pat Morita in Karate Kid) to "wax the floor" and "paint the fence." The implication is that philosophy-based design is the *result* of the thinking behind system design. Once one understands the thinking, only then does the true usefulness of the philosophy, rules, and maxims become more clearly understood. This is the power—and bane—of philosophy-based approaches.

However, one can argue that engineering systems are complex and require a rigorous systems approach to harness and focus the knowledge of multiple constituents. In fact, Wu [1992] concurs that manufacturing system design must apply systems engineering methods to manage the complexity. Suh [1990] submits that one of the goals of academic disciplines such as design, that universities have a role in condensing the "time required to learn a subject through the transmission of codified and generalized knowledge." When a subject relies upon implicit thought processes that cannot be stated explicitly for others to understand, the subject can be learned only through experience, apprenticeship, or trial-and-error. Acceptance of trial-and-error as a design approach has been instilled in many as the norm. Recall the well-known adage claims 'we learn from our mistakes.' However, as the Quality VP of Toyota Motor Manufacturing – Kentucky put it, "the only thing we learn from out mistakes is not to do it that way" [Kreafle, 2001].

The precept of this thesis is that an ideal systems engineering approach should provide a framework that is consistent at the overall process level—first and foremost, a consistency in its thinking. By focusing attention on the thinking process, deviations are permissible as long as the result is consistent with the intent. The result is a framework that is robust across a variety of systems [Cochran, Won, 2002]. As reflected in this thesis, an ideal design approach requires aspects of both design approaches—the thinking of philosophy-based approaches and the explicit rigor of systems engineering approaches. The integrated design approach provides the depth and balance needed to achieve a total system design.

1.2 Thesis Overview

This thesis is devoted to satisfy three primary objectives:

- The identification of a general design approach that satisfies the characteristics of an ideal systems engineering model, as set forth in Chapter 2.
- The application of the ideal systems engineering approach (as identified in Chapter 2) in a manufacturing context, as described in Chapter 3.
- The practical application of the ideal system design model to rationalize behaviors of a real-life system, as reflected in Chapter 4.

Core to the development of this thesis is the notion that 'the thinking' creates the 'structure', and the 'structure' drives the 'behavior' (Figure 1-1). In order to change the system's behavior, one must change the thinking. The idea is that there is a thinking-structure-behavior path-dependency necessary in order to initiate and sustain lasting changes in the system's behavior [Cochran, Won, 2002].

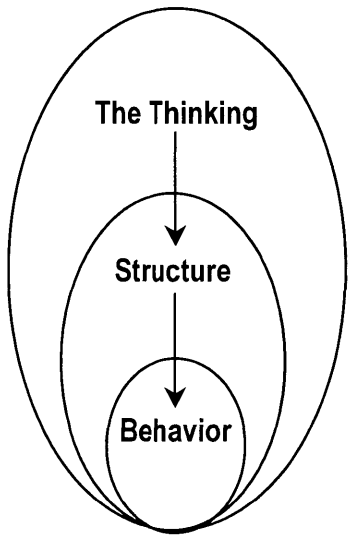


Figure 1-1. General system engineering model [Cochran, Won, 2002]

As a precursor to the body of this thesis, consider the relationship of The Buddha's contemplation over Dependent Origination [Harvard Classics, 1909], and the thinking-structure-behavior model.

> "*At that time The Buddha, The Blessed One, was dwelling at Uruvel at the foot of the Bo-tree on the banks of the river Neranjar, having just attained the Buddhaship. Then The Blessed One sat cross-legged for seven days together at the foot of the Bo-tree experiencing the bliss of emancipation. Then The Blessed One, during the first watch of the night, thought over Dependent Origination both forward and back:—*
>
> *On ignorance depends karma;*
> *On karma depends consciousness;*
> *On consciousness depend name and form;*
> *On name and form depend the six organs of sense;*
> *On the six organs of sense depends contact;*
> *On contact depends sensation;*
> *On sensation depends desire;*
> *On desire depends attachment;*
> *On attachment depends existence;*
> *On existence depends birth;*
> *On birth depend old age and death, sorrow, lamentation, misery, grief, and despair*".

Philosophical notions, such as the Dependent Origination, have been in existence for ages, however their application in technical and human system design has been limited in scope and effectiveness. This thesis aims to expound upon the thinking-structure-behavior model in order to 1) complement the academic and practical efforts put forth thus far by the Production System Design Laboratory at MIT, and 2) to hopefully develop a body of work that is seminal in both academic and pragmatic applications.

Chapter 2 Analysis of System Design Approaches

2.1 Systems and Systems Engineering

2.1.1 Systems

A system is generally defined as a set of elements embodying specific characteristics. Between the elements are relations, or patterns of relationships, representing the functional connections of the elements. These patterns of relationship affect the output of a system as a whole [Cochran, Won, 2002]. The system has a defined boundary to its environment and all elements of the system exist within the system boundary [Linck, 2001].

An open system has definite inputs and outputs and acts on its inputs to produce a desired output [Parnaby, 1979]. Furthermore, a system is comprised of many interrelated sub-systems [Deming, 1993], or elements within the whole system. The ultimate purpose of a system is to achieve defined goals, or objectives [Bruns, 1988].

2.1.2 Systems Engineering

Systems engineering is a structured approach to think about work and work with systems. Wu describes systems engineering as a generic problem solving cycle [Wu, 2000]. From an application perspective, Ulrich and Eppinger [2000] describe systems engineering as a sequence of steps or activities during which a product is conceived, designed, and commercialized. Hitomi establishes four characteristics of systems engineering as [Blanchard and Fabrycky, 1998]:

- **Life-cycle Orientation:** The life-cycle approach communicates the notion of time across a system design. These approaches address all phases of a system from conceptualization, rough design, detailed design, operation, and phase out.

- **Interdisciplinary Approach: T**he intermingling of multiple disciplines such as physics, mathematics, ergonomics, and performance measurement, shape the interdisciplinary complexity of technical and human systems. In general, systems of this type require a cross-disciplined approach to deal with this complexity.

- **Requirements Definition:** The definition of requirements forms the starting point of system design. Without requirements, a system has no purpose to fulfill. System design relates these requirements to design decisions. Evaluations can then be performed relative to the requirements.

- **Hierarchical Approaches:** There are two general hierarchical approaches—top down and bottom up. Top-down approaches start with the high-level system objectives and then determine how individual system elements work together to ultimately influence the overall system performance. The bottom-up approach is the converse as the approach first considers the low-level elements and then

considers the relationships among the elements to create the system. The key characteristic of a hierarchy is to recognize that there is some structure between elements. The depth of the hierarchy is rather an indicator of the complexity, or definition, of the system.

Systems engineering processes may be simply described as the tasks that support and specify all activities though the phases of a system lifecycle. The first two characteristics relate more towards an overarching outline of a systems engineering process—both in time and support, respectively. Time and support refers to classifications such as overall procedures. In contrast, the second two characteristics describe generic approaches found in system design literature—tasks and activities. Tasks and activities describe classifications such as layout and structural organization, tradeoffs in system variables, and control and information flow. Thus, system design is typically considered a subset of systems engineering (Figure 2-1).

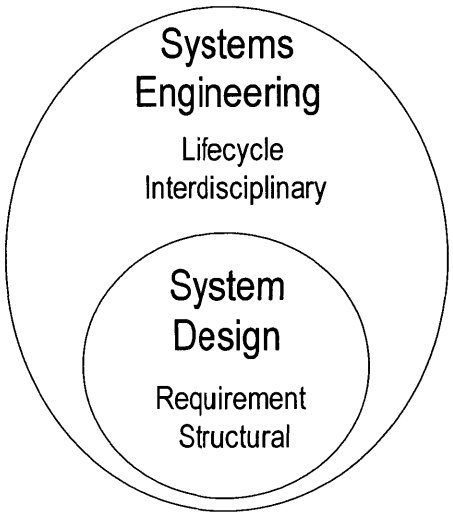


Figure 2-1. Typical relationship between systems engineering and system design

According to Linck [2001], the four characteristics of systems engineering highlight several important aspects of system engineering:

- Systems are designed and improved over time until the system is phased out.
- Systems can be engineered using tools such as synthesis, analysis, and evaluation.
- Systems exist to fulfill a purpose. System requirements must be defined.
- Systems are hierarchical in nature and can be divided into sub-systems.

Synthesis is characterized by the selection and combination of system components in such a way that the defined system requirements can be satisfied [Blanchard, Fabrycky, 1998]. Synthesis occurs at every phase of systems engineering as the system design becomes more and more physical and tangible. Synthesis is also a creative process that

enables the design to satisfy customer requirements. Evaluation occurs after synthesis and assesses how well system requirements have been satisfied. Analysis develops system requirements, performs feasibility studies, and defines evaluation measures. In addition, analysis is a key process in the diagnosis and re-synthesis of systems (Figure 2-2).

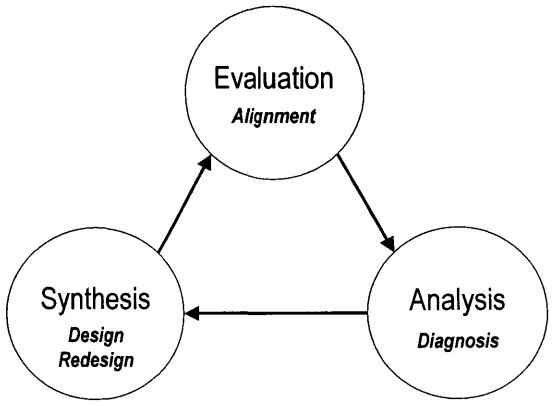


Figure 2-2. Synthesis, Evaluation, and Analysis [Adapted from Blanchard, Fabrycky, 1998]

Though the four characteristics of systems engineering are not collectively exhaustive of the systems engineering process, however they provide a sufficient foundation upon which an ideal systems engineering approach can be developed.

2.2 System Design

System design applies the elements of systems engineering (e.g. lifecycle and interdisciplinary approach) to create a "useful system (static structure and operating procedure) under a specified evaluation criterion by the use of scientific principles" [Hitomi, 1996, p 30]. More specifically, Sullivan [1896] considers the metaphysical-physical relationship of large structures when he states "form ever follows function." Cochran [1994] describes system design from a scientific viewpoint as the simple idea that in order to achieve lasting improvement, one must systematically define *what* must be accomplished in a clear statement of *how* it is accomplished.

The premise is that system design is mutually dependent on systems engineering, rather than either existing as separate disciplines. A powerful corollary to the mutual dependency of systems engineering and system design, is that systems engineering *cannot* be effective without a solid foundational system design approach. There must be an *explicitly-defined and coherent mapping* between the high-level requirements and the lower-level physical system design.

The necessary strong and coherent mapping between systems engineering and system design—sometimes referred to as "Big D(esign)" and "little d(esign)", respectively—has implications for the entire enterprise organization (Figure 2-3). The implication is that the link between traditional strategic management functions and operational execution must be well defined and explicit in order to ensure consistency and alignment throughout the entire organization. The consequence of misalignment is local optimization, rather than global system optimization of the entire system.

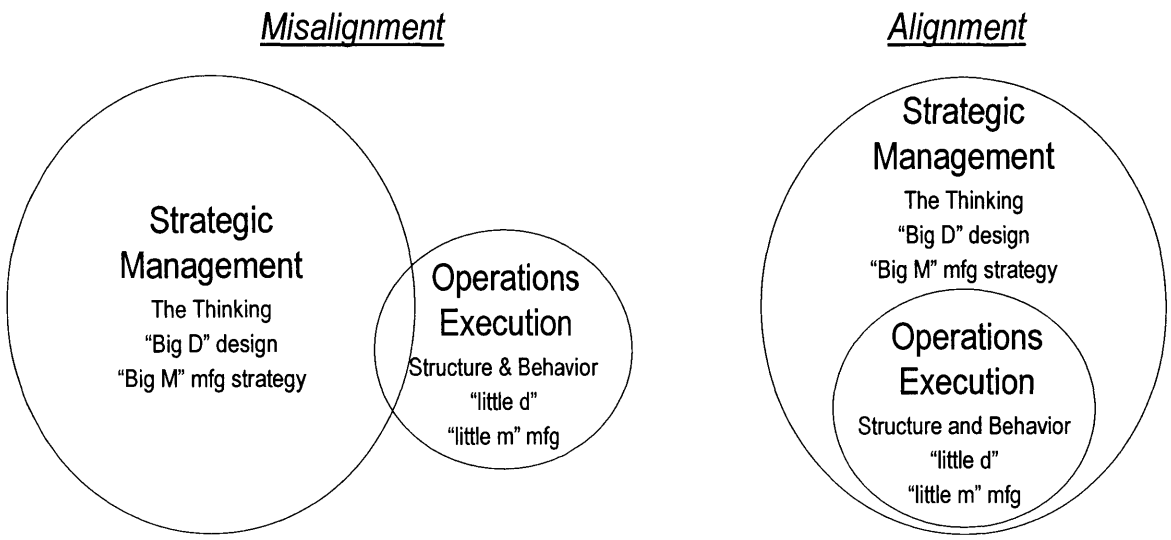


Figure 2-3. The Thinking drives Structure and Structure drives Behavior

2.3 Classification of an Ideal Systems Engineering Approach

Given the characteristics of both systems engineering (Section 2.1) and system design (Section 2.2), a model of an 'ideal' systems engineering approach is developed. The model expands upon the notion that the thinking creates the structure that drives behavior (Figure 2-4). The model is characterized by two elements—the thought formation, and the structural formation.

The thought formation element focuses upon the philosophies that underlie the structural formation. These philosophies include:

- **New Paradigm:** In order to break the apparent paradoxes of one individual's system performance (e.g. the Toyota Production System's simultaneity of quality, delivery, and cost) over another's system performance (e.g. quality-cost-delivery tradeoffs), the thinking behind an ideal design approach must transcend the traditional paradigms of design and systems engineering.

- **Design Focus:** As a corollary to the idea of a new paradigm, the ideal systems engineering approach must focus its fundamental endeavors on the domain of 'new design' versus that of 'redesign.' The domain of redesign, in most cases, focuses on 'brown-field' ventures. Brown-field redesigns can indeed improve performance dramatically, and have significant academic and pragmatic value. However, this should not be the fundamental focus of an ideal systems engineering approach. The ideal should focus upon designing the system correctly and effectively the first time—a lofty goal in and of itself. The notion is that an approach can only achieve as highly as the goals initially set forth in the endeavor.

- **Domain Breadth:** A technical design, such as a space shuttle design, can indeed be limited to the technical domain. Or an organizational management structure may only consider the people aspects. In reality, all systems do and must include both technical and human aspects. An ideal design approach must consider both the technical and people aspects of systems. In every system created by human beings, there is necessarily human interaction. Thus, an ideal systems engineering approach must have the breadth to cover both domains.

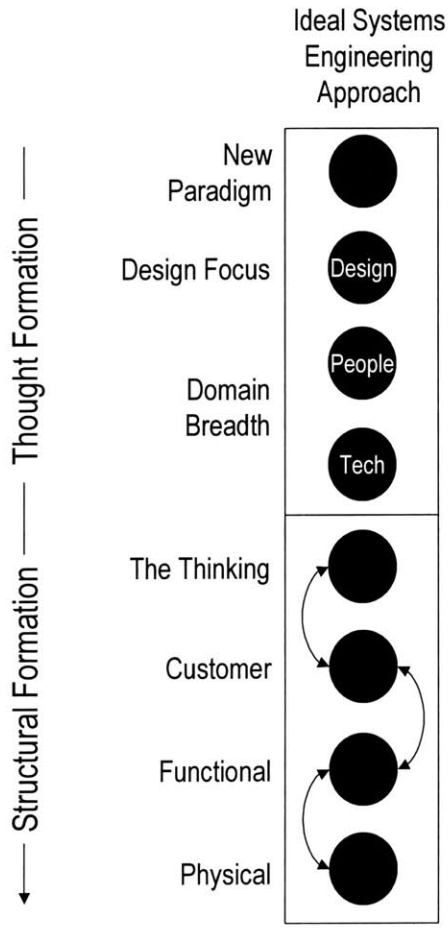


Figure 2-4. The thinking behind the ideal systems engineering approach

The thought formation thus drives the formation of the structural model. The structural form takes the philosophical elements—a new paradigm, design focus, and domain breadth—and creates the structure for ideal systems engineering. The approach is characterized by two main features:

- **Four Domains:** Design is the interplay between four domains, or patterns of relationship, in a system. These domains include the thinking, customer, functional, and physical.

- The ***thinking domain*** is the connection between the philosophies set forth by the element of thought formation. The thinking is the foundation of the structural approach.

- The ***customer domain*** defines purpose towards which a system is created to satisfy. Without a definition of the customer (internal and/or external), there is no purpose for the system to exist. The mapping between the customer and thinking domains is that which connects the system to the engineer. The thinking-customer connection can be thought of as the metaphysical supply-demand relationship in any system.

- The ***functional domain*** is a translation of the customer's needs into requirements that the system design must satisfy. The system must know exactly *what* it is intended to satisfy in order to exist. The mapping between the customer and functional domains is the translation between the sometimes imprecise customers' needs into precise system requirements.

- The ***physical domain*** defines *how* the requirements upon a system are going to be achieved. The mapping between the functional-physical domains is where the concentration of design takes place. Mapping is an important notion, as the *how's* are always intended to explicitly satisfy the *what's*. Typically, the 'physical' is perceived as "that which is a tangible substance or material existence that is perceptible to the senses" [Webster's, 1988]. However, at a high-level of *what-how* mapping, the *how* is rather metaphysical (e.g. strategic solutions). At lower levels of solution definition, these metaphysical solutions become more tangibly defined and designed (e.g. tactical actions).

- **Mapping:** A mapping is defined as direct and structured connections between the four domains. In an ideal systems engineering approach, the mappings are characterized by three features:

  - An ***explicitly defined, coherent*** mapping between the elements.
  - A ***mutual dependency*** amongst each of the elements. Each domain is separately defined and necessary, but none are sufficient by themselves.
  - A ***path dependency*** from the most abstract domain of thinking, down to the most tangible domain of the physical.

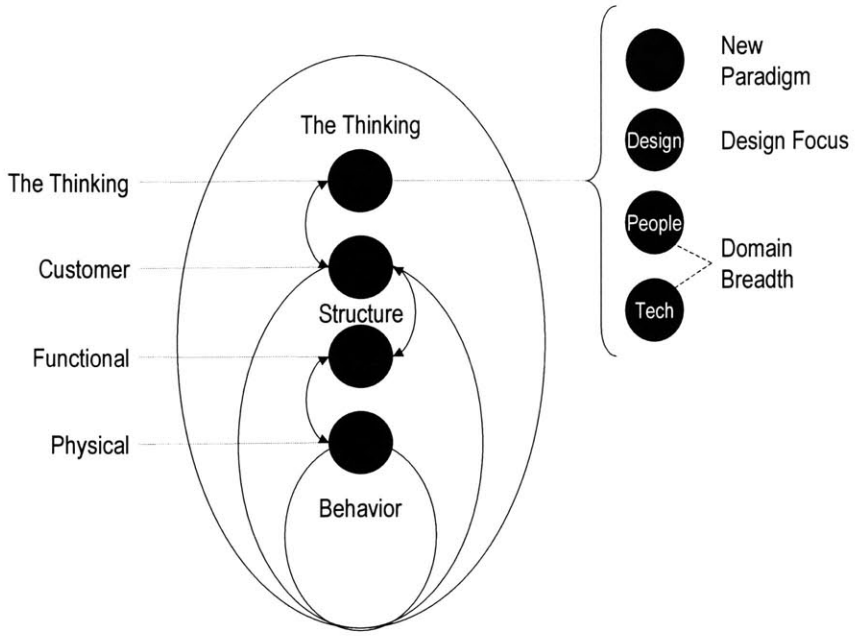


Figure 2-5. The ideal systems engineering model

The model shown in Figure 2-5 reflects a condensation of the attributes described above into three patterns of relationship. The model shown in Figure 2-6 captures the principles of the ideal system engineering approach and distills the significance into three primary patterns of relationships know as 1) the thinking, 2) the structure, and 3) behaviors.

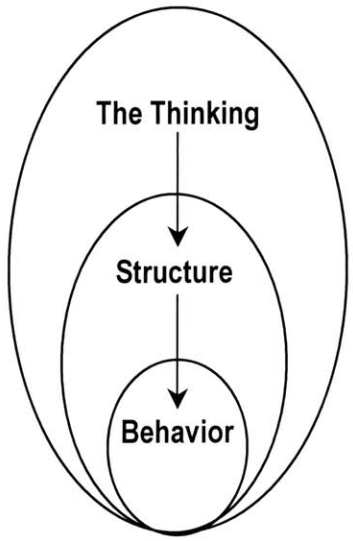


Figure 2-6. The Patterns of Relationship in an Ideal System [Cochran, Won, 2002]

2.4 Review of Five General Design Approaches

2.4.1 Introduction

The subsequent section starts with a review of five distinct, yet related, approaches to structural system design and their relationship to the ideal systems engineering model. Each approach draws upon a number of characteristics of system design, and the approaches have many structural similarities (e.g. hierarchical, matrix representation, or diagraph form). However, each approach's effectiveness in system design, and ultimately its effectiveness in an ideal systems engineering application, becomes apparent when one looks at the thinking behind the development of the approach.

2.4.2 Axiomatic Design

Developed by Suh in the 1970s, Axiomatic Design is a 'green field' (i.e. synthesis-focused) approach to designing systems. The approach defines design as the synthesis of solutions through a mapping process between four domains—customer, functional, physical, and process. Core to the development of the approach is the rejection of a major assumption in the design field—that only subjects dealing with nature (e.g. thermodynamics, geometry, physics) are subject to axiomatization [Suh, 1990].

Fundamental to Axiomatic Design is the notion of design axioms. Axioms are defined as general principles or self-evident truths that cannot be derived but for which there are no counter-examples or exceptions. The use of axioms has played a fundamental role in the advancement of many fields of science and technology. Examples of the use of axioms include Euclidean geometry, thermodynamics, Newtonian physics, and then Einstein's theory of relativity[1] [Suh, 1990]. These fields have transitioned from experience-based practices to the use of scientific theories and methodologies that are based on axioms. The axiomatic design axioms were created by identifying common elements present in all good designs [Suh, 1995].

The Concept of Domains

Design may be described by the continuous interplay between what we want to achieve and how we want to achieve it. Design requirements are always stated in the functional domain, whereas the solutions are always defined in the physical domain. More formally, design may be defined as the creation of synthesized solutions that satisfy perceived needs through the mapping between the requirements in the functional domain and the solutions in the physical domain [Suh, 1990]. The mapping between the functional and physical domain is also referred to as logical mapping. In this instance, logical refers to a mental process.

[1] For an in depth account of use of axioms in other fields, see Suh's (1990) *Principles of Design*. In the book, there is also a historical account of the development of the design axioms.

The success of any system design depends on satisfying the needs of the internal and external customer. System design takes these needs and translates them into system design Functional Requirements (Figure 2-7). System design is about defining the patterns of relationship between Functional Requirements (FRs) and Design Parameters (DPs). This approach requires defining the pattern of thought (i.e. the metaphysical) in the form of Functional Requirements and connecting Design Parameters in advance of the physical design.

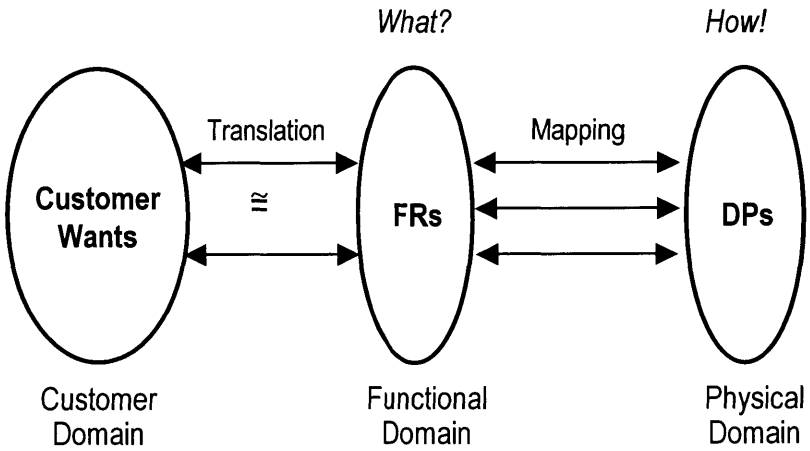


Figure 2-7. System design connects three domains

Functional Requirements and Design Parameters

The fundamental hypothesis of Axiomatic Design is that a logical design's effectiveness can be determined in advance of the physical implementation [Suh, 2000]. The Axiomatic Design methodology thus focuses a designer on first determining the requirements of a design, which are stated in terms of the Functional Requirements of a design. Functional requirements are defined as the minimum set of *independent* requirements, which completely characterize the functional needs of the customer, without redundancy. Functional Requirements are derived to satisfy customer's needs that characterize the customer domain.

FRs are also subject to constraints. Constraints (Cs) are defined as the limiting values, conditions, or bounds a proposed design solution must satisfy. Constraints are different from FRs in that constraints do not have to be independent from other constraints or FRs.

A designer then chooses the Design Parameters to satisfy the stated FRs. Design parameters are the key solutions that logically satisfy the specified set of FRs. The way in which the DPs affect the FRs determines whether the design is predictable, and whether the requirements are indeed independent of each other.

By separating the functional space from the physical space, the design requirements are defined in a solution-neutral environment without any preconceived notion of a physical solution in mind. Axiomatic Design thus guides a designer to solve a particular

Functional Requirement by the selection of a specific means (DP), rather than focusing on just the means themselves. The design process is illustrated in Figure 2-8, where DPs in the physical domain are chosen to satisfy FRs in the functional domain.

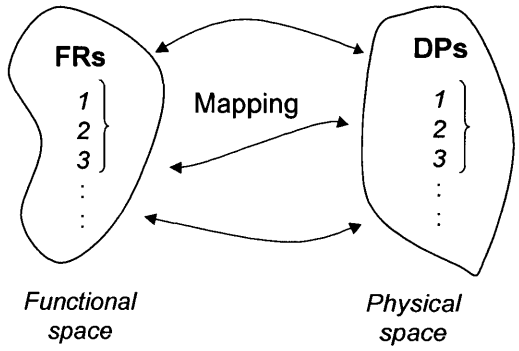


Figure 2-8. Representation of the mapping process [Suh, 2000]

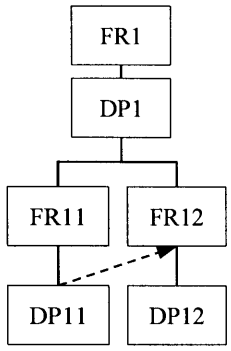
Two Axioms and the Decomposition Process

One element of Axiomatic Design is the process of determining the DPs to satisfy the FRs. Since different logical designs can achieve the same customer needs, Axiomatic Design uses the following two axioms to select the best logical design:

> **Independence Axiom**: Maintain the independence of the FRs through the selection of DPs. The solution set of DPs is chosen to satisfy the FRs so that the FR implementation is independent (i.e. – one-to-one relationship, or uncoupled).
>
> **Information Axiom**: Minimize the information content of the design. Simpler designs are better than complex designs. Among alternatives, the design with the DPs that have the highest probability to meet the FRs, within tolerances, is the best.

The process of decomposition establishes a design hierarchy based upon the selection of DPs to satisfy the FRs at increasingly refined levels of detail. To advance to the next level of detail of decomposition requires the fulfillment of the Independence Axiom. Once a set of DPs has been determined at one level of decomposition, the next step is to decide if further decomposition to another level of FRs and DPs is necessary.

In Axiomatic Design, the relationships between the FRs and DPs are represented in either vector or diagraphical form. In diagraphical form, an off-axis arrow from an FR-DP pair to another FR represents the influence of that DP upon partially satisfying the other FR. The decomposition, or mapping process, is depicted in Figure 2-9 below.



Design Equation

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

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

Figure 2-9. Mapping the FRs to the DPs

In vector form, the design matrix (DM) is defined as the second order tensor that relates the *what* vector to the *how* vector. In the case of product design, the Design Matrix relates FRs to DPs. The relationships between FRs and DPs constitutes [A] matrix—known as the design matrix. In the design matrix an 'X' signifies that a DPj affects FRi. The design equation thus expresses the logical relationship between the FRs and the DPs.

Five Types of Designs

Axiomatic design identifies five main types of designs: uncoupled, path dependent (partially coupled), coupled, incomplete, and redundant. These types of designs can be defined through the logical design equation.

Predictable Designs – Uncoupled and Path Dependent

Of the five types of design types, only two satisfy the Independence Axiom so that a design is predictable—uncoupled and path dependent designs. An uncoupled design results when each FR can be satisfied independently by means of only one DP, resulting in a diagonal matrix (Equation 2-1). This design is the most robust.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ - & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 2-1. Uncoupled design

The second type of design is a path dependent design. This type of design results in a triangular matrix (Equation 2-2) and the independence of FRs can be guaranteed if the DPs are implemented in the proper (path dependent) sequence. The path dependency sequence is based on choosing the DP that affects the most FRs first, followed by the DP that affect the second-most FRs, and so on. The specific implementation sequence results in a physically implementable system design that does not require iteration to achieve the desired FRs. Within Axiomatic Design convention, the implementation sequence is graphically represented by a left-to-right ordering so that the DP that affects the most FRs is on the left.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ X & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 2-2. Path dependent design

Both uncoupled and partially-coupled (decoupled) designs are said to satisfy the requirement of functional independence[2], as stated by the Independence Axiom.

Poor Designs – Coupled, Redundant, and Incomplete

Another form of the design matrix is called a full matrix and results in a coupled design (Equation 2-3). A coupled design violates the Independence Axiom and has a low probability of FR achievement, especially in the presence of DP variation. Such designs often require the designer to repeatedly tweak the DPs in hope of achieving the FRs. Hence, coupled designs create an unnecessary optimization problem [Suh, 2000].

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 2-3. Coupled design

Two other types of less common designs are known as incomplete and redundant designs. Incomplete designs result when there are more FRs than DPs to satisfy them (Equation 2-4). The flaw with this design is that it fundamentally does not meet all the requirements.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ X & - \end{bmatrix} * \begin{Bmatrix} DP_1 \\ - \end{Bmatrix}$$

Equation 2-4. Incomplete design

In contrast, redundant designs typically meet all the requirements but with the use of unnecessary resources (Equation 2-5). This type of design is more costly, and according to the Information Axiom is less reliable than a complete design.

$$\{FR_1\} = \begin{bmatrix} X \\ X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 2-5. Redundant designSummary

The required steps for the Axiomatic Design process can therefore be summarized by Figure 2-10.

[2] Functional independence should not be confused with *physical* integration, which is often desirable as a consequence of Axiom 2. Physical integration without functional coupling is advantageous, since the complexity of the product is reduced.

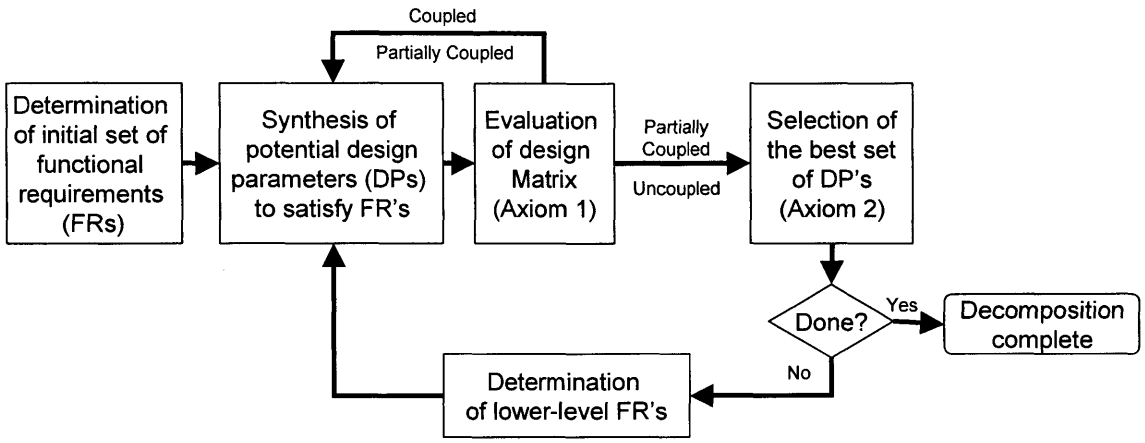


Figure 2-10. Simplified Axiomatic Design decomposition Process [Linck, 2001]

The determination of design solutions is a creative process that requires content knowledge of the subject. Axiomatic Design provides a methodology to structure one's thinking during the design process, and provides a logical approach to defining the functional requirements (FRs) and the means of achievement (DPs).

2.4.3 Quality Function Deployment (QFD) – House of Quality

The focus of Quality Function Deployment is upon capturing the 'voice of the customer' and translating the needs into customer requirements. Fine [1998, p. 189] states that "any product whose development does not capture the voice of the customer begins life with a huge, frequently fatal handicap." Once the customer's true requirements are captured, the approach focuses on providing customers what they want. The approach is intended to focus on the customer, rather than on an organization's impulses to implement a pre-determined science or technology solution. The intention of QFD is similar to a well-known venture capitalist saying that 'products that are designed to fit customers are much more successful than customers who are designed to fit around products.'

The centerpiece tool of QFD is known as the 'house of quality'—a name derived from the diagram which resembles a box with a slanted roof. The general form of the house of quality is shown in Figure 2-11.

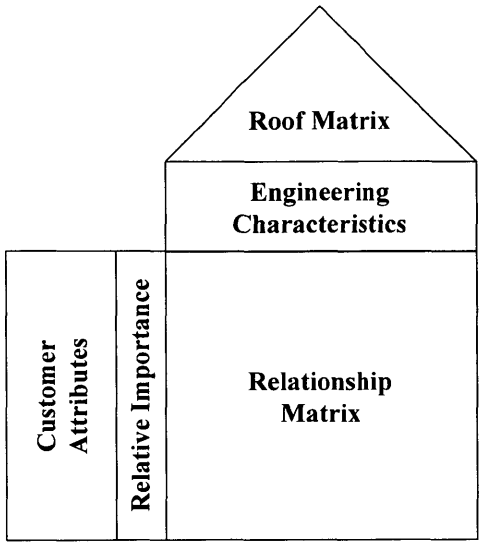


Figure 2-11. House of Quality's five key elements

The house of quality is primarily described by the following five elements [Hauser, Clausing, 1988]:

- **Customer Attributes (CAs):** Customer's needs are called customer attributes, or CAs. CAs are generally stated in the customers' own words and are often grouped into bundles of attributes. For example, 'quietness' might be further described by sub-categories as no wind noise, doesn't rattle, no road noise, etc. CAs typically come from the marketing domain.

- **Relative Importance of CAs:** Weightings, totaling 100%, are given for each CA. The motivation is two-fold. First, customers value certain attributes more than others. This is simply the nature of customers. Secondly, the assumption is that designers will usually have to trade off one benefit against the other. The balancing of attributes will hopefully enable designers to find a creative solution that satisfies all the customers needs, with preference given to those needs which are more heavily weighted.

- **Engineering Characteristics (ECs):** According to Hauser and Clausing [1988], the marketing domain communicates *what* needs to be done, and the engineering domain determines *how* to do it. ECs translate the customers' needs into engineering requirements that describe the product in measurable, or physical, terms (e.g. seal resistance, energy to close door, noise reduction).

- **Relationship Matrix:** The relationship matrix represents the body of the house. The relationship matrix indicates the relationship between ECs and ACs. Typically, these relationships are qualitative and are represented by numbers or symbols according to the strength of the AC-EC relationships.

These relationships may be determined by intuition, judgment, experiments, or even statistics. In a number of cases, an EC may affect more than one CA.

- **Roof Matrix:** Hauser and Clausing submit that engineering is described by creative solutions and a balancing of objectives—the roof matrix is intended to recognize these interactions and facilitate engineering creativity. The house of quality's roof matrix establishes the relationships between ECs themselves. For example, improvement on EC_1 may negatively affect EC_2 but positively affect EC_3. In instances such as these, Hauser and Clausing (1988, p. 7) state that "sometimes one targeted feature impairs so many others that the team decides to leave it alone. The roof matrix facilitates necessary engineering trade-offs."

An example of a partially completed house of quality is shown in Figure 2-12.

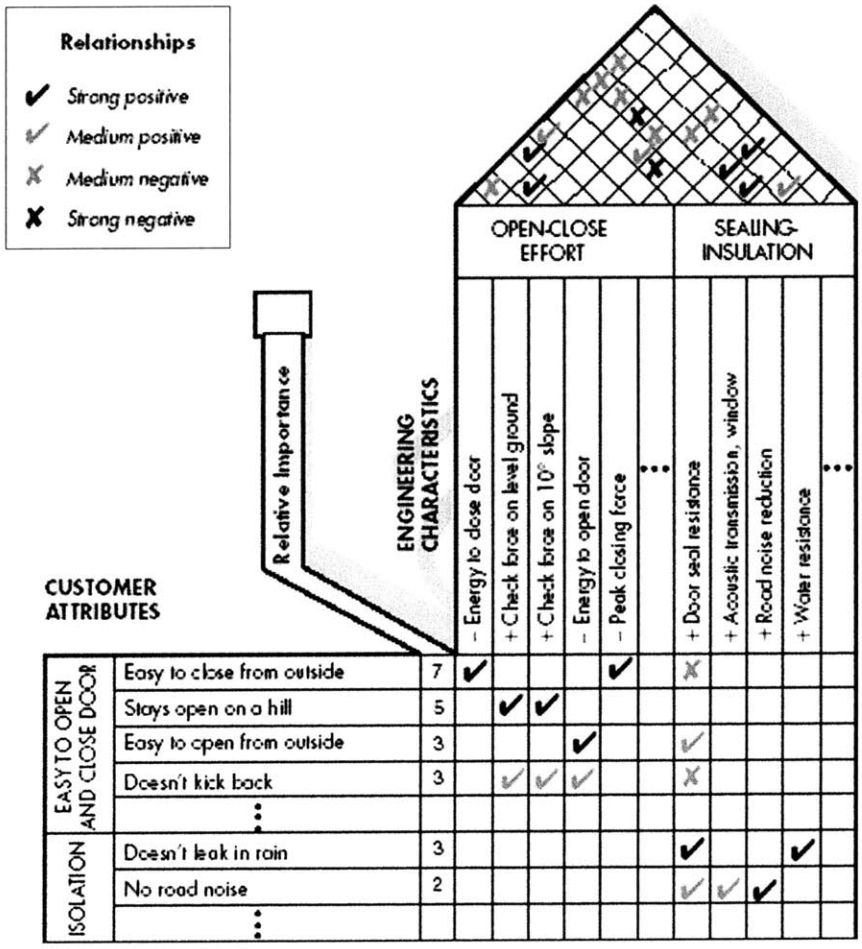


Figure 2-12. House of Quality [Hauser, Clausing, 1988]

The house of quality is intended helps guide designers in driving customer needs into physical requirements. The method structures the design process, and focuses the designer on recognizing inter-dependent relationships, the importance of weightings, and making trade-offs during the design process to arrive at an acceptable solution. According to Hauser and Clausing [1988, p. 11], "the principles underlying the house of

quality apply to any effort to establish clear relations between manufacturing functions and customer satisfaction that are not easy to visualize." Accordingly, the principal benefit is that it gets "people thinking in the right directions and thinking together" [Hauser, Clausing, 1988, p. 13].

2.4.4 Problem-Solving Hierarchy Mapping – Issue Trees and MECE

Issue trees are just one of many tools used in a problem-solving process (Figure 2-13). Issue trees are primarily used in conjunction with idea generating activities, such as brainstorming and literature research. Issue trees focus on the structuring of ideas for analysis and problem-solving, rather than exclusively on the traditional design process.

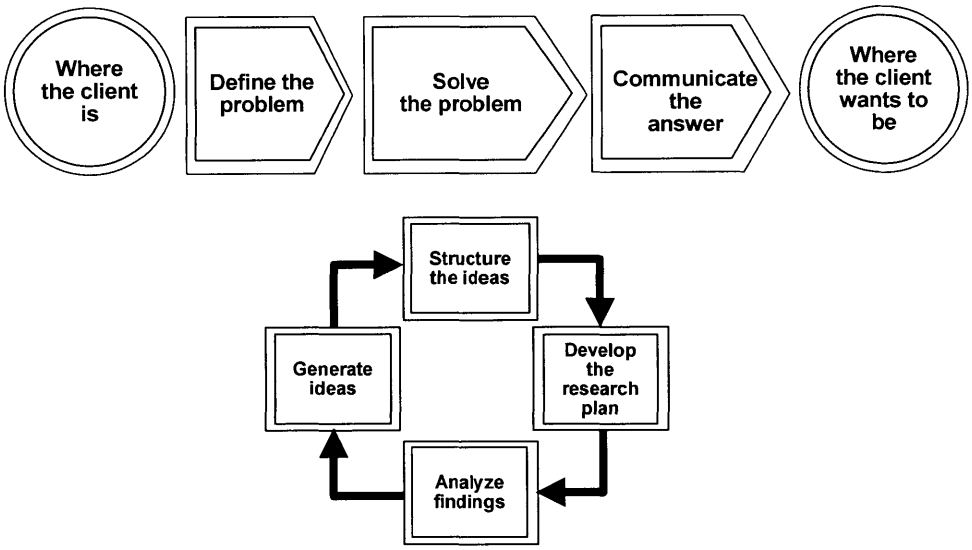


Figure 2-13. Issue-based problem solving [Accenture, 2002]

In general, there are two types of issue trees—those rooted in 1) data, or 2) hypotheses. Data-driven issue trees start with the problem, and breaks it down to generate a solution. The problem/cause decomposition typically makes no assumption about the most likely outcome or most important question to answer. Rather, the data-driven trees are constructed to answer the question of *why*. In contrast, hypothesis-driven trees start with the potential solution and develops a rationale to validate or disprove it. The solution/action approach assumes an answer and creates a structure to test it. The hypothesis-driven method seeks to test the rationale of *how*.

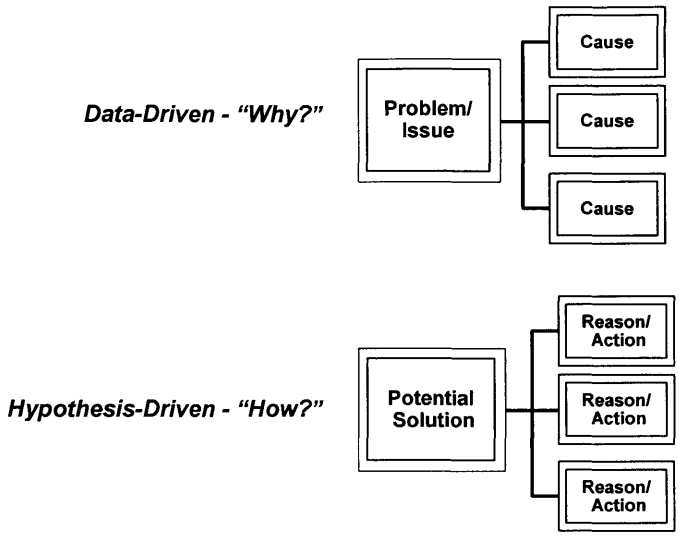


Figure 2-14. Two types of issue-based problem solving approaches [Accenture, 2002]

The key to creating a valid issue tree is to ensure the logical soundness of the decomposition through mutual exclusivity and collective exhaustiveness (MECE). Mutual exclusivity means that the occurrence/existence of events/solutions are independent of each other. Collective exhaustiveness means that the entire set of events/solutions have been defined. The decomposition process involves ensuring the following four elements have been achieved [Accenture, 2002]:

- Logic is complete at every level
- Elements at any level are logically part of the level above
- All possible elements at a level are included at the level below
- Elements in any grouping are the same kind of thing

An illustration of a data-driven tree is show in Figure 2-15. This data tree might be used to perform an analysis of a given problem at hand.

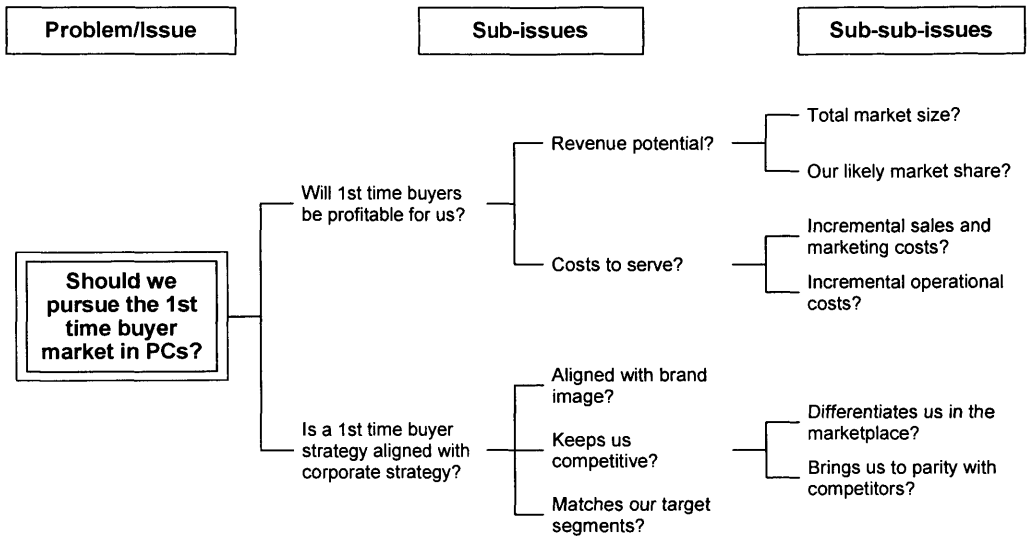


Figure 2-15. Illustration of a data-driven tree for analysis [Accenture, 2002]

From a design perspective, a hypothesis-driven tree looks may look very similar to a Bill-Of-Materials (BOM). Similar to a BOM, the hypothesis-driven tree focuses on defining a high-level *how* and determining lower-level reasons/actions. These decomposition methods disaggregate larger problems/hypotheses into smaller, defined physical chunks. The logic behind this dis-aggregation process is mainly driven by the logic of the MECE test.

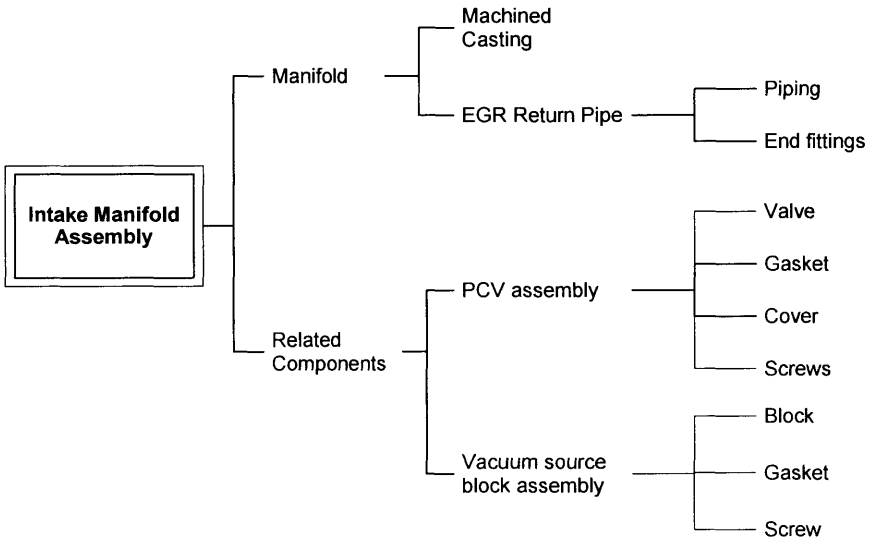


Figure 2-16. Illustration of solution-driven BOM [adapted from Ulrich, Eppinger, 2000]

2.4.5 Design Structure Matrix (DSM)

The Design Structure Matrix (DSM) is described as a tool for systems analysis and project management. The DSM is also known as the Dependency Structure Matrix, the Problem Solving Matrix, and the Design Precedence Matrix. The DSM primary effectiveness is by means of representing and analyzing task interactions, interdependencies, and interfaces between system elements (i.e. sub-systems and modules). The DSM also provides for representation of feedback and cyclic task dependencies—a feature that allows for project representation [Eppinger, 2001].

The use of matrices in system analysis and management can be traced back to Warfield [1973] and Steward [1981]. More recently, the DSM has been applied to industrial project planning and development projects at the task level [Eppinger, 1994]. The DSM method recognizes three types of basic task dependencies: parallel (or concurrent), sequential (or dependent) and coupled (or interdependent). Tasks are represented by boxes and information (data) dependencies are represented by arrows—an information processing view of product development (Figure 2-17).

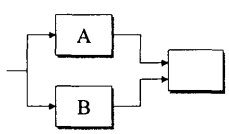
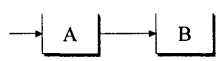
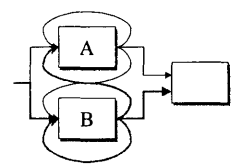
Relationship	Parallel	Sequential	Coupled
Graph Representation			

Figure 2-17. Diagraphs of three basic types of task dependencies [Ulrich, Eppinger, 2000].

Of the three tasks, parallel relationships are not dependent on the output of another task. Rather, parallel tasks are dependent on the same task (i.e. the task beforehand) but are independent of each other. In this instance, understanding the behavior of the individual elements enables complete understanding of the system [Eppinger, 2001]. Thus, no information exchange is required between the two activities. In contrast, sequential tasks are dependent upon the previous task's completion. Thus, one element's influences the behavior of another element in a unidirectional manner. Coupled tasks are mutually dependent, or intertwined. According to Ulrich and Eppinger, coupled tasks "must either be executed simultaneously with continual exchanges or information or must be carried out in an iterative fashion [Ulrich and Eppinger, 2000, p. 324]." This cyclic dependency is referred to as "circuits" or "information cycles" [Eppinger, 2001].

The Design Structure Matrix is a matrix representation of a diagraph that is a binary square matrix with *m* rows and columns, and *n* non-zero elements, where *m* is the number of nodes and *n* is the number of edges in the diagraph [Eppinger, 2001]. The DSM is constituted of two major elements: a row and column of *m* tasks, and a matrix of *m*x*m* dependencies. Project tasks are defined by a row of the matrix. Reading across a row signifies all the tasks whose output is required to perform the task corresponding to the

row. Reading down a column indicates which tasks receive information from the task corresponding to the column. Sequentially dependent, and parallel tasks are represented by a lower-triangular matrix, whereas marks appearing above the matrix diagonal signify coupled tasks (Figure 2-18). Marks below the matrix diagonal represent forward information flow (i.e. feed-forward) to later tasks, whereas, marks above the matrix diagonal represent information fed back (i.e. feedback or coupled) to earlier listed tasks. According to Eppinger [2001], "in the binary matrix representation of a system, the diagonal elements of a matrix do not have any interpretation in describing the system."

Task	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*
A	*A*													
B	*X*	*B*												
C	*X*	*X*	*C*											
D			*X*	*D*										
E	*X*	*X*	*X*		*E*									
F			*X*	*X*	*X*	*F*								
G	*X*	*X*	*X*			*X*	*G*	*X*	*X*					
H	*X*	*X*				*X*	*X*	*H*	*X*					
I							*X*	*X*	*I*					
J					*X*		*X*		*X*	*J*				
K								*X*			*K*			
L							*X*	*X*			*X*	*L*		
M					*X*						*X*		*M*	
N										*X*		*X*	*X*	*N*

Sequential Tasks

Parallel Tasks

Coupled Tasks

Figure 2-18. Example of a design structure matrix [Ulrich, Eppinger, 2000]

The DSM can be used to "optimize information flows" using four methods [Eppinger, 2001]:

- **Sequencing and Partitioning:** These two approaches do not materially affect the task constituents of the organization. Changing the order of tasks can be done by two methods known as sequencing and partitioning. These two methods are meant to create as independent of a matrix as possible (e.g. lower-triangular). The key objective of these methods is to minimize the number of information feedbacks above the diagonal. This is matrix reorganization is done by concurrently sequencing and partitioning the tasks—1) find tasks that can be scheduled early or late, and 2) then group the remaining tasks into (coupled) blocks that bring the X's as close to the diagonal as possible. The goal of partitioning the matrix is to identify, separate, and then manage coupled tasks.

- **Reduction of Information Exchanges:** Re-sequencing will only create a partially lower-triangular matrix. As such, this method involves a change of the content of some tasks. The concept is to break down coupled tasks into smaller sets by changing task specifications. In many cases, this involves the addition of tasks and people, but will result in a reduction in the number and coupling of information flows. Reduction of information exchange can be accomplished in three ways.

    1. ***Transfer key knowledge between teams***. In these situations, the current tasks can be de-coupled by adding to each team someone with expertise in the other task. The objective can be achieved physically through integrated product teams, or virtually through information technology, such as computer-aided engineering software.

    2. ***Introduce simplifying tasks.*** The goal is to simplify subsequent iterations performed by interdependent teams. The new task requires early agreement about common aspects, or interfaces, to the coupled task. For example, separate design teams can agree on common physical interfaces for the location of attachment points.

    3. ***Redefine tasks within coupled groups.*** Iterations between different design groups can be reduced by adding extra tasks that further breakdown and isolate coupled iterations. For example, rather than have three separate design groups work concurrently on a project, a new step may be added which defines that the first two design groups complete and test their design. The results of the test can be used to provide information to the third design group. This type of task refinement requires a trade-off between speed and quality.

- **Management of Unplannable Rework:** The previous three methods assumed that iterations could be planned in an orderly fashion. In some instances, tasks that are completed late in the design process could provide information for tasks completed much earlier in the design process. However, feeding this information back into the development process would mean restarting the entire development process. These mistakes tend to arise because of some fundamental mistake in assumptions made at the beginning of the project [Eppinger, 2001].

  Rather than restart the entire process, these tasks can instead be considered as 'generational learning' feedback, where information can be used in the design and development of subsequent products. Intel's 60-step semiconductor chip development process is one example of generational learning. For example, Intel's product demonstration (Task 48) could reveal that the sales estimates on pricing and volume (Tasks 2 and 3) may have been off the mark.

The DSM method focuses primarily on mapping the interdependencies of physical tasks and information. The approach consists of mapping the current state dependencies, and attempting to form a less coupled matrix by re-sequencing, partitioning, and adding/changing task content. Tasks that still show coupling are managed as generational learning.

The DSM method focuses on mapping and analyzing physical dependencies. To some degree, the DSM method has been used for design—namely for the planning of organizations based on product architectures [Eppinger, 1997]. DSM has also been used in large development projects, where hundreds and even thousands of activities are mapped. The usefulness of DSM is in identifying where there is iteration, when activities should be done in parallel or in sequence, and when overlapping activities can be grouped into one tightly coupled, concurrent subproject [Fine, 1998, p.186].

2.4.6 System Dynamics

Developed by Jay Forrester of MIT in the 1950s, system dynamics is a method to enhance the learning of complex systems—also known as systems thinking [Forrester, 1968]. Systems thinking is described as the "the ability to see the world as a complex system, in which we understand that you can't just do one thing and that everything is connected to everything else. With a holistic worldview, it is argued, we would be able to learn faster and more effectively, identify the high leverage points in systems, and avoid policy resistance. A systemic perspective would enable us to make decisions consistent with our long-term best interests and the long-term best interests of the system as a whole" [Sterman, 2001, pp. 9-10]. Senge describes systems thinking as "the art of... seeing through complexity to the underlying structures generating change. Systems thinking does not mean ignoring complexity. Rather it means organizing complexity into a coherent story that illuminates the causes of problems and how they can be remedied in enduring ways" [Segne, 1994, p.128].

System dynamics is grounded on two disciplines—technical systems and human behavior [Sterman, 2001]. Technical system aspects involve theories of non-linear dynamics and feedback control developed in mathematics, physics and engineering. Human behavioral features are integrated from cognitive and social psychology, organization theory, economics and other social sciences. The combination of these two disciplines creates the field of system dynamics—a language of systems thinking to enable learning and action [Isaacs, 2002]. Learning involves recognizing and understanding dynamic system complexity, whereas action focuses on changing the structure through leverage.

The primary tool of system dynamics is known as the causal loop diagram (CLD). The CLD is used to represent the feedback processes and other elements of complexity[3] that determine the behaviors of the system. System dynamics submits that the dynamics of all behavior arise from the interaction of two feed loops:

[3] Sterman [2001, pp. 11-17] provides a summary of four commonly encountered elements of dynamic complexity. These elements are feedback, time delays, stock and flows, and nonlinearity.

- **Positive, or Self-Reinforcing:** Positive loops tend to reinforce or amplify the effect of event on the system. Self-reinforcing loops are characterized by trends toward extremities. Sterman [2001] describes positive feedback loops as *autocataclytic*—the word that chemists uses to describe self-stimulating processes that, once initiated, generate their own growth.

- **Negative, or Self-Correcting:** Negative loops tend to counteract and oppose change. Self-correcting loops are characterized by trends of goal-seeking. These loops describe behaviors that are self-limiting, and create balance or equilibrium of elements.

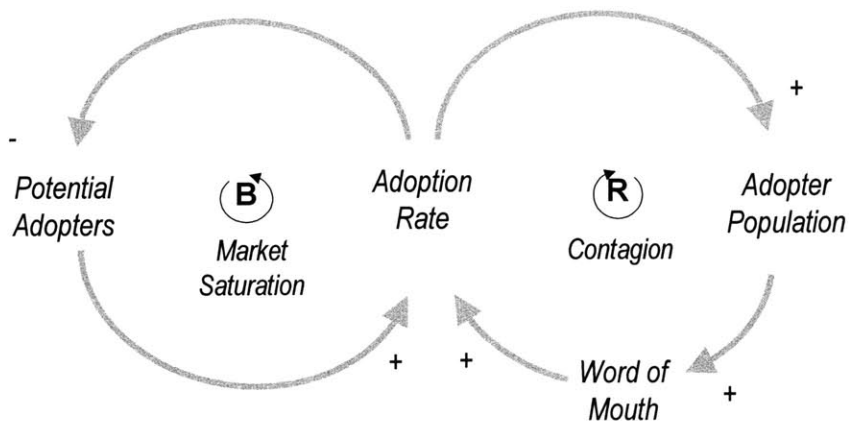


Figure 2-19. Causal loop diagram [Sterman, 2001]

The causal loop diagram of Figure 2-19 illustrates both reinforcing and balancing feedback loops. The intersection of these two behaviors is shown to result in a certain pattern of behavior between exponential and goal-seeking behaviors, as shown in Figure 2-20. The overall dynamics of system depend upon the dominance (both spatially and temporally) of feedback loops [Sterman, 2001].

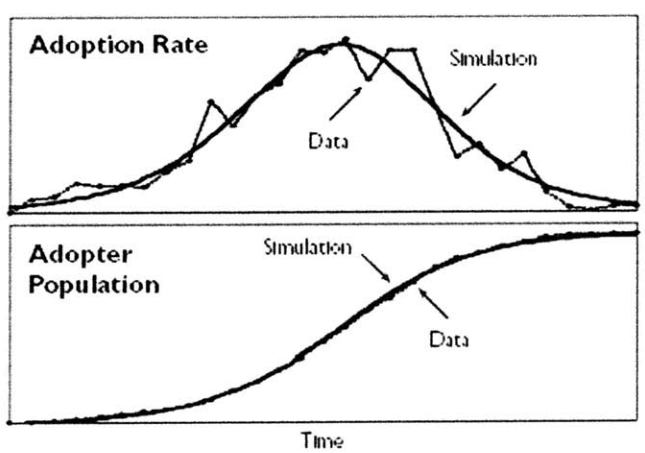


Figure 2-20. The resultant patterns of behavior--predicted and actual [Sterman, 2001]

The core of system dynamics thinking can be distilled in the following four notions:

- **Combinatorial Complexity vs. Dynamic Complexity:** System dynamics distinguishes between two types of complexity—combinatorial and dynamic. Combinatorial complexity arises from the sheer number of elements or events that must be considered in making a decision. Dynamic complexity arises from the interaction of these elements or events over time. Dynamic complexity can arise even in apparently simple system with low combinatorial complexity [Sterman, 2001]. The "Beer Distribution Game" is a well-known illustration of the occurrence of dynamic complexity in an apparently simply physical system[4].

- **Policy Resistance:** For most, people's mental models tend to be "static, narrow, and reductionist" [Sterman, 2001, p.11]. These mental models are used to serve as a lens to view the system and make decisions. Unfortunately, in a dynamic, evolving environment, the result is a mismatch between the view of the system through our cognitive understanding and the reality of the system's dynamics itself. The result is the tendency of the system to negatively respond and defeat the original well-intentioned interventions themselves—this is known as policy resistance [Isaacs, 2002]. In many instances, policy resistance is an unforeseen reaction, or side effect, of the system on well-intentioned efforts to solve the problem itself. Policy resistance describes the system's response to 'fixes that fail', or side effects that add to the problems rather than solve them. The result is a system that is characterized as unstable and oscillatory (Figure 2-21).

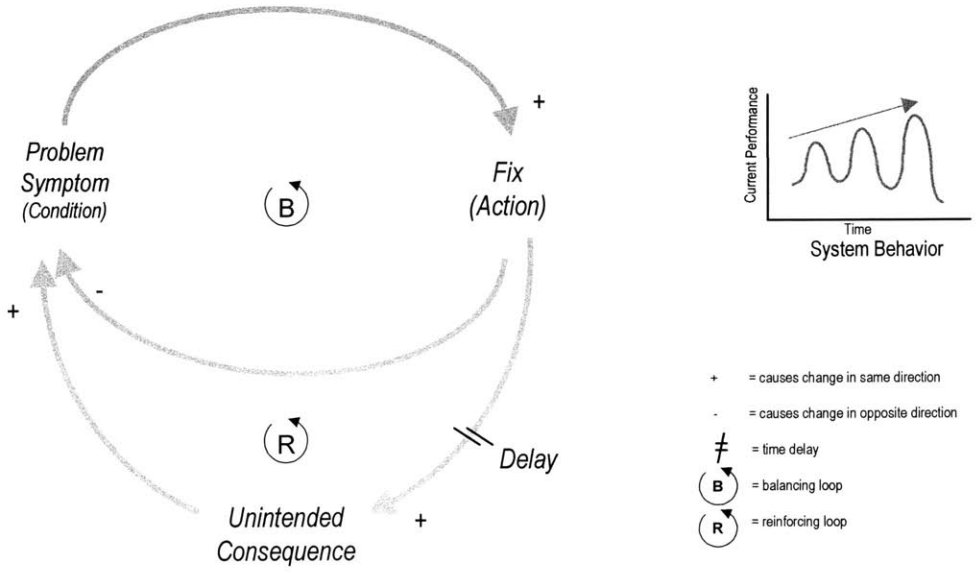


Figure 2-21. System dynamics of "Fixes that Fail"

[4] See Senge's *The Fifth Discipline* for in-depth commentary on the Beer Game.

- **Structure Influences behavior**. Structure is defined as the basic interrelationships that control behavior. These structures are created from both the technical and human behavioral disciplines. According to Senge [1994], different people in the same structure tend to produce qualitatively similar results. Sterman [2001] describes this "structure drives behavior" relationship as the fundamental principle of system dynamics.

  In instances such as that illustrated in Figure 2-21, people are caught in a structural trap[5]. In order to disengage from the trap, one must recognize that there is a structural trap, you are *in* it, and you *are* it [Isaacs, 2002].

- **Change through Leverage:** The recognition of the structure-behavior relationship is not enough to change the system. One must also "change the thinking that produced the problem in the first place [Senge, 1994, p95]. The thinking is that if structure produces behavior, one must change the underlying structures in order to produce different patterns of behavior. This notion is core to the thinking that directs change actions towards directing our attention to the high leverage point for change, and then redesigning the underlying structure using these leverage points [Sterman, 2001]. The bottom line of systems thinking is leverage—"seeing where actions and changes in structures can lead to significant and ensuring improvements" [Senge, 1994, p114].

System dynamics and causal loop diagrams are found to be an extremely powerful approach to dealing with systems that involve both technical and human behavioral aspects. The causal loop diagrams shown above represent only a few types of feedback loops to describe a simple system. However, complex systems can easily contain multiple orders of magnitude in complexity—both combinatorial and dynamic—that are intermingled in a web of coupled relationships, time delays, and feedback. When multiple loops interact, intuition typically fails and computer simulations become the tool of choice.

2.5 Analysis of Five General Design Approaches

2.5.1 A General Model to Analyze the Underlying Thinking

The thesis posed notion of three elements of systems engineering: the thinking, structure and behavior. According to Cochran and Won [2002], the three elements of systems engineering are characterized by:

- A **mapping** between the elements that is explicitly-defined, coherent

[5] "Fixes that Fail" is a structural trap that Senge describes in *The Fifth Discipline*. More generically, structural traps are just one of many system archetypes. According to Senge [1994, p95], the purpose of systems archetypes is "to recondition our perceptions, so as to be more able to see structures at play, and to see the leverage in those structures."

- A **mutual dependency** amongst each of the elements
- A **path dependency** from thinking, to structure, to behavior

The thinking drives the structure created during the system design process. The consequence of the structure is the system behavior. Systems engineering seeks a two goals—an *alignment* of the elements to create a system, and a successful *global* performance of the system (Figure 2-22). In order to achieve the ultimate goal of lasting success, one must fundamentally change the thinking that creates the system. Given the importance of the thinking on the success of the entire system, the following review focuses on an assessment of the thinking, or mental models, that each approach is based upon.

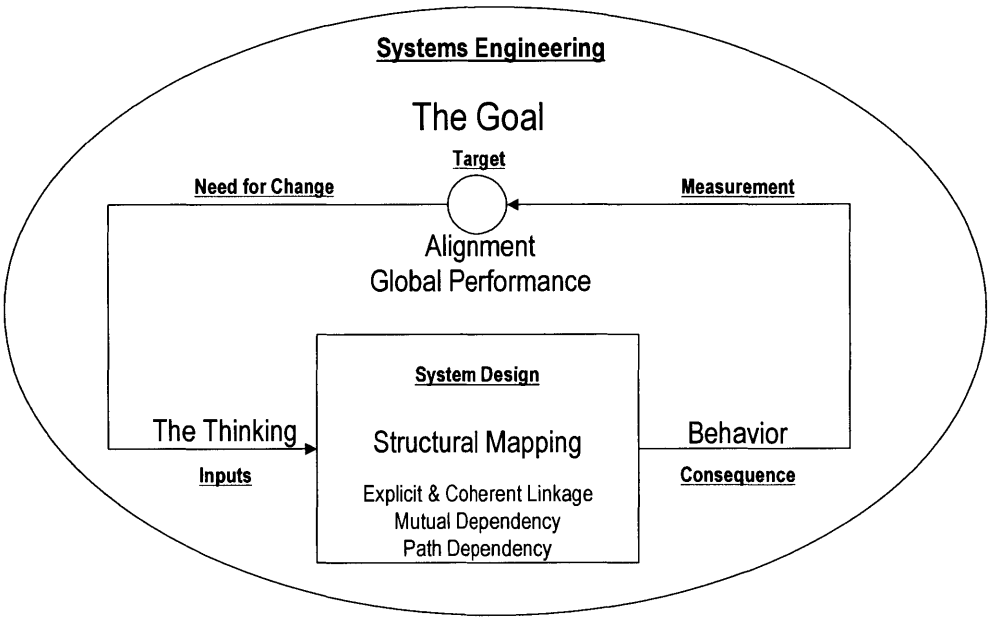


Figure 2-22. General relationships in systems engineering

Rather than take a traditional and oft-used approach of focusing on the structural approaches to design, there is great insight to be gained by understanding the thinking behind each approach. A structural comparison of each approach would be moot without first understanding and comparing each approach's intentions and goals. There are two primary discriminators that succinctly characterize each approaches mental models toward design. These discriminators are:

- **Goal of the Design Approach**. A goal is defined as "the purpose toward which an endeavor is directed" [American Heritage, 2000]. A goal is also defined as "the final purpose… to which a design… aims to reach or attain" [Webster's, 1998]. Intended goals offer insight into the aspirations of each approach and sheds light on how far the design approach will take the designers. Recall the old saying that states that *when we reach for the stars, they'll take us there*. When the optimism meets pragmatism, Burnet [1985] states that "…you may not quite get one, but you won't come up with a handful of mud either."

- **Mental Model of Design**. Paradigms describe the mental models each approach bases the respective design approach upon. These mental models are, in fact, the core thinking behind the design of the design approach itself.

Achievement of the goals set by each individual approach, in and of itself, is a success. However, in the search for an ideal design approach for overall systems engineering, the goal is to find one that explicitly and coherently maps the thinking and structures in order to create behaviors that produce enduring system success.

Mental models upon which the approaches were created upon can best be captured by the direct quotation from the creators of the approach themselves. Included in the following analysis are relevant and insightful thoughts.

2.5.2 Axiomatic Design

Goal: The goals of Axiomatic Design are to establish a science base for design and to improve design activities by providing the designer with 1) a theoretical foundation based on logical and rational thought processes, 2) tools [Suh, 1990]

Description: Axiomatic design is primarily used as a synthesis-evaluation-analysis (i.e. design) tool. Axiomatic design deals with the design of systems from concept to detailed design phases. Axiomatic design was founded as a generic design tool, and it's primary application and focus has been upon technical systems. However, axiomatic design has been applied to systems that include people [Cochran, 1994].

The Thinking: Axiomatic Design is based upon the idea that the design process can be codified into a science-based approach. Axiomatic design intends to use a science-base to make human designers more creative, to reduce random search processes, to minimize the iterative trial-and-error process, to determine the best designs among those proposed, and to endow the computer with creative power through the creation of the science base for the design field [Suh, 1995]. Axiomatic design does not suggest that design is not a creative process. In fact, axiomatic design is about harnessing the inherent creativity in humans and guiding the design process with fundamental design axioms. According to Suh [1995], in order to make a practical impact on industrial competitiveness, products must be designed through an augmentation of the human knowledge, imagination, experience, and hard work with scientific methods and theories.

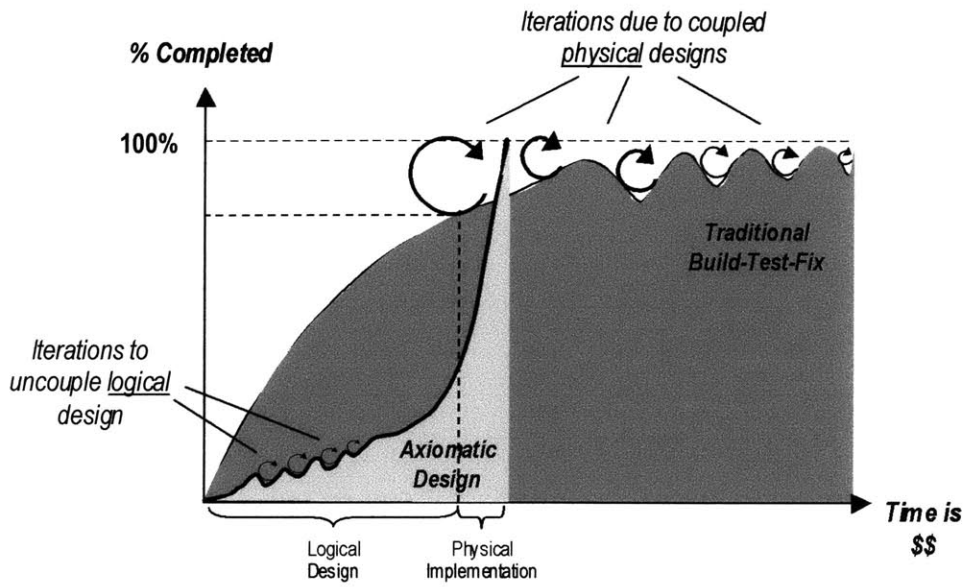


Figure 2-23. Development cycle for Axiomatic Design vs. Build-Test-Fix [Adapted from Suh, 2002]

The Axiomatic Design approach is unmistakably unlike the traditional design approach of build-test-fix (Figure 2-23). By logically defining a design (i.e. mapping between functional and physical domains), the number of *physical* iterations can be reduced to zero. Since logical domains are more metaphysical than physical, design changes can be done quickly and more cost-effectively[6]. The fundamental hypothesis of Axiomatic Design is that a logical design's effectiveness can be determined in advance of the physical implementation [Suh, 2000]—a significant paradigm shift in the design field.

> "Experience is important since design cannot be done without the information and know-how one gains through experience. However, this experiential knowledge is not always reliable, especially when the context of application changes. It cannot be generalized and therefore, can be very limiting in its applicability and in pedagogic value" [Suh, 1995].
>
> "Although human knowledge (i.e. a form of database), imagination (which requires an effective use of the database in the human brain), experience (which results in accumulation of facts, paradigms and data), and hard work will continue to part of the industrial efforts, these must be augmented by scientific methods and theories, because experience is ad hoc and not all experience-based knowledge is correct or applicable in all situations" [Suh, 1995].

[6] Typical "lean engineering" approaches focus on compressing the development time of the traditional build-test-fix mode of operation—a redesign approach. As reflected in Figure 2-23, Axiomatic Design is fundamentally different from the physically-focused approach of "lean engineering." Method improvements on an Axiomatic Design approach will tend to be far superior over method improvements over traditional development approaches, as seen in "lean engineering" approaches.

"Good design decisions are not as random as they appear to be but are a result of systematic reasoning, the essence of which can be captured and generalized to enhance the design process" [Suh, 1995].

"There are two ways to deal with design: axiomatic and algorithmic. The algorithmic approach is founded on the notion that the best way to advance the design field is to understand the design process by following the best design practice. The axiomatic approach to any subject begins with a different premise: that there are generalizable principles that govern the underlying behavior. Axiomatic approach is based on the *abstraction* of the good design decisions and processes" [Suh, 1995]

Current Paradigm

Establish science base for Design
Coupling = A Flawed Design
Uncoupled = Design Goal
Design = Thinking/Customer/Function/Physical
Design = Mapping between Functional and Physical

Figure 2-24. The Thinking behind Axiomatic Design

2.5.3 Quality Function Deployment (QFD) – House of Quality

Goal: QFD is intended design a product based upon a clear link between customer requirements to design solutions, while balancing the internal resources with the external needs. The house of quality is designed to focus people in an organization on the system design itself rather than focus on the functional silos within many organizations.

Description: The House of Quality is typically applied as a synthesis-evaluation-analysis (i.e. design) tool. In addition, QFD deals with structuring of the design development process and not just the detailed design of the system.

The Thinking: The House of Quality is intended to "focus and coordinate skills within an organization, first to design, then to manufacture and market goods that customers want. The foundation of the house of quality is the belief that products should be designed to reflect customers' desires and tastes" [Hauser, Clausing, 1988]. According to Hauser and Clausing [1988], the "principles underlying the house of quality apply to any effort to establish clear relations between manufacturing functions and customer satisfaction when they are not easy to visualize."

The House of Quality is focused upon linking customer needs to the design requirements (i.e. Customer Attributes) and corresponding solutions (Engineering Characteristic). The

fundamental belief is that products should be designed to satisfy all customers' needs at once. However, the House of Quality is also built on the idea that there are necessary tradeoffs designers must balance. The House of Quality is also founded on the idea that engineering characteristics (i.e. design solutions) are likely to affect more than one customer attribute. As such, design comes to involve necessary tradeoffs—balancing between which customer needs to satisfy with certain solutions

The definition of separate domains is an important distinction, as the House of Quality views the process of design only in the physical realm. The House of Quality thus represents systems in terms of customer-functional-physical relationships.

> "Engineering is creative solutions and balancing of objectives. Sometimes creative solutions can be found that satisfies all needs. Usually, however, designers have to trade off one benefit against another" [Hauser, Clausing, 1988].
>
> "The house of quality's distinctive roof matrix helps engineers specify the various engineering features that have to be improved collaterally." "In many ways, the roof (matrix) contains the most critical information for engineers because they use it to balance the trade-offs when addressing customer needs" [Hauser, Clausing, 1988].
>
> "An elegant idea ultimately decays into process, and processes will be confounding as long as human beings are involved. But that is no excuse to hold back. If a technique like the house of quality can help break down functional barriers and encourage teamwork, serious efforts to implement it will be many times rewarded."
>
> "The principle benefit of the house of quality is (that)....it gets people thinking in the right directions and thinking together."

Current Paradigm

Link Requirements to Solutions
Coupling = Necessary Tradeoffs
Design = Balancing Customer Needs and Solutions
Design = Thinking/Customer/ Functional/Physical

Figure 2-25. The Thinking behind the House of Quality

2.5.4 Problem Solving Hierarchy Mapping - Issue Trees and MECE

Goal: Issue trees are used to achieve one primary objective—to solve the customer's problems at hand through a logical structuring of problems to generate a solution.

Description: Issue trees are typically applied as an analysis-synthesis-evaluation (i.e. redesign) tool. The problem-solving approach is focused on a four-stage iterative approach (i.e. develop the research plan, analyze findings, generate ideas, structure the ideas). Core to the problem-solving approach is the structuring of ideas. Structure is intended to clarify and simplify the problem-solving process [Accenture, 2002]. Issue trees serve as tools to design system solutions at the conceptual and preliminary phases. In addition, issue trees have been used to design solutions in both the technical and people domains.

The Thinking: Issue trees are founded upon the notion that finding creative solutions often begins with brainstorming seemingly absurd and obvious ideas. Issue trees are thought to be a method to sort through these ideas by structuring thoughts and analyzing them in more detail [Accenture, 2002]. The belief is that there is no single correct issue tree for a given problem, however one may be more useful than another for constructing and testing hypotheses for solutions.

The fundamental precept of issue trees is the notion of sound logic. Issues trees seek to ensure sound logic through the guiding principles of Mutual Exclusivity and Collective Exhaustiveness (MECE). Mutual exclusivity is intended to ensure that the sub-issues are indeed independent from each other. Collective Exhaustiveness conveys the idea that all sub-issues have been defined. MECE focuses the problem-solving process on defining independent and complete sub-issues at each stage. Issue trees conceptually focus on either problem issues (*why's*) or potential solutions (*how's*), but never both concurrently. Thus issues trees view the design process as *either* in the function realm or in the physical realm, but never both at the same time. Issue trees thus represent systems either in terms of physical states or functional states.

Current Paradigm

Logic structures thoughts into Sound Solutions
Mutual Exclusivity = Independent/Uncoupled
Collectively Exhaustive = Define Complete Design
Design = Functional or Physical

Figure 2-26. The Thinking behind Issue Trees

> "To be logically sound, every grouping must be mutually exclusive and collectively exhaustive (MECE). When reviewing trees, use the MECE test to identify gaps in logic and correct common errors" [Accenture, 2002].

> "Don't go for perfection. Not only is it unnecessary, but the issue tree may be revised several times during the project as more is learned about the problem. During this process hypothesis will be discarded and replaced" [Accenture, 2002].

2.5.5 Design Structure Matrix (DSM)

Goal: The Design Structure Matrix is meant to answer the question of 'what other information does a designer need before a design task can be completed,' in order to determine the balance of speed and innovation that best suits the company's needs.

Description: DSM is primarily used as an analysis-synthesis-evaluation (i.e. re-design) tool. DSM is a tool primarily used to deal with design development processes, or design-in-the large, rather than focusing specifically on detailed design processes. This is different from the other system design approaches the DSM is not specifically intended to deal the actual design of the system. However, the abstract concepts of a development process and detailed system design are not altogether dissimilar—as both deal with the design of a system.

The Thinking: The Design Structure Matrix (DSM) characterizes design as an inherently iterative process with parallels and necessary tradeoffs. The DSM draws parallels between physical iteration (e.g. information exchanges and tasks), and innovation. Thus iteration and innovation are considered to go hand-in-hand. If one considers innovation a good thing, then iteration is also a good thing. Eppinger also classifies a tradeoff between iteration and wasteful redesign.

According to Eppinger [2001], unnecessary iteration (i.e. coupling) must be reduced in an existing system in order to improve the design development speed. Any coupling which could not be reduced by the DSM is managed. The thinking behind the DSM is that if coupling is recognized, then it can be managed. Managed coupling is then argued as beneficial, since managed coupling is analogous to managed innovation.

The DSM treats design development processes as being characterized by the exchange of information. This is an important distinction, as the DSM views the process of design (and it's redesign) only in the physical realm. The DSM thus represents systems in terms of physical-physical relationships.

> "Developing a new product involves trial and error… and such flows of information allow for experimentation and innovation." [Eppinger, 2001].

> "Product development… requires innovation, and innovation requires complex learning (feedback) loops. You repeat prior tasks as you learn from subsequent ones. Interdependent tasks that benefit each other in this way are known as

coupled tasks." "The information from such iteration is precisely what helps you find the improvement" [Eppinger, 2001].

"A coupled process encourages iterations and the search for creative solutions and thus is more likely to produce a significant improvement in the quality of the product being developed. But sometimes speed is more important than innovation. Then a faster, less coupled process is preferable" [Eppinger, 2001].

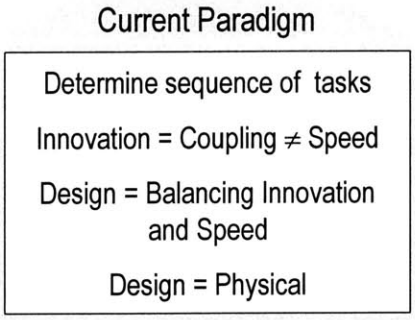


Figure 2-27. The Thinking behind the Design Structure Matrix

2.5.6 System Dynamics

Goal: The goal of system dynamics is to enable an understanding of the interactions between elements (i.e. technical and people) in an entire system. With a systems view, one can learn to recognize patterns of relationships, avoid policy resistance to change, and find high-leverage policies to produce sustainable benefit.

Description: System dynamics is primarily used as an analysis-synthesis-evaluation (i.e. re-design) tool. System dynamics is a tool that is primarily used for strategic policy changes rather than upon the detailed design and implementation. As an analysis-synthesis-evaluation tool, system dynamics does not specifically deal with the design of new systems.

The Thinking: System dynamics is based upon the notion that systems can only be changed if people's perspectives, or mental models, about systems change. There is a fundamental belief that the structure drives behavior of individuals in systems. System dynamics is aligned with the notion that the thinking drives the creation of structures (intentionally or subconsciously), and the structures guide people's behaviors. In order to create enduring and substantial change, system dynamics enables people to recognize the patterns of behavior (i.e. to change people's mental models), and find high-leverage policies that ultimately change people's behaviors.

According to a system dynamics view, dynamic complexity is the primary reason that people's judgment on systems is not intuitively reliable. One of the primary elements of

dynamic complexity in systems is coupling. System dynamics views physical coupling as the result of the systems thinking. In order to change the physical coupling, high-leverage policy changes are made. The idea is that, as a result, systems will naturally drive toward behaviors that are desired, and behave with less complex dynamics.

System dynamics recognizes a connection between the thinking and the physical. System dynamics does not, however, provide a structured and explicit means to fundamentally change the underlying structure (i.e. functional-physical relationship). Policy changes focus more upon the domain of thinking, policy, and strategy.

> "Policy resistance arises because, as wonderful as the human mind is, the complexity of the world dwarfs our understanding. Our mental models are limited, internally inconsistent, and unreliable. We take actions that make sense from our short-term and parochial perspectives, but due to our imperfect appreciation of complexity, these decisions often return to hurt us in the long run." [Sterman, 2001]
>
> Just recognizing the structure underlying a particular problem "...can lead to solving a problem, but it will not change the thinking that produced the problem n the first place" [Senge, 1994].
>
> "Structure means the basic interrelationships that control behavior... Structure produces behavior, and changing underlying structures can produce different patterns of behavior" [Senge, 1994].
>
> "System dynamics... helps us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies" [Sterman, 2001].
>
> "High leverage policies often cause worse-before-better behavior, while low leverage policies often generate transitory improvement before the problem grows worse." [Sterman, 2001]
>
> "The bottom line of systems thinking is leverage—seeing where actions and changes in structures can lead to significant enduring improvements." [Senge, 1994]

Current Paradigm

Patterns of Relationships High-Leverage Policies
Coupling = A Result of The Thinking
Design = Change the Thinking
Design = Thinking/Physical

Figure 2-28. The Thinking behind System Dynamics

2.5.7 Comparative Thinking Amongst the General Design Approaches

Figure 2-29 presents a comparison of the aforementioned structural characteristics of an ideal systems engineering approach alongside the five design approaches (see Section 2.5.1). The comparison communicates two salient messages:

- **Axiomatic Design exhibits a Technical Thinking Focus.** Axiomatic Design possesses a strong focus on each of the four characteristics. However, the link between the thinking and the other three of the domains is not an explicitly strong one. The 'weak' link is indicative of the approach's stronger focus on the 'technical' aspects of the thinking, rather than a balanced focus with the philosophical aspects.

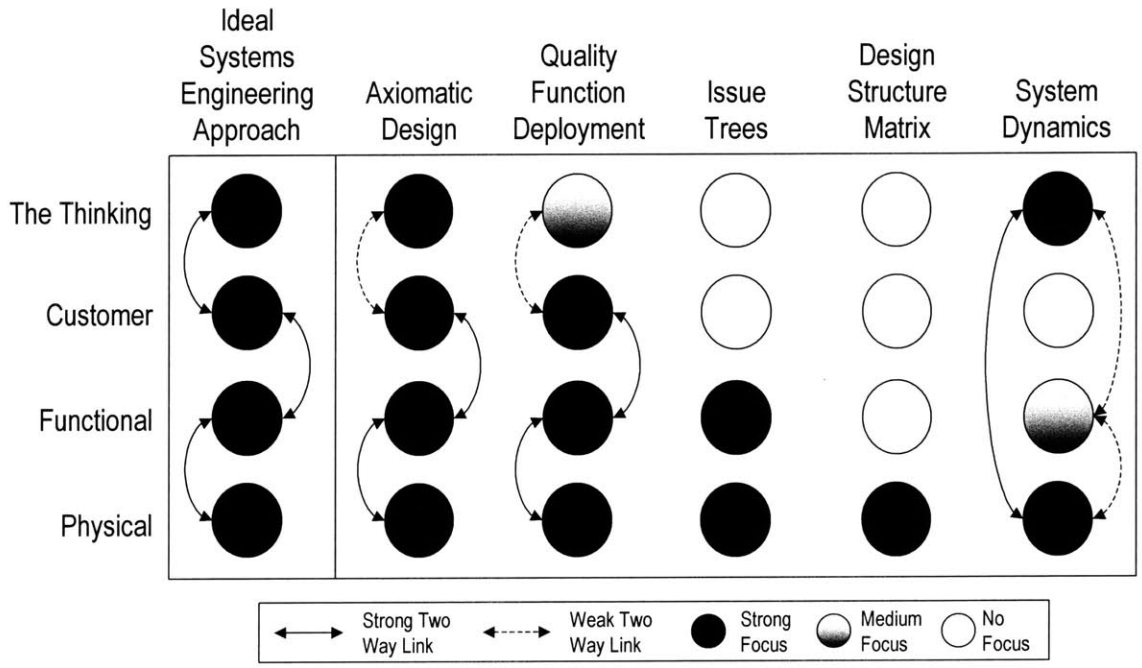


Figure 2-29. Comparison of the structural formation

- **System Dynamics exhibits a Philosophical Thinking Focus.** System dynamics shows a strong, path-dependent link between the thinking and physical. However, the linkage does not explicitly map between the functional and physical domains. Rather, the approach focuses heavily upon changing people's philosophy and paradigms of systems. System dynamics views physical change as the result of a shift in thinking. However the approach itself does not provide technical rigor along the domains of customer, functional, and physical to enable this change.

Figure 2-30 captures the essential differences of each approach's thought formation. These distinctions can be summarized by three key messages:

- **Axiomatic Design and System Dynamics are based on New Paradigms.** Axiomatic design submits that coupled designs are poor. Coupling does not mean innovation, creative balancing necessary for design, or some set of necessary tradeoffs that must be made. A coupled design is a flawed design, by definition. Uncoupled (good) designs can be created based upon fundamental axioms of good design.

  System dynamics proposes that our mental models must change in order to understand dynamic complexity. Coupling is a result of the thinking that created the structure, thus system dynamics focuses on changing people's thinking through high-leverage policy changes.

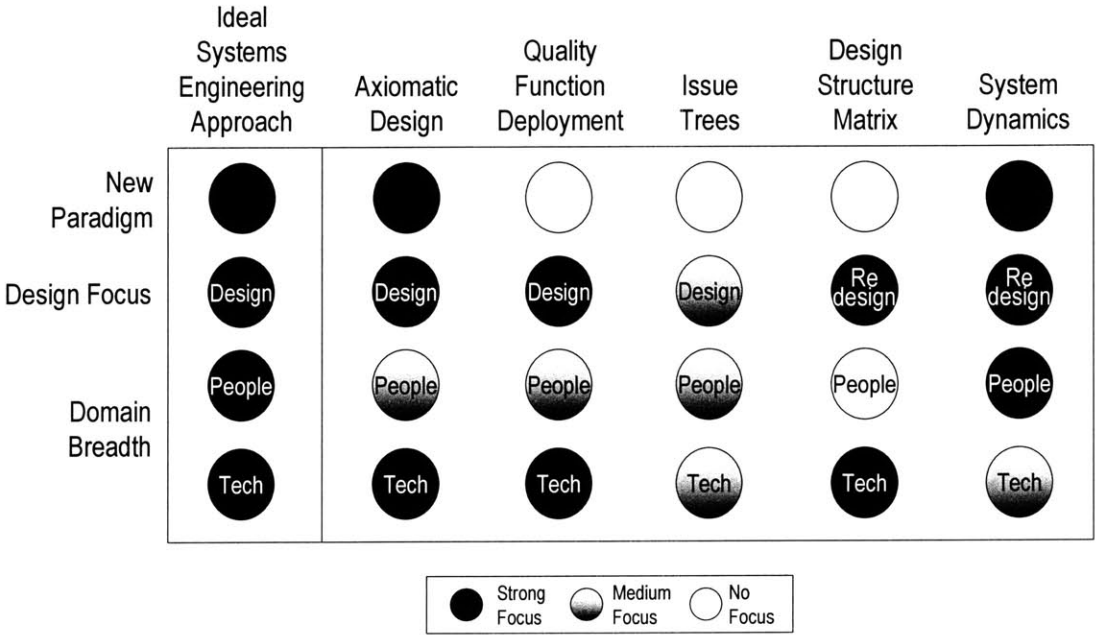


Figure 2-30. Comparison of the thought formation

- **A Pure Design Focus promotes Open Thinking about Design Freedom.** The advantage of a 'clean sheet' is that the logical mapping between customer requirements and solutions can be designed without any preconceptions of existing physical solutions. This open thinking focus promotes a drive to find a wholly uncoupled design solution, rather than upon trying to improve an existing 'brown-field' system.

  Recall the saying that states that *when we reach for the stars, they'll take us there*. Preconceptions of physical solutions (and worse yet, the actual physical solutions in existence) usually prevent the people from designing a system that achieves true 'star' potential. A pure design approach can enable people to think beyond the existing 'barriers' and design truly creative solutions to meet *all* the customer needs with an uncoupled system.

- **No Approach has a Strong Focus on both People and Technical Aspects of Systems.** Since many large systems include both human and technical factors, there is importance in including both these aspects. Three approaches focus strongly on the technical aspects, however only one has a strong focus on the human aspects. This suggests that all five approaches are not complete in their domain breadth.

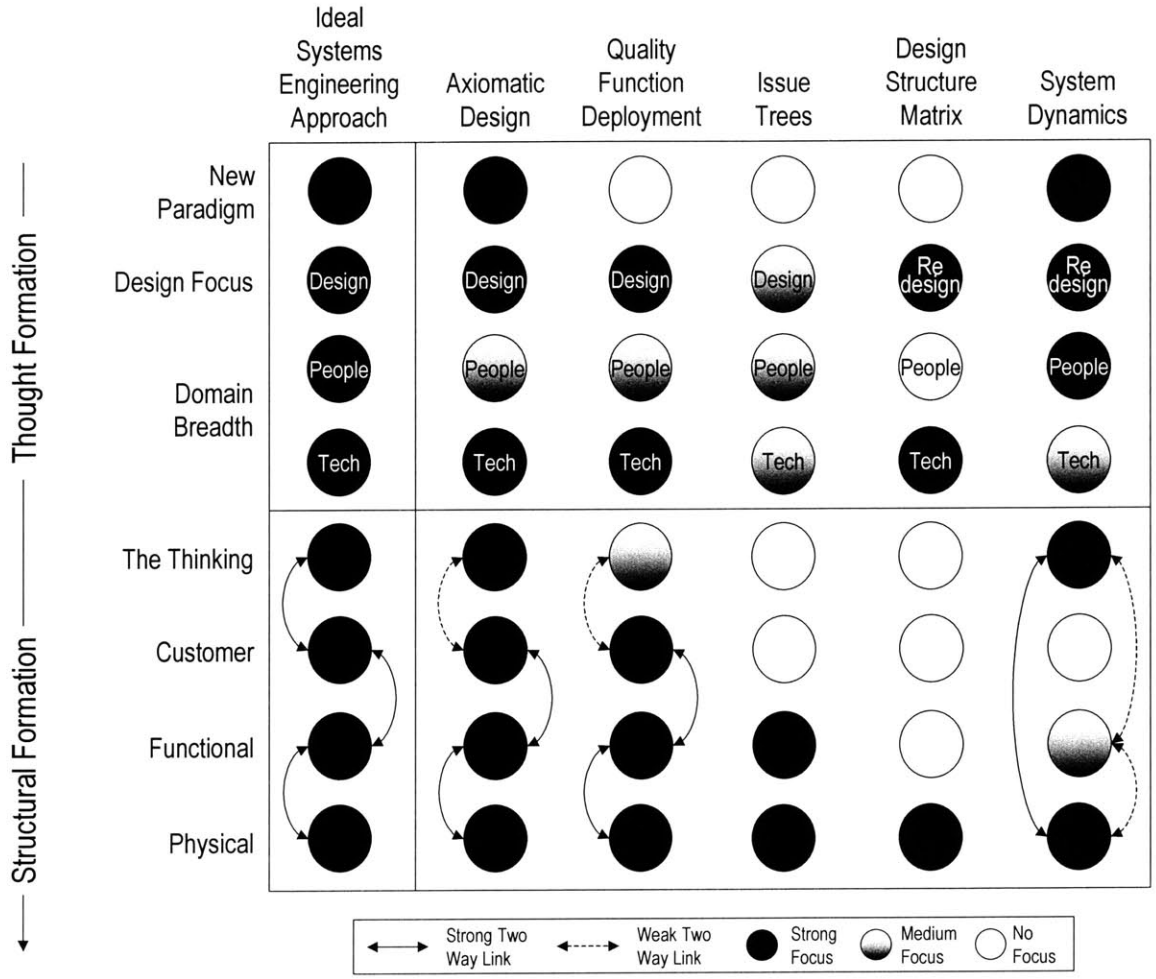


Figure 2-31. Complete comparison of approaches

These findings suggest that the strength of axiomatic design and system dynamics may be combined to cover the range of an ideal approach (Figure 2-31). The key is to start with the fundamental thinking that creates a design approach—the paradigm of design.

2.6 A Paradox Revealed: Axiomatic Design and System Dynamics

The notion of a new paradigm is an important one. Paradigms describe the mental models each approach bases the respective design structure upon. These mental models are not only the core thinking behind the design of the design approach itself, but they also become the way of thinking for the designers themselves. Without a new paradigm

that truly understands uncoupled design, coupling will always seem like a necessary tradeoff. The paradigm of uncoupled design that seeks to meet all customer requirements becomes an apparent paradox to those mired in the 'old paradigm.'

The word paradox is derived from the Latin paradoxum, which translates directly to mean (para) beyond (doxa) opinion. Paradoxes are also described as "seemingly contradictory statements that may nonetheless be true" [American Heritage, 2000]. Paradoxes are also defined as "apparently sound arguments leading to a contradiction" [Howe, 2001]. The notion of self-contradiction arises from the verity that the contradictions themselves are based upon opinions, premises, or internal perspectives on reality—also known as mental models. Paradoxes thus arise when reality does not match with the mental models that serve us. According to Howe [2001], paradoxes "stem from some kind of self-reference." It is this self-reference that serve as the lens with which one views reality.

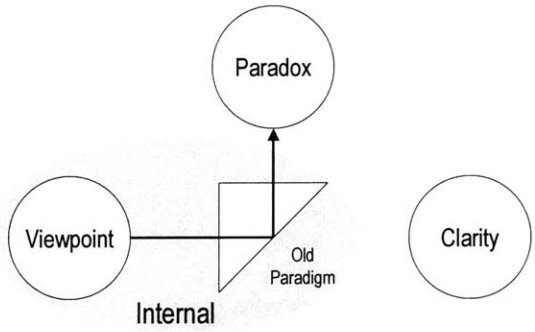


Figure 2-32. Our own mental models create the perception of paradox

Paradigms, a concept first conceived many hundreds of years ago, are described as "sets of assumptions, concepts, values, and practices that constitutes a way of viewing reality for the community that shares them" [American Heritage, 2001]. Since the 1960s, paradigm has been used in science to refer to a theoretical framework, as when Nobel Laureate David Baltimore cited the work of two colleagues that "really established a new paradigm for our understanding of the causation of cancer." Since then, researchers in numerous fields often saw themselves as working in or trying to break out of paradigms [Howe, 2001]. Since reality is true and unchanging, the truth is uncovered only when our own mental models of reality shift—also known as a paradigm shift. These paradigm shifts often result in clarity, or an epiphany as to the true nature of systems (Figure 2-33).

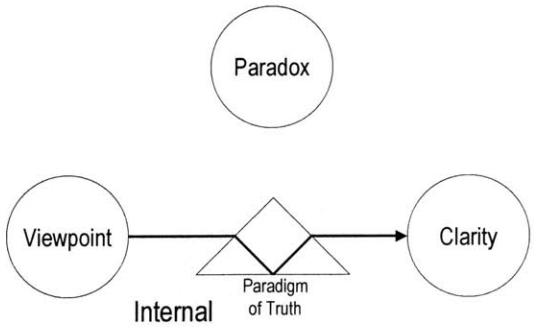


Figure 2-33. Clarity results from the right way of thinking

By providing new paradigms in thinking, the unification of axiomatic design and system dynamics (out of the five approaches) provides a way to understand design and the fallacy of coupling with clarity. As a redesign approach, system dynamics is a powerful tool for converting people's mental models from the 'old' to the 'new.' Once people have a glimpse of clarity, axiomatic design provides the ultimate insight into system design. Only a detailed system design approach, such as axiomatic design, can provide the insights and tools necessary to make the logical connection between all four domains—the thinking, customer, functional, and physical. Both system dynamics and axiomatic design together can provide the thinking necessary to safely cross the 'chasm of paradox' and endow people with a deep consciousness of true systems engineering (Figure 2-34).

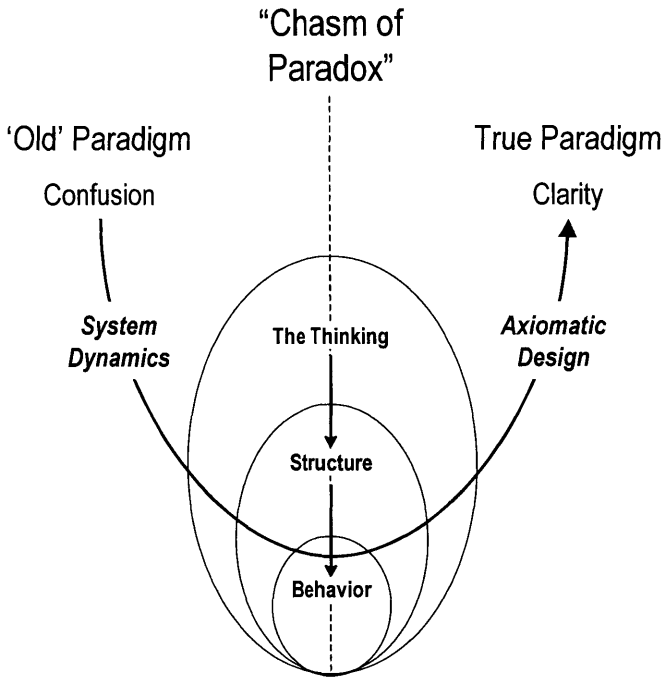


Figure 2-34. Crossing the Chasm of Paradox[7]

[7] The notion of a 'chasm' was inspired by Moore's [1999] book entitled *Crossing the Chasm: Marketing and Selling Hi-Tech Products to Mainstream Customers*. Moore's chasm focuses primarily upon the 'chasm' between *early adopters* and the *early majority* of customers, as reflected in the Technology Adoption Curve.

Chapter 3 Manufacturing System Design Decomposition

3.1 Introduction

Various theories for the design and operation of manufacturing systems have been advanced to rationalize the system design process. Fundamentally, many provide a framework to relate tools for the design and operation of manufacturing systems [Gilgeous, Gilgeous, 1999] [Monden, 1983] [Hopp, Spearman, 1996] [Duda, 2000]. An essential aspect of the Manufacturing System Design Decomposition (MSDD) is the de-emphasis on the tools and methods (i.e. the physical) with a focus upon understanding the relationships between the requirements and the means (i.e. functional and physical). Tools and methods, in the absence of functional understanding, or systems thinking, do not explicitly connect the means to the system's overall requirements. Within manufacturing systems, it is argued that effective management necessitates a framework that systematically balances requirements with the means to achieve them [Hopp, Spearman, 1996]

3.2 Manufacturing Systems

A manufacturing system is a subset of the production or enterprise system [Black, 1991] [Cochran et. al, 2002]. More specifically, a manufacturing system is the arrangement and operation of elements (machines, tools, material, people, and information) to produce a value-added physical, informational or service product whose success and cost is characterized by measurable parameters of the system design [Cochran, 1994] [Chryssolouris, 1992] [Wu, 1992].

There are four types of operations in any manufacturing system: transport, storage, inspection and processing. To 'optimize operations' means to improve one element or operation of the system at a time. Improvement of operations in most cases does not lead to improvement of the system [Deming, 1993] [Shingo, 1989] [Johnson, Broms, 2000]. Improving system performance requires understanding and improving the interactions among the elements within a system.

A primary requirement of any manufacturing system is to sustain the desired results. Aspects of a firm's desired results may be to provide jobs, increase market share, or increase return on investment. A system design defines these relationships, or the work that is necessary to achieve a system's desired results. Results are only achieved by improving the underlying interrelationships within the system that is responsible for the achievement of the desired results.

3.3 Manufacturing System Design

A manufacturing system design covers all aspects of the design *and* operation of a manufacturing system to achieve the desired results. Design includes the physical arrangement of equipment, equipment selection, work loop design (manual and

automatic), standardized work procedures, etc. The result of the design process is the factory as it looks during a shut down. Operation includes all aspects, which are necessary to run the created factory.

A manufacturing system design may also be thought of as an enabler to reduce cost. To reduce true cost in a manufacturing enterprise requires a system design that enables the elimination of true waste. To eliminate waste, a system must be designed to expose waste. Many companies have attempted to target areas within their companies for waste reduction only to find waste reemerging in another part of the business. In general, these wastes are defined as overproduction, conveyance, inventory, waiting, processing, motion and correction [Ohno, 1988]. Reducing waste outside of the context of a system design can be an arbitrary, wasteful activity.

3.4 Manufacturing System Design Decomposition (MSDD)

The primary objective of the Manufacturing System Design Decomposition (MSDD) framework is to provide a structured approach for the design of manufacturing systems through the definition of design requirements and the means of achievement. These requirements are decomposed from a broad or high level to a detailed level of operational activities. The MSDD attempts to satisfy the following requirements of a system's design:

1. To clearly separate requirements from the means of achievements

2. To relate high-level goals and requirements to low-level activities and decisions, thus allowing designers to understand how the selection of manufacturing solutions impacts the achievement of the requirements of the manufacturing system.

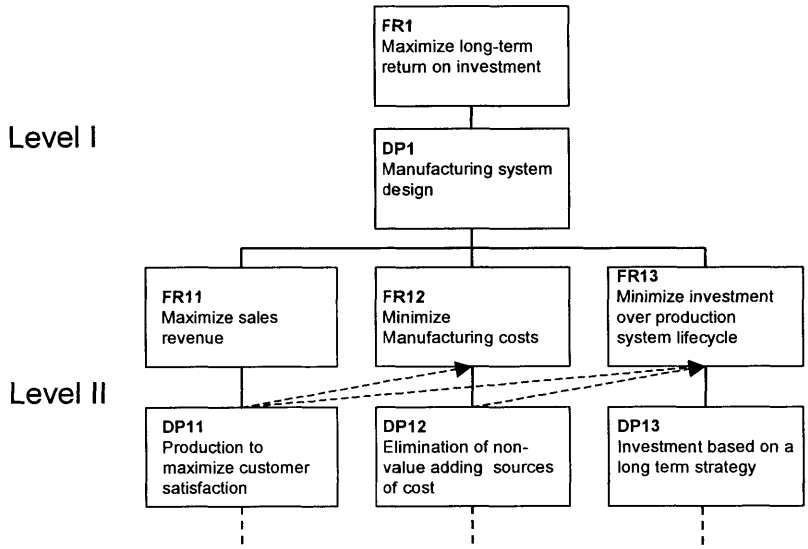
3. To portray and limit the interactions among different elements of a system design.

4. To effectively communicate the decomposition of requirements and means for an organization, so that manufacturing system designers have a roadmap to achieve the "strategic" objectives of an organization [Hayes and Wheelwright, 1984].

In order to satisfy the above requirements, the MSDD was developed using axiomatic design—a methodology that has been developed by Suh to provide a structured approach for the generation and selection of good design solution [Suh 1990].

Based on the axiomatic design methodology, the MSDD currently defines the foremost requirement for any manufacturing system as 'maximization of long-term return on investment.' The DP for this requirement was determined to be the design of the manufacturing system. The DP (i.e manufacturing system design) is requirement is then decomposed into three sub-requirements: maximize sales revenues, minimize production cost, and minimize investment over the manufacturing system's lifecycle. Accordingly, DPs are selected to satisfy the given Functional Requirements and the Independence

Axiom. Figure 3-1 illustrates the first two levels of decomposition as a path-dependent design.



Design Equation

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix}$$

Figure 3-1. First 2 of 6 levels of the MSDD's mapping

Each of these three DPs is then decomposed into FRs and DPs at the next lower level. At this next level, the FRs are organized into six different branches (1-Quality, 2-Identifying and Resolving Problems, 3-Predictable Output, 4-Delay Reduction, 5-Operational Costs and 6-Investment). The decomposition process continues through succeeding levels until activities and decisions reach an operational level of detail. The basic structure of the MSDD is presented in Figure 3-2. A detailed outline of the Manufacturing System Design Decomposition is included in Appendix A.

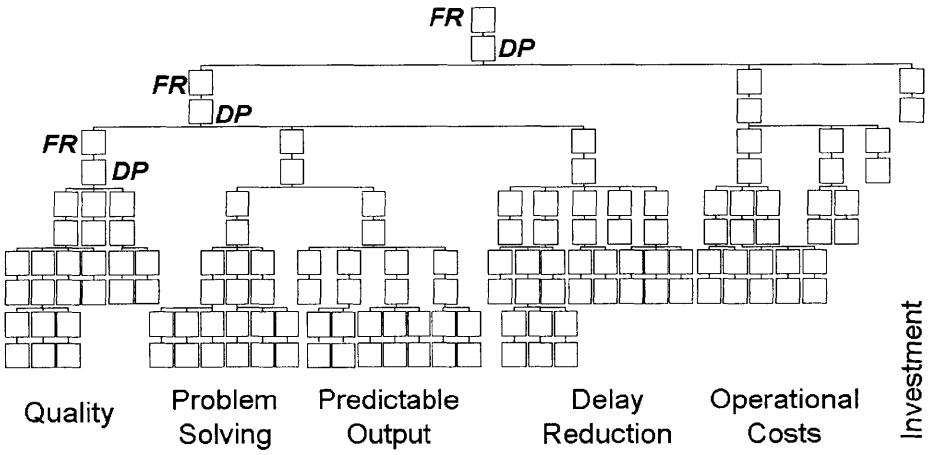


Figure 3-2. The MSDD and its different branches

Six Requirements for System Stability

Underlying the MSDD is the philosophy that management goals cannot be achieved by unstable systems [Deming, 2000]. Waste can only be reduced when a manufacturing system has been designed to be stable. The six Requirements (Rs) of a stable manufacturing systems are defined by Cochran as:

R1. Provide a safe, clean, quiet, bright, and ergonomically sound environment.

R2. Deliver perfect quality products to the customer every shift (time interval).

R3. When a problem occurs in R2, R5, or R6, identify the problem condition immediately and respond in a standardized (pre-defined) way.

R4. Do R2, R5, and R6 in spite of operation variation.

R5. Produce the customer-consumed quantity every shift (time interval).

R6. Produce the customer-consumed mix every shift (time interval).

These attributes for a successful manufacturing system are discussed, in some form or another, in a variety of writings [Cochran et. al., 2002] [Monden, 1998] [Schonberger, 1996] [Spear, 1999]. Achieving these requirements defines a *stable* manufacturing system.

Only when the manufacturing system is stable can waste be permanently reduced. When true waste is reduced, true cost is reduced [Cochran, 1999] [Johnson and Broms, 2000]. Since waste is a *result* of the system that created it, the notion is that the system must be *designed* to produce stable outputs. The basic model for design and implementation for system stability is shown in Figure 3-3—known as the two-sided coin.

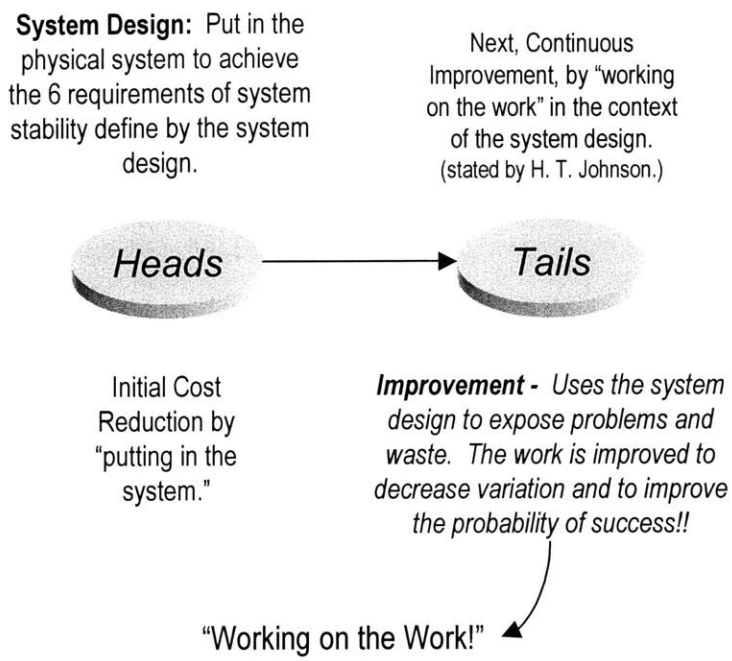


Figure 3-3. Two-sided approach to design and implementation of stable systems

The concept of system stability is further described in Figure 3-4. The figure communicates the idea that systems must be *designed* to produce stable outputs. Deming states that managing systems by the system's outputs—also known as management-by results (MBR)—is just as effective as driving down a winding road (e.g. uncertain future) by looking through the rearview mirror. Rather, Deming suggests that the components of a system interact to achieve some results. Rather than focus on the results, one must identify the system and work on the interactions for the system to function properly [Latzko, Saunders, 1995].

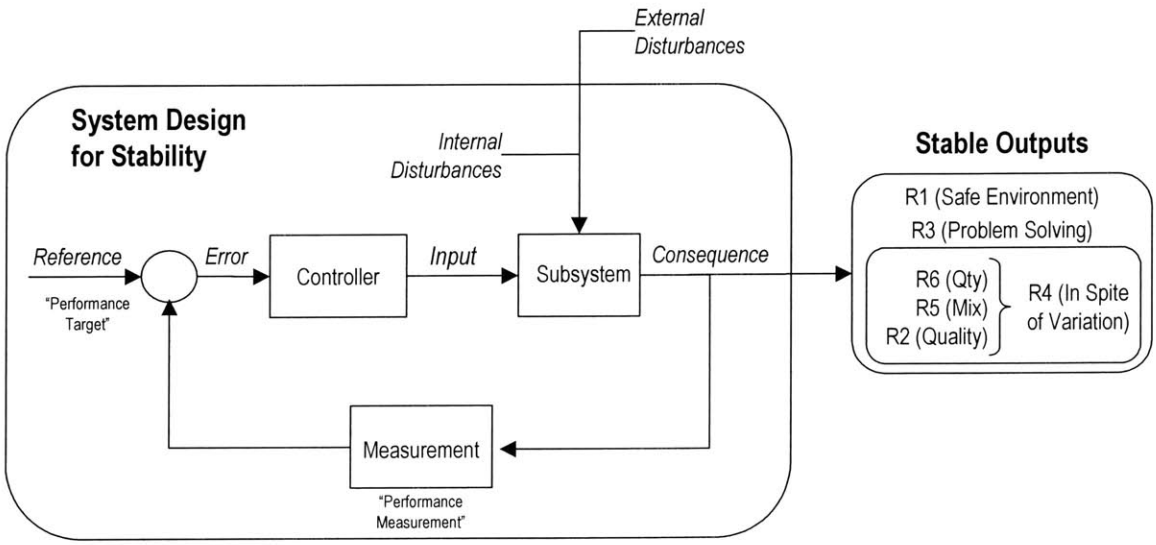


Figure 3-4. Control systems view of System Stability

The objective of the MSDD is to provide a design framework that enumerates the requirements and solutions necessary to achieve a stable and improvable manufacturing system design that is based on a logical, science-based foundation. The MSDD is a logical design of a stable and improvable system that ultimately produces at the right pace, the right mix of products as demanded by the customer, and with perfect quality. Inherent in the creation of the MSDD is the idea that safety is the foundation upon which systems are designed, thus safety is the first Requirement of a system design (Figure 3-5). Minimum cost is the result of the system design. The MSDD is a design of a stable system, whose outputs are stable, and is driven from the high-level needs (e.g. strategic, customer) of the enterprise.

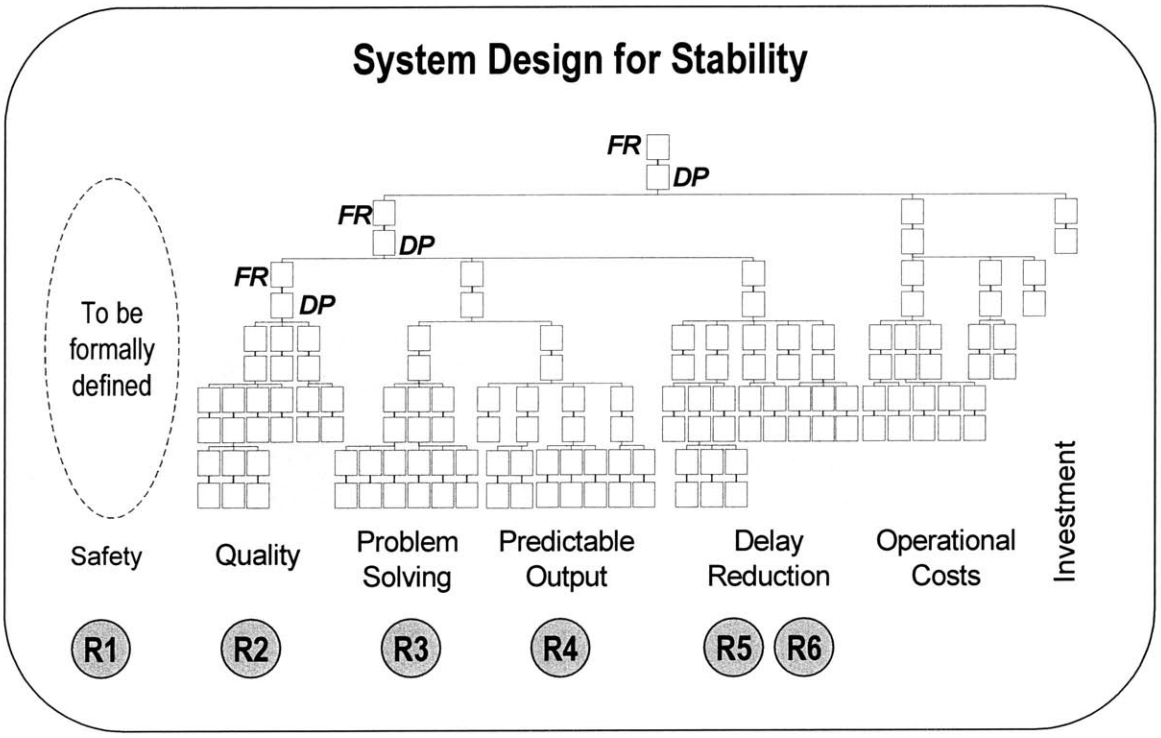


Figure 3-5. The MSDD and the Six Requirements of System Stability

As a path-dependent design, the MSDD states that *stable* manufacturing system design is dependent upon the correct implementation sequence, as reflected by the left-to-right ordering of the MSDD's branches. The significance of the implementation sequence, for example, describes why reducing cost (i.e. Operational Cost branch) without consideration of Quality, Problem Identification & Resolution, Predictable Output, and Delay Reduction will not have sustainable long-term cost reduction impact.

Summary

Inherent in the creation of the MSDD is the concept that all sources of variation can be reduced through system design. These sources of variation not only pertain to

disturbances in equipment processes, but to variations such as in methods (e.g.-problem solving), materials (e.g-purchased parts), and planning (e.g.-part flow logistics).
As a consequence of giving equal importance to the requirements, the solutions, and the logical dependencies between them, the MSDD creates a holistic, systems-view for understanding the design relationships necessary for any manufacturing system.

The MSDD helps structure and communicate manufacturing problems in a way that gives clear reasons (requirements) for the solutions being implemented [Cochran, 1999]. Through the axiomatic design decomposition approach, the MSDD focuses on selecting the appropriate solutions to support the requirements, rather than aimlessly implementing best practices or using rules that are thought to be universally applicable [Won, Cochran, and Johnson, 2001]. Furthermore, the MSDD incorporates sources from industry and literature such as Shewart and Deming's quality framework [Latzko and Saunders, 1995], Shewart's idea of assignable and common cause [Shewart and Deming, 1990], and Gilbreth's ideas on wasted human motion [Gilbreth, 1973]. Leaders in 'lean' system design, such as Toyota, weren't the first to discover any of these ideas, however they were the first to put most of them to use in a systemic way. The MSDD attempts to encompass and codify all these ideas into one coherent framework.

3.5 Production System Design and Deployment Framework

The innovation of the MSDD is its wide application to a variety of repetitive, discrete-part manufacturing systems and its ability to satisfy the Six Requirements of Stability aforementioned. However, the MSDD is still a general framework. It doesn't guide a designer to the complete specification of the physical manufacturing entity. The MSDD helps a designer understand the critical relationships and interactions between requirements (FRs) and solutions (DPs). Thus, the MSDD may be used as a design decision support tool, which may be used with other physical design methods.

With these basic attributes of the MSDD in mind, unique tools to provide a larger framework for system design are under development. Known as the Production System Design and Deployment (PSDD) Framework [Cochran, 1999], a few of these tools include:

MSDD Questionnaire and Evaluation Tool: Using the MSDD, this tool evaluates how well a design can achieve the overall objectives set for a system. Moreover, it identifies, in a given system, where problems are and how to resolve them. It allows measuring the quality of a given design by identifying areas where objectives are (or can not be) met. This tool is further described in Section 3.6.

Deployment Steps for Implementation: Using the MSDD as a step in the design of the new system, this tool provides users the steps to follow in a manufacturing system design process.

Manufacturing System Design Flowchart: Shows the precedence of design parameters (DP's) in implementing a system design.

Equipment Evaluation Tool: Using the MSDD, this evaluation tool evaluates if existing material/capital equipment allows the system to achieve its requirements and provides useful guidelines when considering the acquisition of new equipment.

3.6 The MSDD Questionnaire and Evaluation Tool

Known as the MSDD Evaluation Tool, or the 'Questionnaire,' the tool is a questionnaire with associated questions for each leaf-FR-DP pair [Linck, 2001]. The purpose of the MSDD Evaluation Tool is three-fold:

- Have a standard way to evaluate a manufacturing system relative to the MSDD
- Point out system design weaknesses and opportunities for improvement
- Establish the criteria for a good production system design

The Questionnaire contains specific questions about the FR-DP pairs stated in the MSDD. The questions use a five-point Likert scale (also known as summated scales). Each scale measures a specific content i.e. the content of a particular FR-DP pair. Questions are answered with one of the following choices: (1) strongly disagree, (2) disagree, (3) neither agree nor disagree, (4) agree, (5) strongly agree, and (0) not applicable. The answers for each FR-DP pair are averaged (omitting zero scores) in order to determine the achievement of each FR (Figure 3-6).

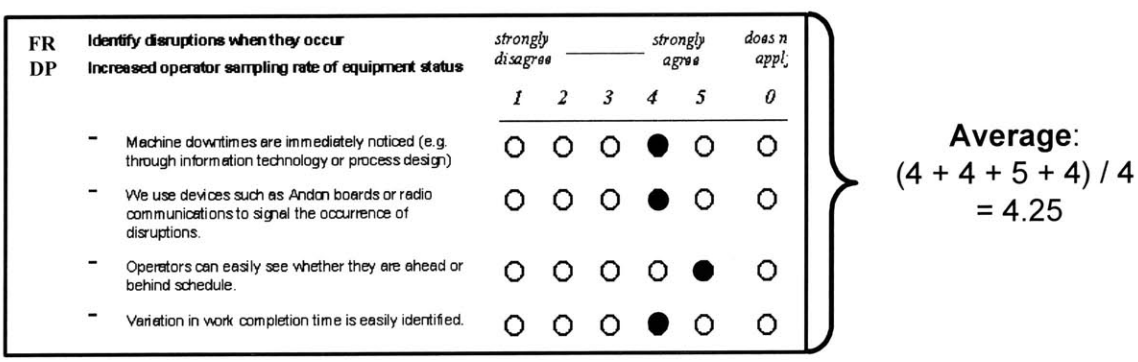


Figure 3-6. Illustration of score calculation

The questions evaluate how well an FR-DP pair has been satisfied. The answers on the scale of 1 to 5 are translated into a measure of "goodness" of the system design. A "good" system design would be one that satisfies the FR-DP pairs as stated in the MSDD. In general, "strongly agree" means that the system design satisfies the FR-DP pair very well and vice versa for reverse scales. The measure of "goodness" is defined by a performance scale as shown in Figure 3-7.

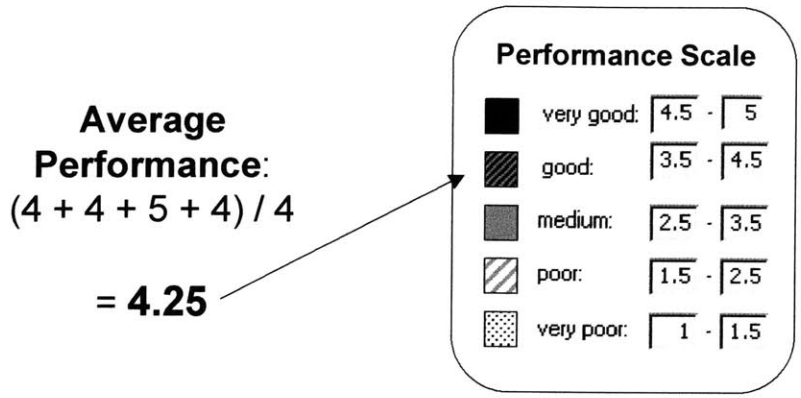


Figure 3-7. Translation of average into a measure of "goodness"

A graphical illustration of a sample questionnaire's results is shown in Figure 3-8. A more detailed analysis and categorization is necessary to interpret the findings and derive improvement suggestions.

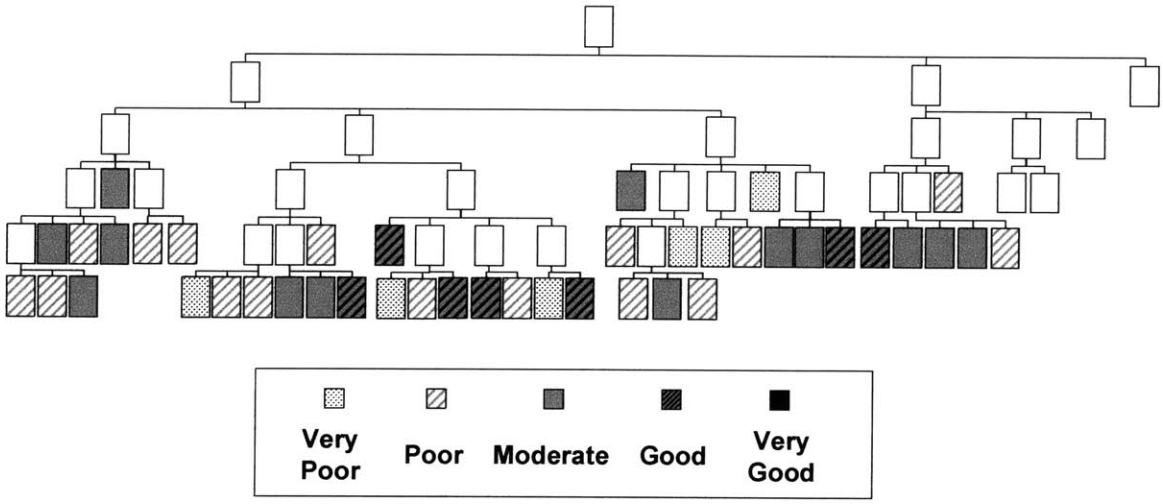


Figure 3-8. Illustration of a completed MSDD evaluation

A complete detailed development of the Evaluation Tool can be found in Chapter 5 of Linck [2001].

Chapter 4 Axle Production Case Study

4.1 Introduction

The following chapter focuses upon fulfilling the following three objectives:

- Provide detailed illustrations of the general systems engineering model proposed in Section 2.3.
- Illustrate a practical application of the 'chasm of paradox' model proposed in Section 2.6.
- Apply the MSDD to baseline, evaluate and draw insights into actual manufacturing systems (see Section 3.6).

Three case studies are presented herein to achieve these goals. As shown in Figure 4-1, the case studies focus on rationalizing that an axle production unit of Company A is still entrenched in an 'old' paradigm—thinking that applying 'lean' tools (i.e. physical structure) can achieve system success.

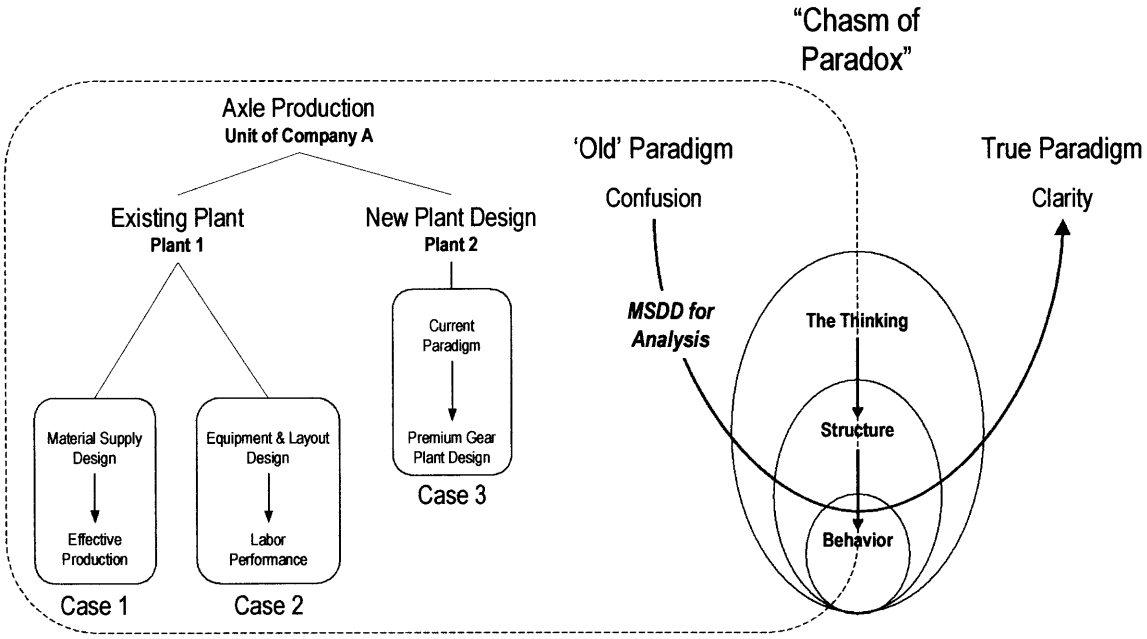


Figure 4-1. Application of the 'Chasm of Paradox' model in axle production

The first two cases focus upon the connection between the structural design and the resultant behavior of the system. The third case study provides support to the supposition that Company A is still very much entrenched in their traditional paradigm—one that has not produced the desired results. Even though there has been movement towards changing the thinking, the focus has been very strongly upon the physical structures and behaviors.

Rather than incorporate a collection of background information on these facilities, the three cases featured herein attempt to distill the core connections as they relate to the objectives set forth above. Further detailed narratives on these facilities are discussed by Tapia [2001] and Low [2001].

4.2 Case 1: Relationship of Material Supply Design to Effective Production

Material supply supports the manufacturing system by interacting with the three major elements of any manufacturing system design: people, equipment/material, and information. In addition, material supply interacts with manufacturing systems on two levels: externally and internally. The first layer, *external*, describes the exchanges that result in material transfer from external suppliers into initial contact with the requesting source. The second layer, *internal*, focuses upon the interactions that result in the completion of material delivery to the requesting source. Within the framework of the MSDD, effective material replenishment strategies are characterized by designs that successfully integrate all five elements into a stable manufacturing system design. The notion is that a stable system design establishes successful behaviors and results of the system. In this case, the clarity of structural improvements have shown positively upon the behaviors and consequences of the system design.

The objective of this case example is to highlight the dependencies of production effectiveness (i.e. the behavior) on material supply design and operation (i.e. the structure). As such, twenty-three FRs within the MSDD have been identified to material replenishment functions (Figure 4-2). For this case example, six FRs and their DPs have been selected to highlight these dependencies as reflected in the MSDD.

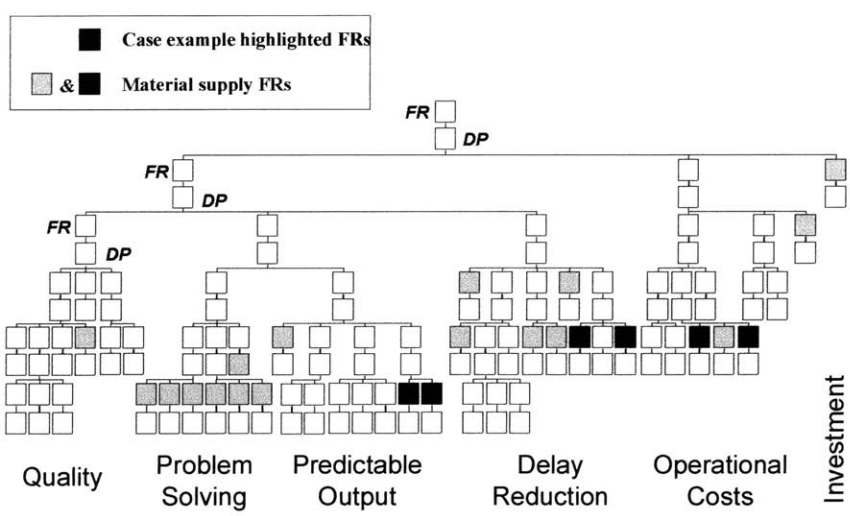


Figure 4-2. FRs that affect Material Supply Design and Operation

4.2.1 The 9.75 Case/Carrier Assembly Line – Department 91

Many aspects of Department 91 typify material replenishment practices throughout much of Plant 1. For example, internally produced components are transported in standard size containers (or dunnages) via tram transports (i.e. – stringers) or forklifts. Depending on size, hundreds to thousands of parts may be transported in these containers. In similar fashion, purchased parts are transported in large quantities on forklifted pallets. Inventory is typically stored in holding areas within the area but outside the primary processing area. Figure 4-3 illustrates the external location of material within the assembly department.

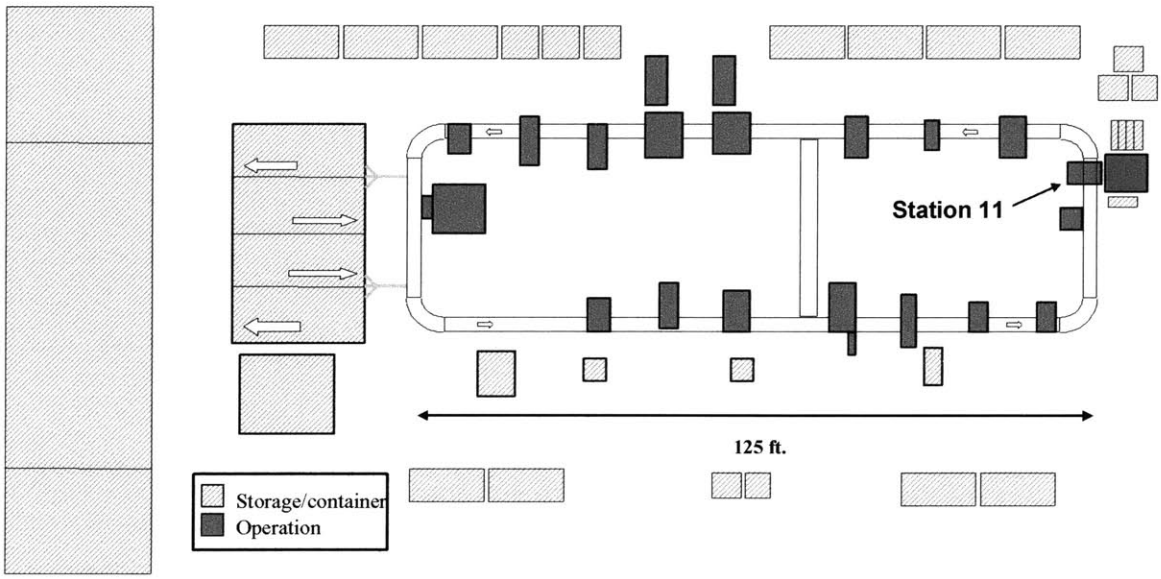


Figure 4-3. Illustration of external material location in Department 91

From an external viewpoint, material delivery between departments is based upon MRP[8] scheduling practices. To meet production numbers, in many cases, production is based upon component availability rather than planned schedules. Thus, incoming receipt of components is based upon the upstream department's own component availability. As a consequence of reliance upon planning schedules (rather than actual production consumption), production across the value stream is characterized by material shortages, stock chasing, production re-scheduling, 'fire-fighting', and general system instability.

Internally, material supply is characterized by self-replenishment practices and double-handling. The large dunnage sizes require mechanized transportation via forklifts. Due to operator safety concerns over forklifts, containers are dropped a distance away from

[8] Material Requirements Planning, or MRP, is based upon information such as customer demand, available inventory, physical resources, average defect rates, and lead times. Sources of 'error' in MRP can be attributed to information that is not based on actual numbers (e.g. – demand, usage), but rather created by forecast or projection.

workstations. From this point on, the operators are responsible for material replenishment at their individual workstations.

Figure 4-4 shows an overall MSDD evaluation of 6 material supply FR-DP pairs (i.e. logical relationships of the structure). The poor-to-moderate performance among these pair indicates a non-systemic, incomplete logical design for material supply. The evaluation reflects the observations previously described—inconsistent component availability, and inconvenient material location and presentation.

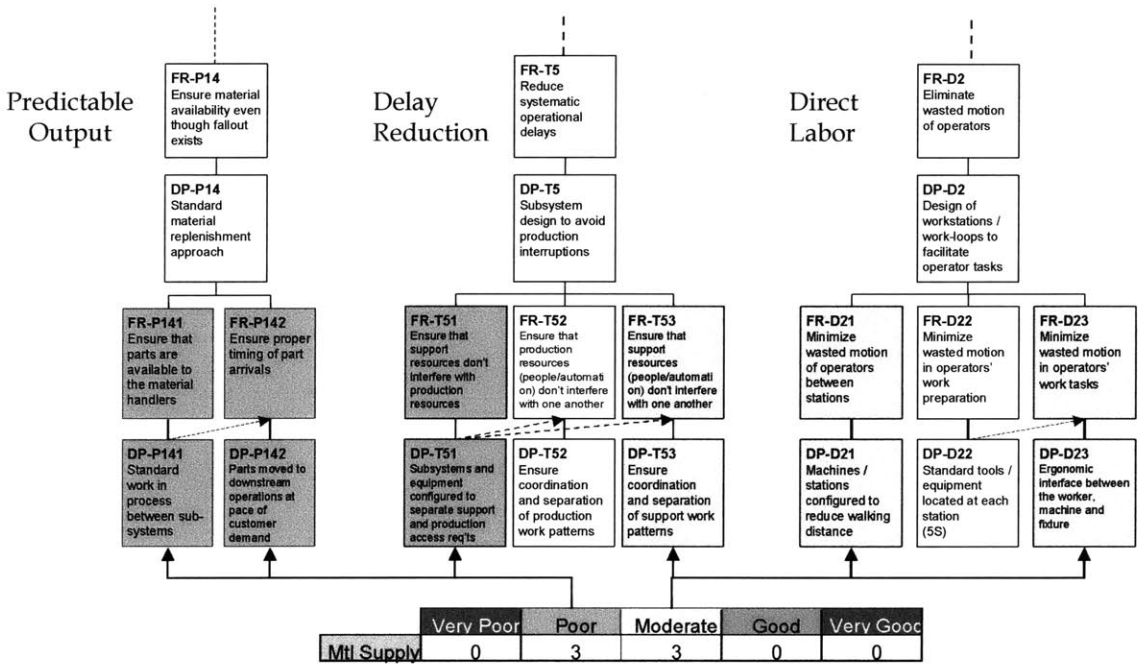


Figure 4-4. Overall assessment of Dept 91 in 6 material supply FRs

Illustration in Depth – Station 11

To illustrate the dependencies between the logical design (i.e. the structure) and the system's performance (i.e. the behavior), a model workstation from the assembly cell was chosen. The flange press operation is one of twenty-one operator-assisted stations in Department 91. Station 11 provides an illustration of Department 91's best material replenishment practices. A high-level schematic of Station 11 is shown in Figure 4-5.

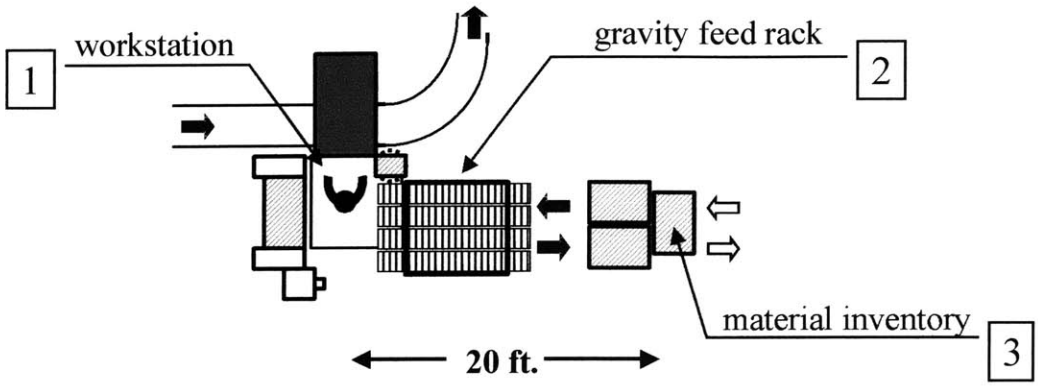


Figure 4-5. Schematic of Station 11-Flange Press

Area 1-Workstation The primary workstation area consists of the flange press machine flanked by component materials (e.g. – flanges, crimps, washers, bearings). The operator's primary function is to place these parts onto the differential case and initiate the automatic press. In general, the workstation has been laid out with some ergonomic consideration. As featured in Figure 4-6, flanges and other component parts are in close vicinity of the active worksite, reducing operator walking (FR D21). The flanges arrive pre-arranged in large containers that are placed on a tilt stand (FR D23). However, improvements in parts access and advantages in assembly orientation are lost because the large size of the dunnage and its still-inconvenient location motivates operators to double-handle the flanges (FR D23). At the operator's preference, a large number of these flanges are then placed into a smaller container that sits on a stool very close to the workstation (FR D21). From the small container, a flange is then inserted into the differential case. The flange's movements are represented by the counterclockwise motion of the flange arrows on Figure 4-6.

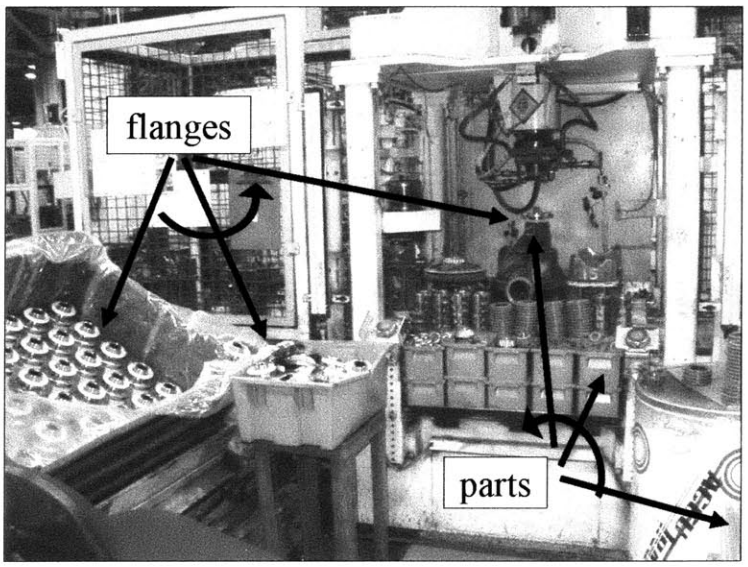


Figure 4-6. Detailed view of workstation

Similarly, the component part bins are also double-handled (FR D23). Parts arrive from the gravity feed rack in the small blue bins. The blue bins are then moved and stacked on the workstation's front shelf. Additional bins can be emptied onto part-holding 'pegs' located behind the bin area (Figure 4-7). Depending on part size and operator preference, some component parts may last 2 hours whereas others last more than a day.

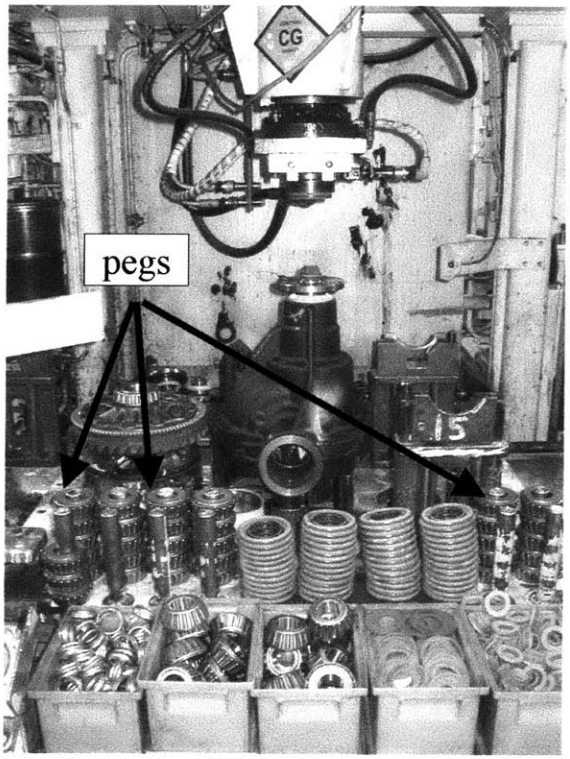


Figure 4-7. Material supply in front of flange press station

Area 2-Gravity Feed Rack In general, gravity feed racks are intended to serve three material supply functions: 1) separation of material feeding from production consumption (FR T51), 2) standardized, single-point feeding locations (FR T53), and 3) presentation of material in an ergonomic manner (FR D23). The flow of material to and from the workstation is reflected by the right-to-left and left-to-right arrows, respectively (Figure 4-8). The rack design combined with the use of small bins achieves these three functions.

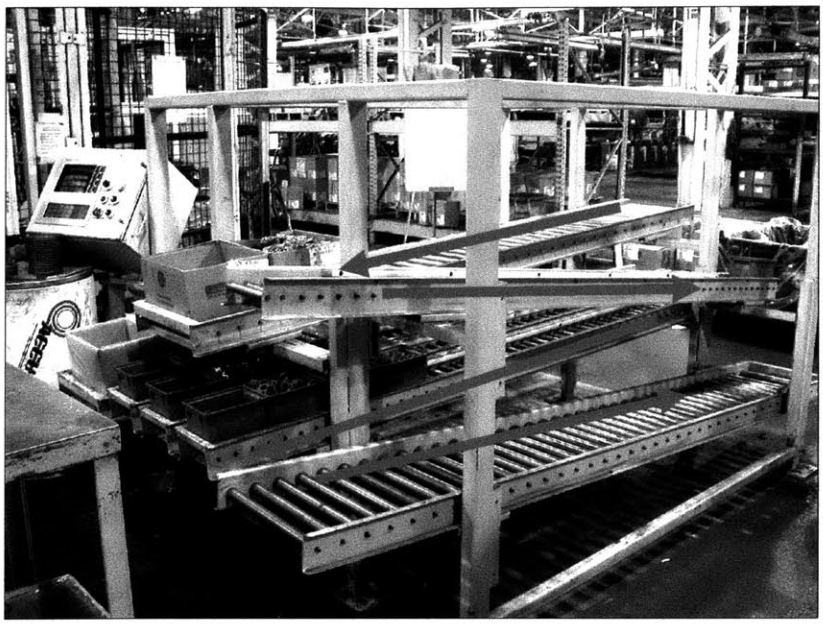


Figure 4-8. Gravity feed rack feeding material to the workstation

However, operator responsibility for self-material replenishment negatively affects two FRs—one from the Delay Reduction branch (FR T51) and one from the Labor branch (FR D21). Previously, the use of the gravity feed rack fulfilled the principle of FR T51. However, self-replenishment defeats the purpose of 'ensuring that support resources don't interfere with production resources.' Additionally, the length of the rack and equipment configuration adds additional non-value adding walking distance and consumes time which should be spent on value-adding processing tasks (D21).

Area 3-Material Inventory The material inventory represents the point of differentiation between *internal* and *external* material supply. Within the realm of internal material supply, operators fill empty bins from the gravity feed rack with parts from the large dunnages, then send the filled bins down the gravity chute. As reflected in Figure 4-9, the filling technique consists of shoveling parts from the dunnage to bin.

Figure 4-9. Illustration of material feed technique

External material supply of component parts consists of centrally scheduled production orders and shipments. Issues with external material supply not only affects Station 11, but the entire assembly line. In many cases, materials are not there when they are scheduled to be (FR P141 and P142).

The primary and 'most effective' response to the problem is for the supervisor or another operator to ride a scooter over to the supplying department to go and look for parts. In many cases, the parts are waiting to be transported or are already somewhere in transit. However at times, the supplying department may have adjusted their individual production schedule based upon their own component availability. Material supply complications are only magnified by the physical distances between departments, as reflected in Figure 4-10.

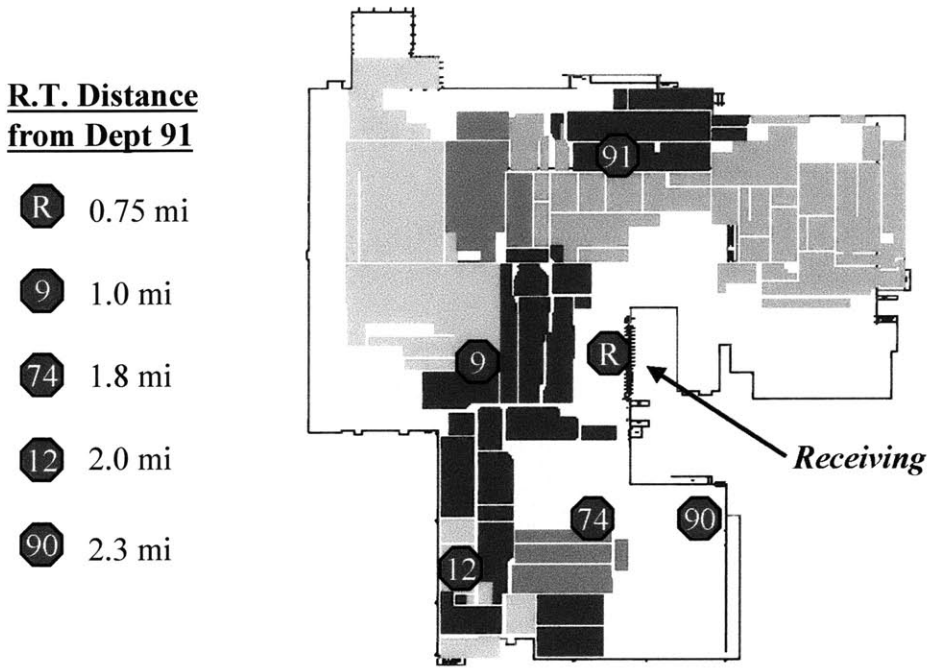


Figure 4-10. Round-trip distances between Dept 91 and supplying departments

Relationships

The relationships between observation, performance of the three areas of Station 11, and the effects of external and internal material supply can be linked to the overall MSDD performance of Department 91. The two left-most columns of Table 4-1 represent the six highlighted material supply FRs. The remaining four columns illustrate the specific area's effect (i.e. – positive, null, or negative) upon the given FRs, and the evaluation of the total system. The arrows represent the linked nature of the plant-wide material supply practices (i.e. – external material supply) to the local workstation effectiveness (i.e. – internal material supply).

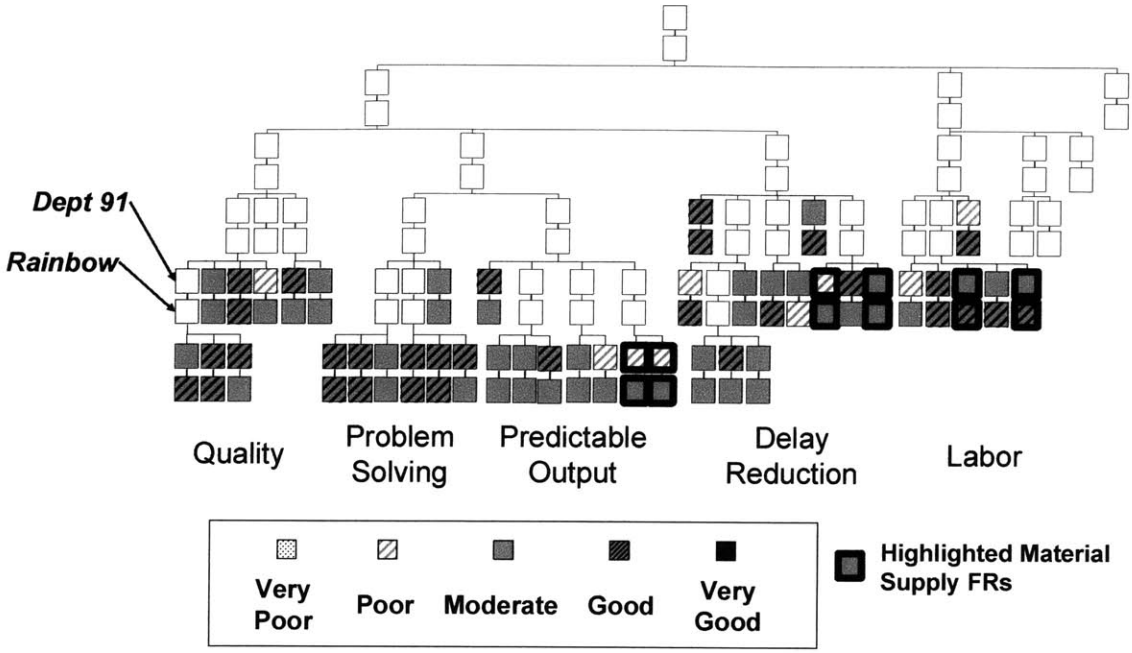
Table 4-1. Performance of Station 11 in relation to Overall MSDD Evaluation Scores

	Functional Requirements	1 - Material Inventory	2 - Gravity Feed Rack	3 - Workstation 11	MSDD Score
Pred Output	FR-P141: Ensure that parts are available to the material handlers	- Parts are not always there when they need to be			Poor
	FR-P142: Ensure proper timing of part arrivals	- Divergence from schedule and actual production			Poor
Delay Red	FR-T51: Ensure that support resources don't interfere with production resources	- Work and support work patterns are not separated (self-replenishment)	0 Separation of feeding point from consumption; however operator is the support resource		Poor
	FR-T53: Ensure that support resources (people / autonomation) don't interfere with each other	- Some parts are obtained from the common inventory area; interference with other operators	+ Allows for single-point feeding from the rear		Moderate
Labor	FR-D21: Minimize wasted motion of operators bewteen stations	- Setup does not facilitate minimization of walking as distance is far	- Length increases distance operator needs to walk	+ All work is designed into one workstation	Moderate
	FR-D23: Minimize wasted motion in operators' work tasks	- Double-handling of material from dunnage to small bins	0 Provides material within reach of workstation; however still not convenient enough	+ Provides for material within easy reach of direct work area	Moderate

The table demonstrates that performance of the system design is highly dependent upon factors external to (and out of the control of) the Department—namely the current material delivery practice of central schedule, drop shipment via forklift, and large dunnage requiring double-handling. Improvements such as a gravity feed rack and improved material presentation at the workstation level have only had moderate influence upon the overall system design's performance. The system design—which has shown relatively poor performance against the logical design of the MSDD—drives the relatively poor behavior and results. In essence, the poor behavior and performance was a direct and strong consequence of the poor logical design.

4.2.2 The Rainbow Differential Case Assembly Cell – Dept. 15

As one of the newest assembly areas, the Rainbow Assembly Cell exemplifies some of Plant 1's most recent undertakings into manufacturing system design. At the time of the plant visit in late June of 2001, the Rainbow area was continuing ongoing ramp-up efforts for full production scheduled in late October of 2001. The MSDD evaluation for Rainbow assembly showed an overall performance on the moderate-to-good level, whereas the evaluation for Department 91 indicated an overall moderate performance (Figure 4-11).



	Very Poor	Poor	Moderate	Good	Very Good
Dept 16	0	8	19	15	0
Rainbow	0	1	26	15	0

Figure 4-11. Comparative MSDD evaluations for Dept 91 (top) and Rainbow (bottom)

Of the six highlighted material supply FRs, Rainbow Assembly showed a higher level of performance over Department 91 Assembly. A comparison of Department 91 and Rainbow, based upon these FRs, is shown in Table 4-2.

Table 4-2. Comparison of Dept 91 and Rainbow

		MSDD Scores	
	Functional Requirements	**Dept 91**	**Rainbow**
Pred Out	FR-P141: Ensure that parts are available to the material handlers	Poor	Moderate
	FR-P142: Ensure proper timing of part arrivals	Poor	Moderate
Del. Red	FR-T51: Ensure that support resources don't interfere with production resources	Poor	Moderate
	FR-T53: Ensure that support resources (people / autonomation) don't interfere with each other	Moderate	Moderate
Labor	FR-D21: Minimize wasted motion of operators bewteen stations	Moderate	Good
	FR-D23: Minimize wasted motion in operators' work tasks	Moderate	Good

A high-level schematic of the Rainbow assembly cell is shown in Figure 4-12. Of particular note is the existence of an inner and outer cell. The inner cell refers to the

primary work area surrounded by the conveyor, whereas the outer cell refers to the secondary work area external to the conveyor loop.

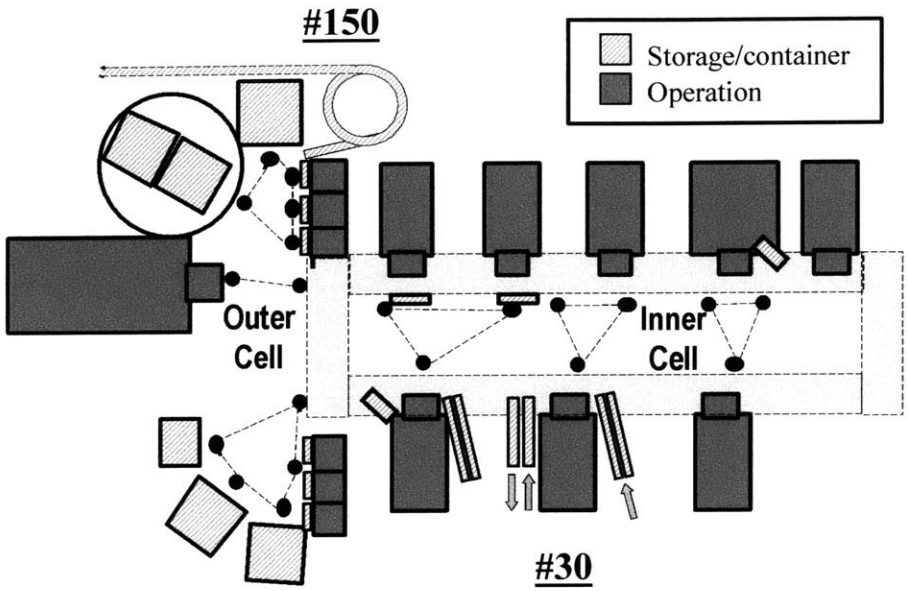


Figure 4-12. Layout of Rainbow final assembly cell

The assembly area consists of both an inner and outer cell primarily for financial reasons. In order to reduce the expenditures associated with pallets and conveyors, all the press operations were determined to be outside of the conveyor loop. This resulted in the outer cell location of two workstations—namely that of #150 and #10. Additionally, the fairly large shipping dunnage sizes (i.e. – two 48"x54" containers), width of the Veritek tester (i.e. – 7' width), combined with the closed-loop conveyor design resulted in the current arrangement of an outer cell design.

Inner Cell: Station 30 – Flange Press Station

Reflecting upon the relative performance of Department 91's assembly area, there are apparent improvements in Rainbow's material supply design and operation. To illustrate these improvements, Station 30 from Rainbow's inner cell area was selected. This model workstation performs operations analogous to Station 11 of Department 91—namely the placement of the outer pinion cone, collapsible spacer, and the flange. A high-level schematic of the station within the assembly area is shown in Figure 4-13.

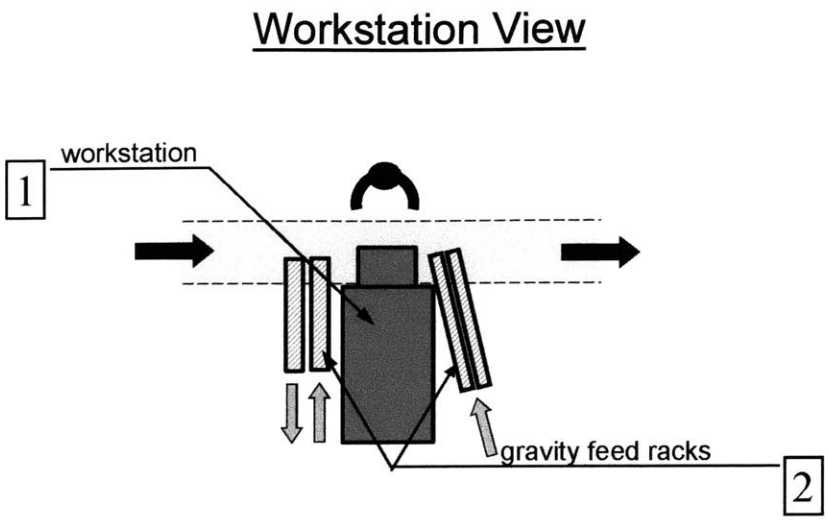


Figure 4-13. Schematic of Station #30-Flange Press

The workstation consists of the flange press machine flanked by component materials (e.g. – flanges, collapsible spacers). The main body of the differential case is built-up on fixture-mounted pallets. A conveyor re-circulates these pallets around the sequence of assembly stations. In addition to the operation of Station 30, the worker operates Stations 100 and 110 to complete the work loop. The minimal aisle width of 4 ½ feet minimizes the operator motion between workstations (FR D21).

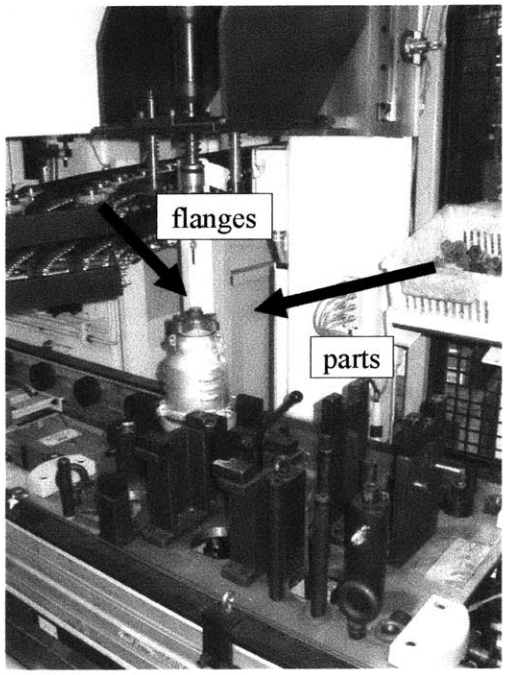


Figure 4-14. Material supply to Station 30

As featured in Figure 4-14, flanges and component parts are in the direct vicinity above the active worksite. Flanges arrive pre-arranged in gravity flow racks, improving part presentation, eliminating double-handling, and enabling direct insertion of the part (FR D23). Reusable bins supply component parts via a two-way gravity flow rack. In addition, materials are fed by a material replenisher along a designated route, referred to as a milkroute (FR T53). The material replenisher feeds parts from the outside of the cell, separating supply activities from production (FR T51). The goal of the milkroute is to replenish parts on a 2-hour consumption based interval (FR P142).

From an external material supply perspective, component parts are taken from an area-side inventory, known as the Rainbow marketplace. The marketplace is capable of holding two hundred twenty-five 4'x9' racks, and occupies floor space nearly the size of the entire assembly area. Due in part to the ramp-up, the quantity of inventory necessary has not been firmly determined and standardized (FR P141). However, there are two fundamental concerns over part assurance during full-scale operation. The practice of using a non-standard inventory is typical within Plant 1. Also, the Rainbow marketplace will continue to run within an MRP-forecast, part-procurement environment.

Outer Cell: Station 150 – Differential Case Build-up station

Compromises in the ideal system design structure have strongly affected aspects of Rainbow's material replenishment practices. To illustrate to point, one of three outer cell workstations was selected. Station 150 completes the differential sub-assembly with the insertion of the matching gear set, pinion cones, and bolts. The workstation consists of three machines including the ring gear press, pinion cone press, and semi-automatic torque machine. Materials are presented to the operator in three modes: a parts silo, parts bins, and dunnage. A schematic of Station 150 within the assembly area is shown in Figure 4-15.

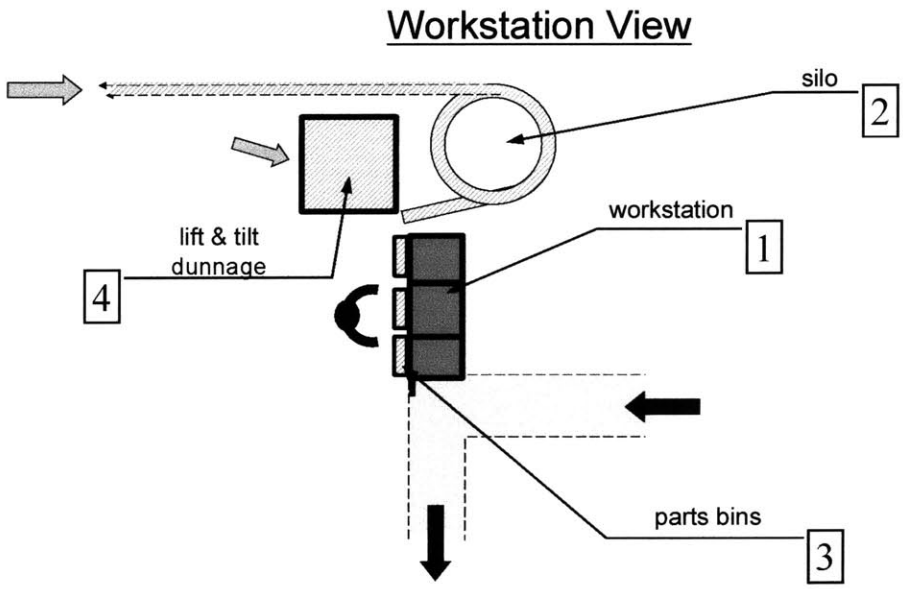


Figure 4-15. Schematic of Station #150-Diff Case Build-up

Internally, material supply is characterized by practices ranging from good-to-poor. The silo embodies an example good material supply practices. Cases are supplied from the differential case cell via an overhead roller-conveyor feed (FR T51). The conveyor feeds a helical silo that stores approximately a day's worth of production inventory (FR P141 & P142). The silo directly outputs to a convenient and minimally obtrusive location less than two feet from the workstation (FR D21 & D23).

As is typical within Plant 1, gear sets arrive in large dunnage sizes. The size of these incoming containers take up a considerable amount of space and add to the amount of walking necessary (FR D21). However, the dunnages used in the Rainbow project possesses some positive features including caster wheels for manual transportation, molded slots to uniformly orient gear sets, and a lift & tilt feature improving the ergonomics of part procurement (FR D23).

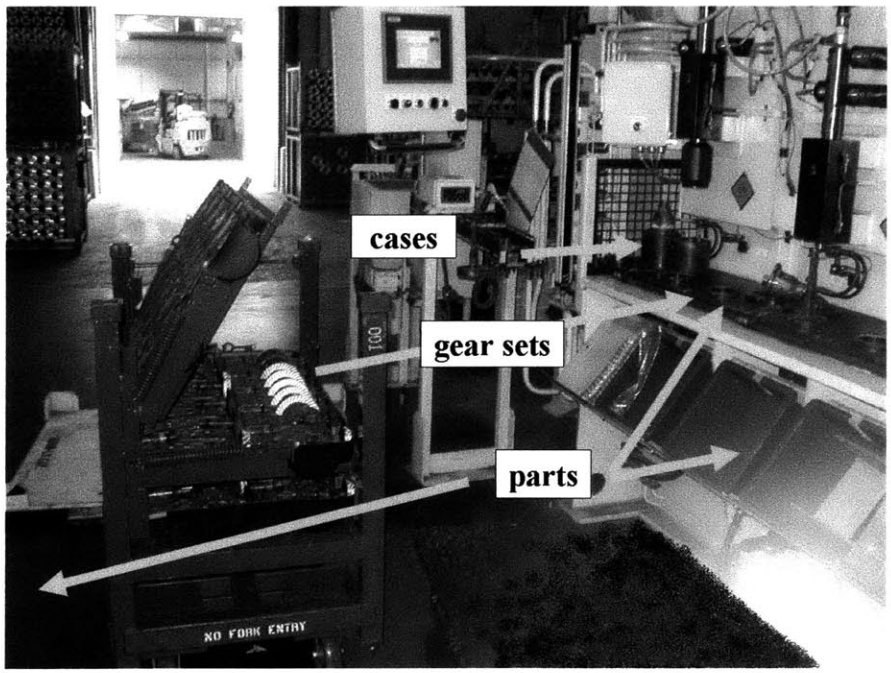


Figure 4-16. Material supply to diff case build-up station

An illustration of poor material supply practices is reflected by the parts containers directly below the workstation. Due to the outer cell design, convenient material feed from the rear is not possible. The material replenisher brings over components and deposits them into the containers. Parts typically are presented in plastic sleeves or are randomly dumped into the containers. In some cases, the entire opened box is placed into the part bin. As a result, material replenishment results in the interruption of production activities (FR T51). The movement of the component parts can be seen in Figure 4-16.

Structure-Behavior Relationships

The performance of these three aspects of Rainbow assembly reflects the dependent relationship between internal and external material supply practices. From an internal aspect, improvements over Department 91's material supply have been achieved through

improved design. Throughout the inner cell, gravity-feed racks have been integrated into the equipment and workstation design, reducing wasted motion. However, areas within the outer cell still require self-material replenishment. Externally, component parts are supplied to the workstations in 2-hour intervals. However, assurance of part availability is compromised by the operation of a consumption-based production cell within an MRP-forecast, part-procurement environment. Overall, improvements in equipment design and operational progression to consumption-based material supply have positively affected the production performance of the assembly cell. However, there are still many opportunities for positive improvement. These observations are summarized in Table 4-3.

Table 4-3. Performance of Stations 30 and 150 to Overall MSDD Evaluation Scores

	Functional Requirements	Supermarket	Inner Cell Workstation #30	MSDD Score	Outer Cell Workstation #150
Pred Output	FR-P141: Ensure that parts are available to the material handlers	0 Goal is to replenish parts on a 2-hour consumption based interval, however material availability within an MRP/forecast environment is still a problem		Moderate	
	FR-P142: Ensure proper timing of part arrivals			Moderate	
Delay Red	FR-T51: Ensure that support resources don't interfere with production resources	+ Work and support work patterns are separated by 'feed from rear' physical design; however not with drop-ship practices	+ Separation of feeding point from consumption	Moderate	- Self-matierial replenishment from line-side drop area; halts production
	FR-T53: Ensure that support resources (people / autonomation) don't interfere with each other	+ One material replenisher gathers parts from the supermarket	+ Allows for single-point feeding from the rear	Moderate	- Process design does not ensure coordination of support resources
Labor	FR-D21: Minimize wasted motion of operators bewteen stations		+ Work is designed into one workloop with convenient material supply	Good	0 Some compromises made on workloop/workstation design (e.g. - Veritek, dunnage)
	FR-D23: Minimize wasted motion in operators' work tasks		+ Provides for material within easy reach of direct work area; minimal occurences of double-handling	Good	+ Once material is in place, provides for easy reach of direct work area

4.2.3 Relationship to The Thinking

Traditionally, accounting practices based upon the minimization of unit cost (e.g. – production, handling, shipping) have resulted in investment strategies targeted towards production and transportation of materials in large containers. The thinking also implies that the assurance of material replenishment through physical design was considered secondary to implementing scheduling practices under the guidance of a centrally-based, MRP strategy. Thus, the thinking resulted in operationally-focused design approaches that did not strongly consider material replenishment as integral to manufacturing systems.

Material supply design & operation can affect production in varying grades of support or interference. The case examples presented herein illustrates instances of both effects, and highlights the importance of integration through design and operation. In its simplest

form, the relationships between production and the 6 highlighted FRs can be summarized as shown in Table 4-4.

Table 4-4. Relationship of material supply upon production

	Functional Requirements	Effects on high-level MSDD FRs	Effects on Production
Pred Out	FR-P141: Ensure that parts are available to the material handlers	throughput time variation increase	No material --> no production
	FR-P142: Ensure proper timing of part arrivals		
Delay Red	FR-T51: Ensure that support resources don't interfere with production resources	mean throughput time increase	No operator --> no production
	FR-T53: Ensure that support resources (people / autonomation) don't interfere with each other		
Labor	FR-D21: Minimize wasted motion of operators bewteen stations	non-value adding manual task addition	Wasted motion --> reduced production effectiveness
	FR-D23: Minimize wasted motion in operators' work tasks		

The synergistic operation of both the internal and external factors of material supply—a systems thinking—is required for effective production performance of the total manufacturing system design. In this respect, Rainbow assembly is progressing towards this paradigm. In light of the MSDD, effective material supply is just one component—necessary but not sufficient—of the entire manufacturing system design.

4.3 Case 2: Relationship of Equipment & Layout Design to Labor Performance

As seen in the MSDD, the Labor branch focuses upon the effective utilization of direct labor by elimination of non-value adding (NVA) sources of costs. The objective of this case example is to highlight the relationship between equipment/layout design on the effectiveness of labor with manufacturing systems. Taken from the systemic viewpoint of the MSDD, the activity of NVA elimination requires a symbiotic relationship between three types of design: equipment, layout, and work design.

4.3.1 High Speed Axle Assembly Line – Department 16

Department 16's axle assembly illustrates the difficulty in balancing the worker's job content in a high-speed assembly line. In a high-speed assembly line, workers typically stand at a single station performing repetitive tasks as the conveyor moves at a constant rate. Because the speed of the conveyor is limited by the slowest operation in the line, it is possible that the workers performing the faster operations may spend 50% or more of their time waiting for the next part to arrive. Figure 4-17 provides the internal assessment of Labor performance of the high speed axle assembly line. The evaluation shows a 'poor-to-moderate' performance of Department 16.

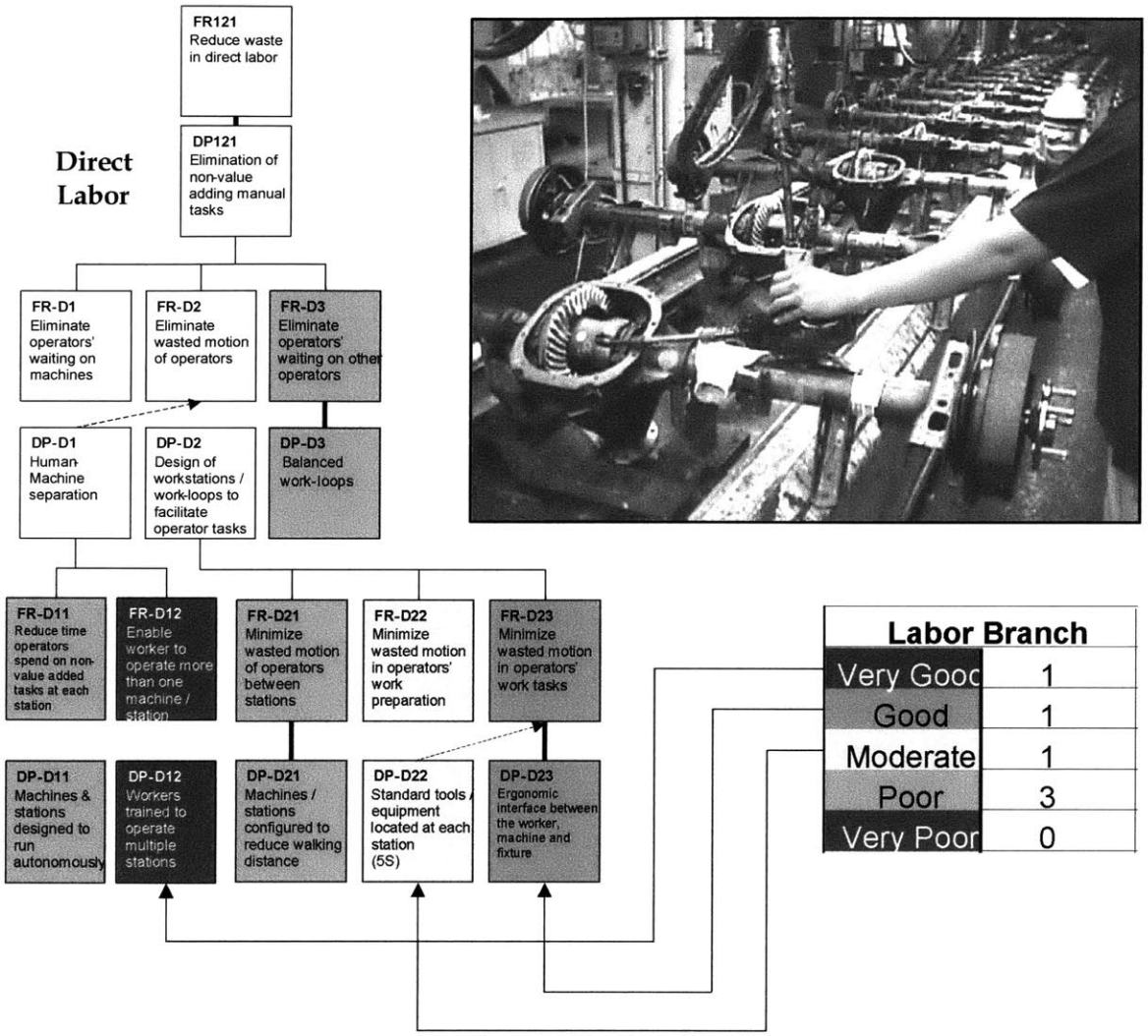


Figure 4-17. Internal assessment of Dept 16 in Labor Branch

Figure 4-18 shows a schematic of the assembly line with a breakdown of the work content. The cycle time for this line is approximately 8.5 seconds (425 parts per hour). Note that some operations require work done on both the left and right side of the axle, and that there are 120 fixtures for 24 workstations. The figure shows that the operator cycle times are not well-balanced across the line. For example, Operation 220's cycle time is only 2.2 seconds. Compared to the speed of the line of 8.5 seconds, 74.1% of the worker's time is wasted waiting for the next part.

Naturally, the shorter the cycle time specified for a production unit, the more it will be able to produce. However, as the cycle time decreases work balancing becomes more difficult. The resultant is a layout that resemble typical high-speed asynchronous lines, where one operator is isolated to one machine. On the other hand, as the cycle time increases there are more operations that need to be performed. Consequently, more mistake-proofing devices need be incorporated.

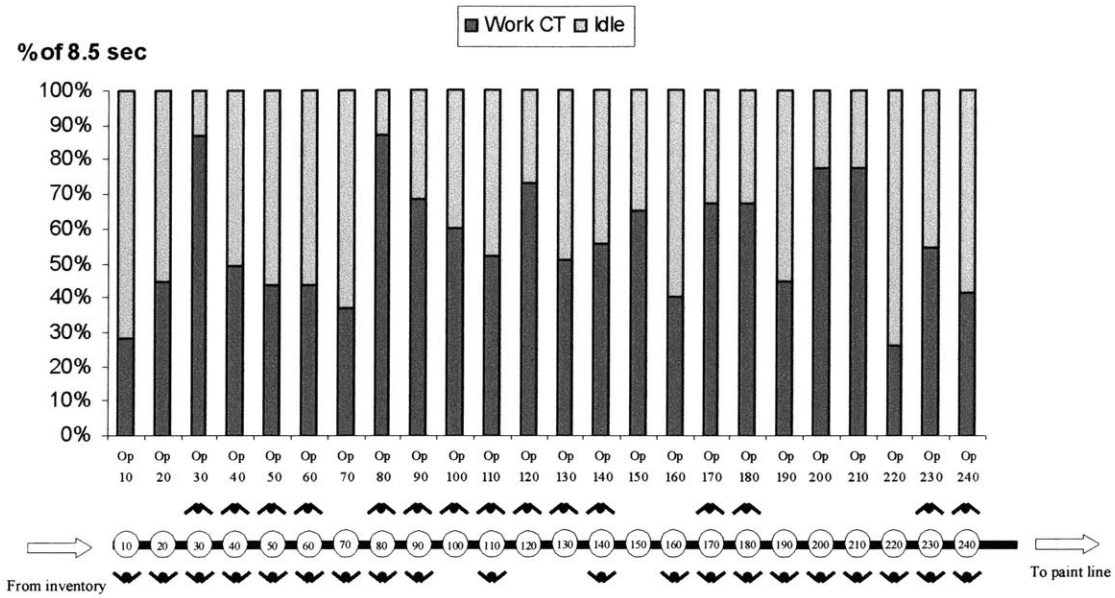


Figure 4-18. Work content breakdown of axle assembly line.

Based on the experience from Professor David S. Cochran, an 'ideal' range has been identified between approximately 30 seconds to 2 minutes. When operating in this range of cycle time, the workers are able to perform various operations and thus maximize their available time. Also, the difficulty to balance the line and the amount of training and mistake-proofing devices required is minimum as shown in Figure 4-19.

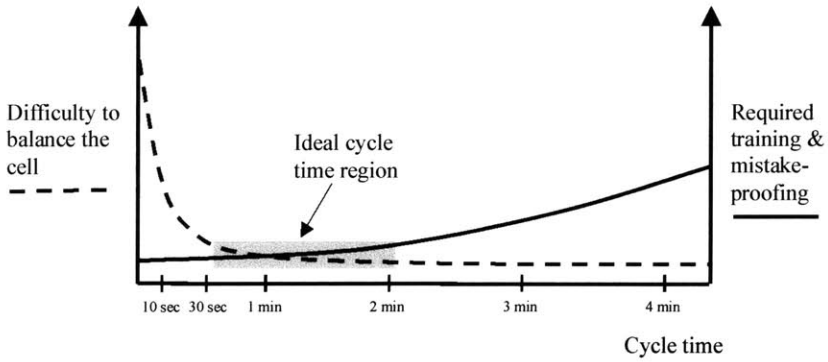


Figure 4-19. Trade-offs and Ideal Cycle Time for Capacity Selection in Cells [Cochran, 2001]

Taken from the perspective of the MSDD, the root cause of the balancing problem lies with the fact that the high-speed synchronous design limits one man to one operation (FR-DP D1). According to the evaluation, there was poor performance in D11 (machine design for autonomation) and very good performance in D12 (worker ability to multi-task). Thus, the synthesis of these two FR-DP pair result in an incomplete separation between the human and machine.

Of the 6 leaf FR-DP pairs in the Labor Branch, three FR-DP pairs are strongly affected by layout and machine design (i.e. – D11, D21, and D3). All three of these affected pairs scored poorly on the evaluation, highlighting the importance and dependence of machine design and layout on the overall effectiveness of workforce utilization in manufacturing system design.

4.3.2 Case/Carrier Loop Assembly Line – Department 91

In similar fashion, the outer loop assembly design of Department 91 reflects a situation where equipment/layout design influences the effectiveness of workers within a given manufacturing system design. Department 91 provides another example of the difficulty in reducing waste in direct labor with a given layout design. Similar to the high-speed assembly line, workers typically stand at a single station performing repetitive tasks. Pallets on the conveyor advance to the next station only once the operation has been completed. In this case, the speed of the assembly loop is limited by the longest manual or robotic cycle time rather than controlled by conveyor speed. Figure 4-20 is an overall assessment of the Labor performance of the case/carrier assembly line. The evaluation shows a 'moderate' performance of Department 91.

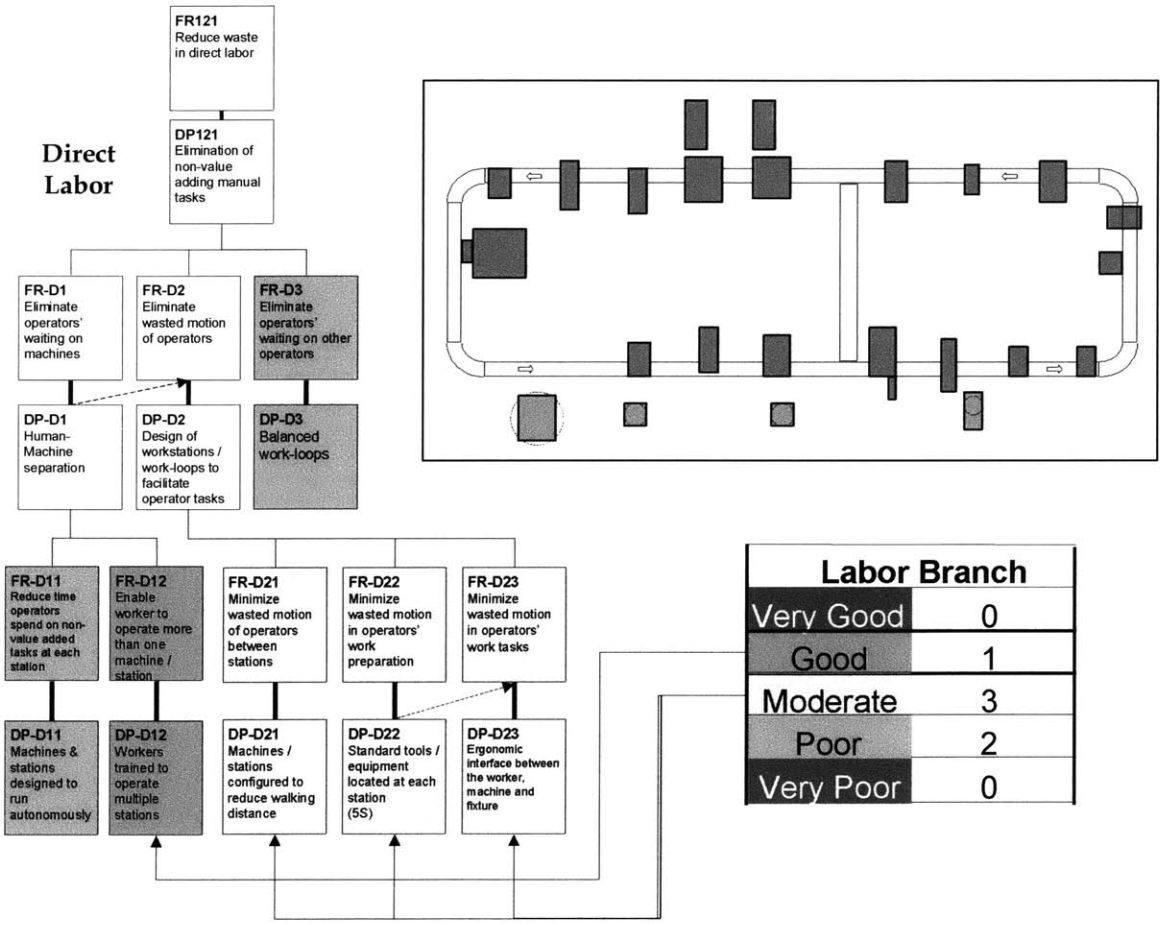


Figure 4-20. Overall assessment of Dept 91 in Labor Branch

Figure 4-21 shows a schematic of the assembly line with a breakdown of the work content. On average, the actual running cycle time for this line is controlled at Operator 4. Thus the assembly line produces parts at approximately 35 seconds (represented by the arrowed line), which is less than the target cycle time of 42 seconds.

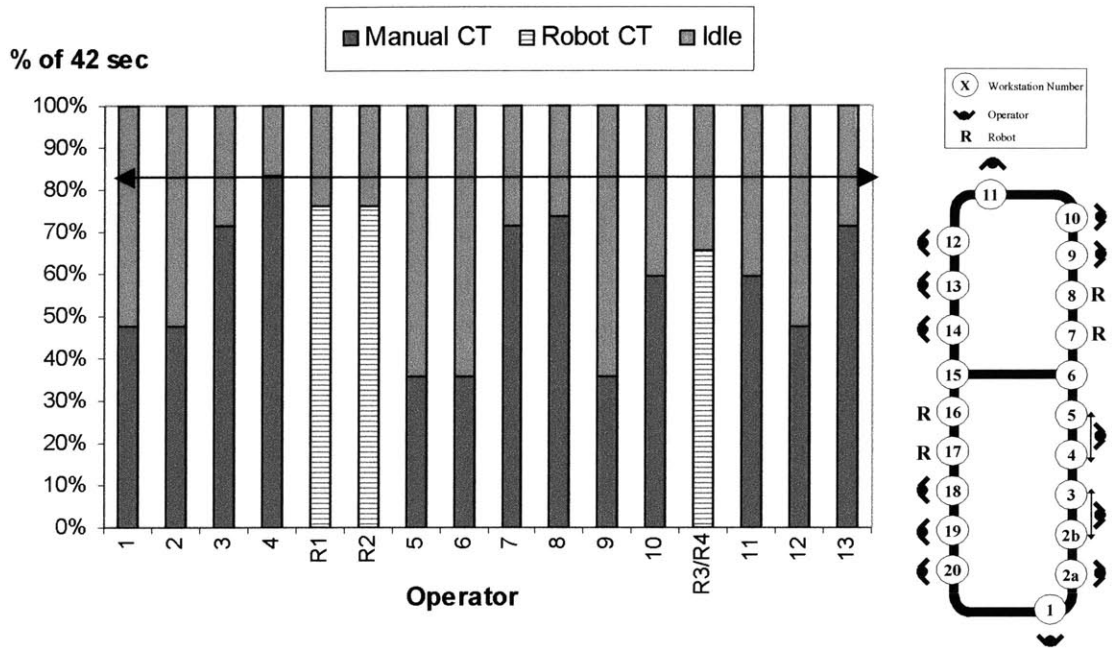


Figure 4-21. Work content breakdown of case/carrier assembly line.

In particular, Figure 4-21 highlights the fact that work content is not well-balanced across the assembly line. In 11 of 13 instances, the outer-loop layout and protruding machines prevent operators from multi-tasking between workstations. Of the two exceptions, Operators 3 and 4 perform tasks at two workstations resulting in work content more closely matching the robotic cycle times. The resulting cycle times more closely match the cycle times of the robotic workstations.

Similar to the high-speed assembly line, the root cause of the balancing problem lies with the fact that the layout and equipment design limits one man to one operation (FR-DP D1). According to the evaluation, there was poor performance in D11 (machine design for autonomation) and good performance in D12 (worker ability to multi-task). Again, the synthesis of these two FR-DP pair resulted in poor separation between the human and machine. Recalling the 'optimal' cycle time range of 30 seconds to 2 minutes (Figure 4-19), Department 91's cycle time falls within this range, however the equipment design and layout does not enable the plant to take advantage of the cross-trained operators. Again, the example highlights the importance and dependence of machine design and layout on the overall effectiveness of workforce utilization in manufacturing system design.

4.3.3 Case/Carrier Assembly Cell – Rainbow

Rainbow provides an evolutionary example of a situation where equipment/layout design positively influences the effectiveness of workers within a given manufacturing system design. Rainbow's design is similar to that of Department 91 in many aspects. For example, the overall layout and machine design appears similar with the exception that Rainbow is an inside-out, smaller version of Department 91. Also, the Rainbow assembly cell utilizes a circulating pallet transfer design to transport fixtures about. A salient difference is that the Rainbow system design enables improvements in work improvements to have substantial effect on worker utilization, primarily through human-machine separation and workloop balancing. Figure 4-22 shows an overall 'good' assessment of the Labor performance of the Rainbow assembly area.

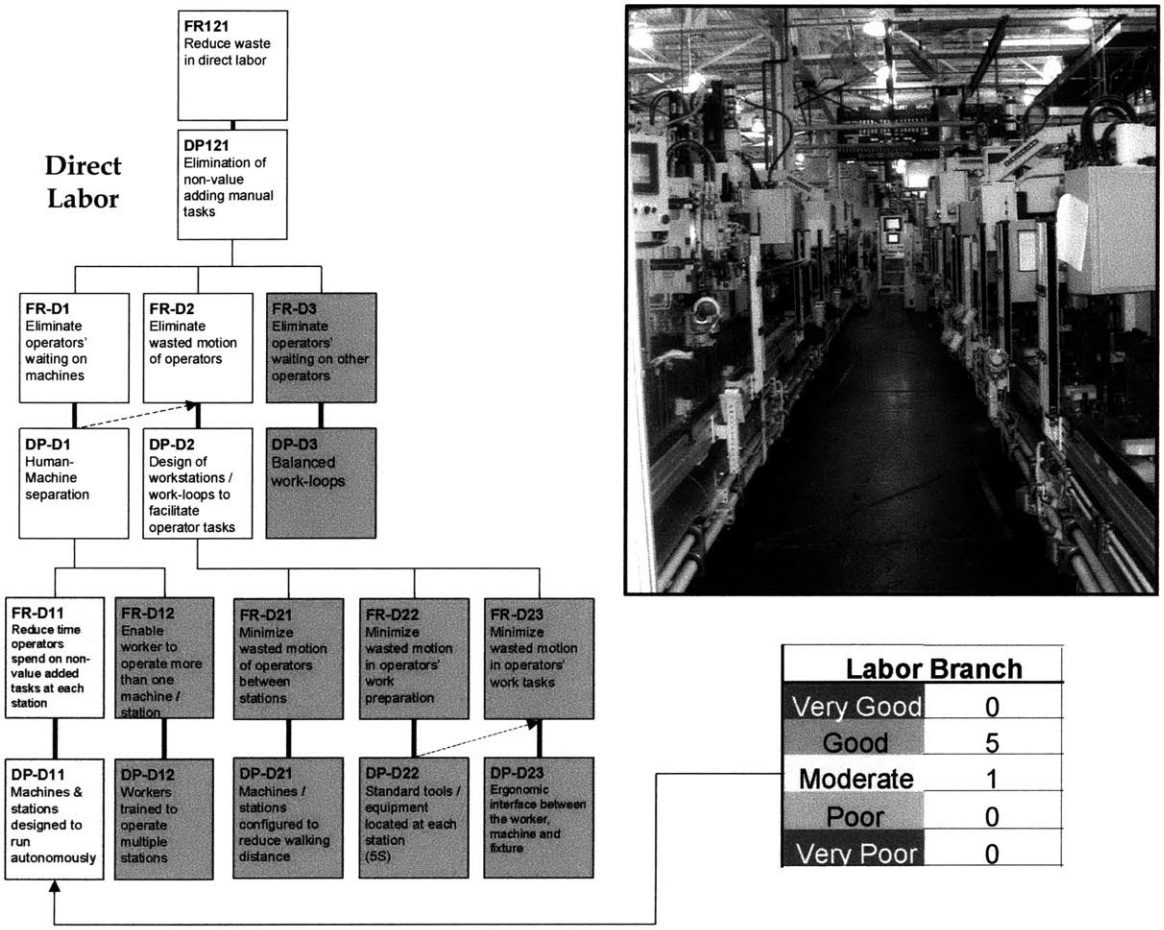


Figure 4-22. Overall assessment of Rainbow Assembly in Labor Branch

Figure 4-23 shows a schematic of the assembly line with a breakdown of the work content. As shown in the Figure, the work is highly-balanced across the line. In fact, the operators' cycle times are virtually equal to the target takt time of 70 seconds.

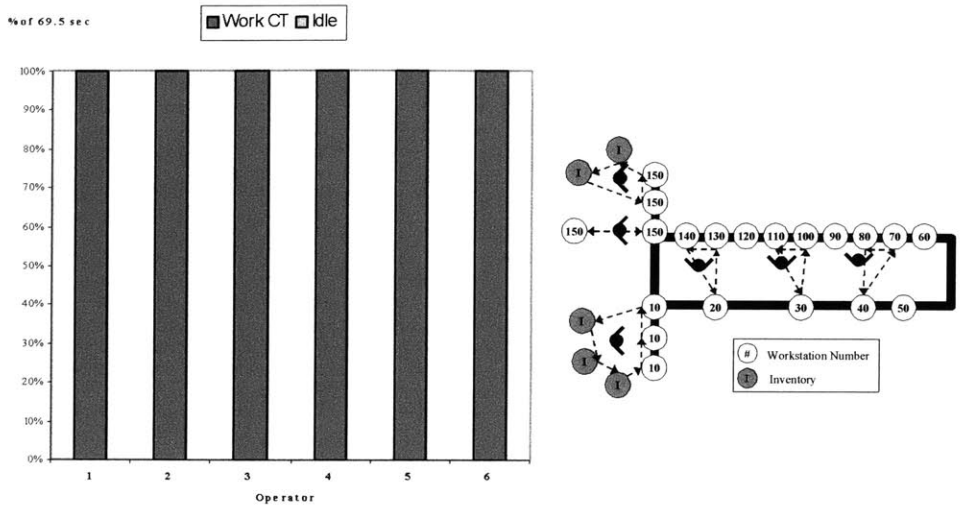


Figure 4-23. Work content breakdown of Rainbow Assembly line.

As reflected in the MSDD, autonomous equipment design and cross-trained workers are *both* necessary to enable human-machine separation (FR D1). Wasted motion of operators can be eliminated (FR D2) only once human-machine separation is achieved. This requires workstation design and layout design to facilitate operator tasks. Typically, the physical layout design (e.g. parallel rows of equipment, U-shaped, narrow equipment) is considered a sufficient ingredient to successful 'cellular' design, however the MSDD highlights the essential prerequisite for human-machine separation. In similar fashion, workloops cannot be balanced (FR D3) without the first achieving human-machine separation, and having workstations designed to facilitate operator tasks. As reflected in the MSDD evaluation of Figure 4-22, the Rainbow assembly area has been successful in achieving many of these Functional Requirements—all necessary in order to achieve the higher-level business objective of reducing waste in direct labor (FR 121).

5.2.5 Structure-Behavior Relationships

Table 4-5 summarizes the labor effectiveness (in terms of work balance) and each value stream's evaluations in these categories. For both Departments 16 and 91, the root cause of poor labor utilization was the incomplete human-machine separation—a reflection of the focus on equipment cycle times rather than the human-machine interface. For Department 16, the 8.5-second cycle time, high-speed line is a flagrant example of no man-machine separation. For Department 91, the 42-second cycle time is within the 'ideal' cycle time range, as recommended by Figure 4-19. However, the equipment and outer-loop layout was designed without the 'human-machine interface' as a high priority system design requirement. The result is the virtual inability to further improve worker effectiveness. In contrast, Rainbow's overall 'good' performance in labor utilization reflects the focus upon designing the equipment and layout to *enable* workers to be effective. Work loops are not only balanced (as shown by the low variation) but the cycle times are virtually identical to the target cycle time. In the Rainbow value stream, the target cycle time is the actual takt time of the downstream customer!

Table 4-5. Performance of the three value streams in the Direct Labor Branch

		Dept 16	Dept 91	Rainbow
	MSD Description	High-speed assembly line	Outer-loop assembly line	Assembly cell
	Target Cycle Time (sec)	8.5	42	69.5
FR	DP			
Eliminate operators' waiting on machines	Human-machine Separation	Poor	Poor	Moderate
		Very Good	Good	Good
Eliminate wasted motion of operators	Workstation design to facilitate operator tasks	Poor	Moderate	Good
		Moderate	Moderate	Good
		Good	Moderate	Good
Eliminate operators' waiting on other operators	Balanced workloops	Poor	Poor	Good
	Variation across Work Balance (% of Target CT)	56% ± 34%	58% ± 28%	100%

4.3.4 Relationship to the Thinking

The case examples presented herein illustrates the relationships between three types of design—equipment, layout, and work design—in achieving effective labor performance. In many instances, the thinking has focused strongly upon driving improvements in labor efficiency by method improvements. This type of thinking is non-systemic and truly fits within the paradigm that 'optimization of the piece-parts results in the optimization of the whole.'

The MSDD is a logical design structure that enables stable, low-cost performance of the system. The MSDD subscribes to the approach of physical design *to enable* work improvements—rather than driving worker improvement through method improvements. This systems thinking is reflected in the Labor Branch. Of the six leaf-level FRs in the Direct Labor Branch, only one focuses upon the worker while the remaining five concentrate upon design as the physical enablers to labor effectiveness. In light of the MSDD, effective labor utilization is just one component—necessary but not sufficient—of the entire manufacturing system design.

4.4 Case 3: Premium Gear Plant – Replicating the Old Paradigm

The catalyst for the conception of the "premium" gear plant (i.e. Plant 2) can be distilled into two main objectives:

- **Tactical:** Alleviate the overall company's production pressure and enlarge the production capacity to supply hypoid gear sets (pinion and ring gear sets) to Plant 1.

- **Strategic:** More importantly, demonstrate to corporate management that axle production unit has mastered "lean thinking" by creating a truly 'lean' plant in a 'greenfield' environment.

As will be shown in the following case study, the thinking that had enabled the creation of such poor performing systems in the past (e.g. Department 91, Department 16) was still very much the 'paradigm for success' in Company A.

4.4.1 Layout

Upon initial examination, the Plant 2 reflects a similar material flow as the traditional departmental, poor performing machining area of Plant 1. The one difference was that Plant 2 was on a smaller scale (Figure 4-24). The design of Plant 2 shows that the production processes are laid out in a departmental manner. All the machines for green-end processes are grouped together and located on the right side of the plant. The heat treat process is located in the middle part of the shop floor, while all the hard-end processes are located in the left side.

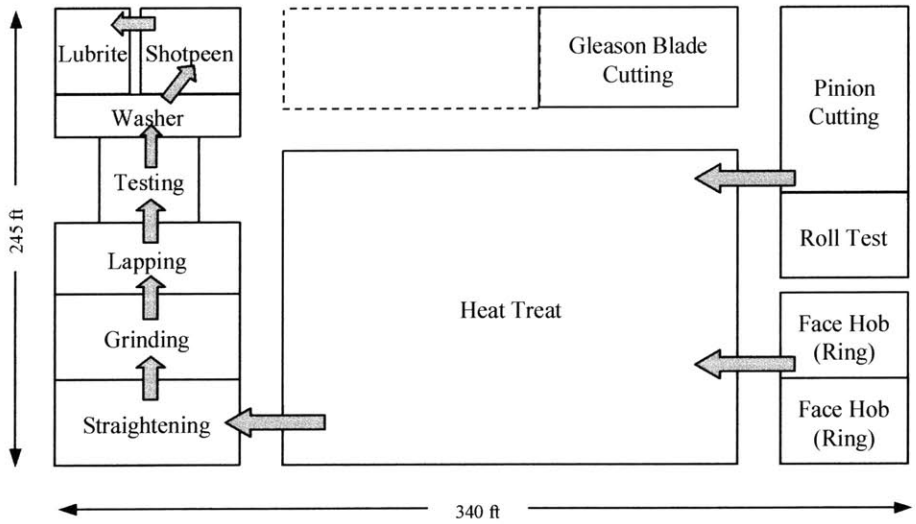


Figure 4-24. Layout of Plant 2

Looking into more detail, each department consists of a different number of machines (Figure 4-25). Tracing through the possible number of paths that a gear could travel

through reveals the hidden complexity of the apparently simple manufacturing system design at Plant 2. From start to finish, there are 120 possible flow paths through the pinion processes alone. In almost every case, the layout indicates the thinking that the path of the gear should depend upon which machine is available at the next stage of operations. However, the grouping the machines based function into departmental layouts has created additional waste in the system with regards to transportation distance, unnecessary inventory between operations, poor labor utilization, longer throughput times, and decreased sensitivity to production disruptions—an unforeseen result of the thinking that says 'parts should travel to the next available machine to increase machine utilization and reduce cost.'

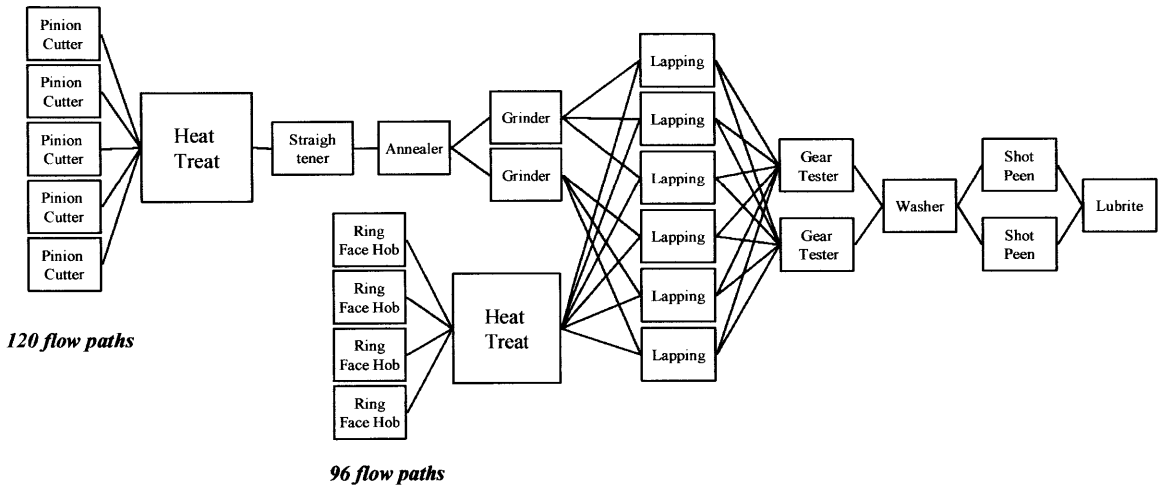


Figure 4-25. Possible material flow paths through plant

4.4.2 Equipment Design

From an equipment design viewpoint, there is duplication of the departmental layout even to the detail of the machines. For example, the face hobbing department on the lower right hand side of Plant 2 layout is nearly the same concept as that of the blanking process in the pinion gear department at Plant 1, as shown in Figure 4-26.

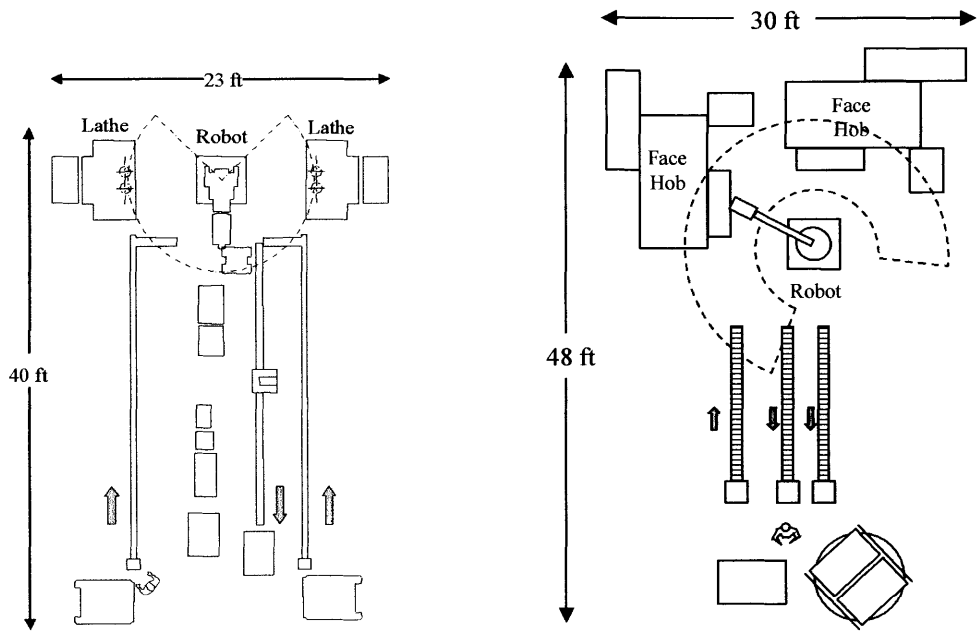


Figure 4-26. Plant 1's blanking department layout (left) and Plant 2'sface hob layout (right)

The thinking is that 'equipment utilization should be maximized in order to reduce cost.' As a result, the operator is in charge only of loading and unloading the conveyors (as shown by the arrows), while a large robot arm picks up a part and places them in either of the machine. The thinking also says that 'material transportation cost is minimized when parts are transported in large containers.' As a result, finished parts are placed on the conveyor where the operator packs out the gears in huge ZE-1 tubs (33" by 48"). With poor human-machine separation, operators would tend to have high amounts of idle time while the machine is processing the parts. In addition, a focus on equipment utilization rather than the operator effectiveness retracts from the need to focus on work methods and ergonomic improvements. Two consequences of poor ergonomics in Plant 1 was a high absenteeism rate, and a resulting system that could not effectively operate. From the similarity in the thinking that created the structural design, these negative consequences will most likely transfer over to the new Plant 2 as well.

4.4.3 Material Flow

The thinking also says that 'equipment utilization is increased if parts are transported more quickly via automation.' However, this non-systemic thinking has adverse effects. From the value stream map shown in Figure 4-27, we can see that the operations are unbalanced to takt time resulting in parts transfer in batch sizes. In addition, overhead conveyors (monorails) are used again. Many aspects of the proposed design is quite similar to the one in Plant 1 where parts have to travel excessive distances, and it is very difficult to identify and resolve problems found downstream due to the use of monorails and overhead conveyors.

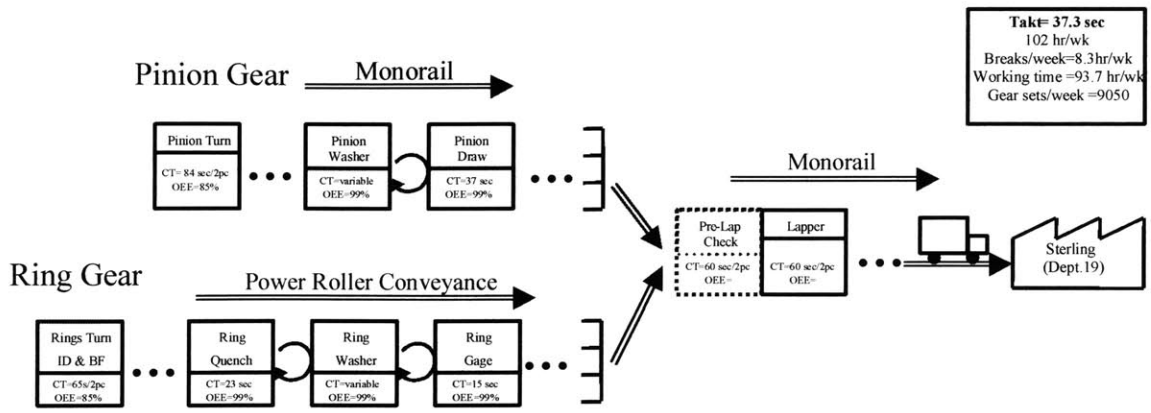
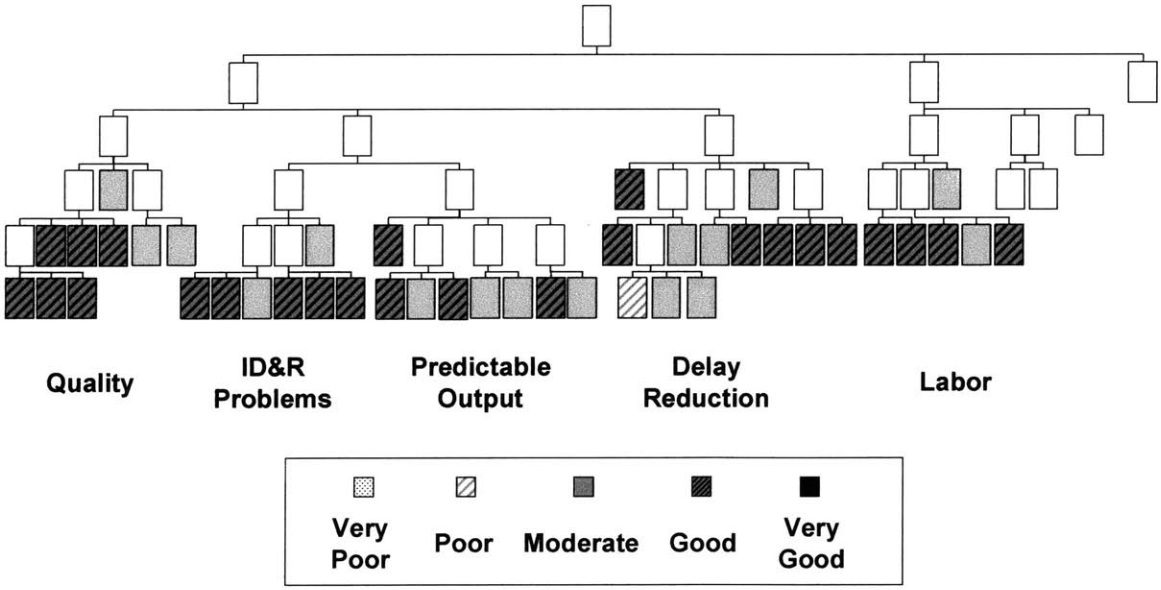


Figure 4-27. Value stream map of Plant 2

4.4.4 Internal MSDD Evaluation - A Perspective on Plant 2's Thinking

Figure 4-28 shows an internal MSDD evaluation of Plant 2. The score of each FR-DP comes from the average of 3 respondent's answers including a production supervisor and two engineering supervisors. An external evaluation, mainly focused on the two branches of Labor and Delay Reduction, was completed by Professor Cochran. This evaluation has not been included into the general evaluation listed in Figure 4-28.

The internal MSDD evaluation shows that out of 42 leaf-level FR-DP pairs, there are 1 poor, 16 moderate and 25 good scores. The score distribution suggests that the designers believe the system has moderate-to-good performance in all five branches. In each branch, more than half of the FR-DP pairs have a good score. Overall, one FR-DP pair is shown to be below moderate.



	Very Poor	Poor	Moderate	Good	Very Good
Quality	0	0	3	6	0
ID&R Prob	0	0	2	5	0
Pred Output	0	0	4	4	0
Delay Red	0	1	5	6	0
Labor	0	0	2	4	0
Total	0	1	16	25	0

Figure 4-28. Internal MSDD evaluation result of Plant 2

Table 4-6 list the top and bottom FR-DP pair performers for Plant 2. The evaluation shows high scores for human-machine separation (D11 & D12). In addition, the evaluation reflects that the plant has been designed to avoid production disruptions (T51 & T52). The second-highest overall score of R112 suggests that problem identification through simplified flow paths has been achieved. However, reflecting upon Figure 4-25, flow paths are far from straightforward.

Table 4-6. Top and bottom pair performers of Plant 2

Premium Gear Plant

Top 5 FR-DP pair performers

ID Num	FR	DP	Score
T52	Ensure that production activities don't interfere with one another	Ensure coordination and separation of production work patterns	4.5
R112	Identify disruptions where they occur	Simplified material flow paths	4.3
D12	Enable worker to operate more than one machine / station	Train the workers to operate multiple stations	4.3
T51	Ensure that support activities do not interfere with production activities	Subsystems and equipment configured to separate support and production access req'ts	4.3
D11	Reduce time operators spend on non-value added tasks at each station	Machines & stations designed to run autonomously	4.2

Premium Gear Plant

Top 5 FR-DP pair performers

ID Num	FR	DP	Score
T31	Provide knowledge of demanded product mix (part types and quantities)	Information flow from downstream customer	3.1
T222	Ensure that manual cycle time <= desired production pace (or takt time)	Design of appropriate operator work content/loops	3.0
T223	Ensure level cycle time mix	Stagger production of parts with different cycle times	2.9
P122	Ensure availability of workers	Perfect Attendance Program	2.9
T221	Ensure that automatic cycle time <= minimum desired production pace (or takt time)	Design of appropriate automatic work content at each station	2.4

Of the bottom performers, three FR-DP pairs reflect the condition that production has not been well-designed to takt time (T221, T222, T223). Also, major production issues with regarding personnel attendance have still not been addressed with great forethought in Plant 2 (R112). As a simple observation, the evaluation shows that the new plant was designed with much attention paid to the physical aspects, and not so much upon the systemic implications of designing manufacturing systems from a systems perspective.

4.4.5 Comparison and Analysis of Evaluations – Differences in Thinking

An external evaluation, completed by Professor Cochran, mainly focused on the two branches of Labor and Delay Reduction. A comparison of the questionnaire answers between Prof. Cochran and the internal evaluation is provided in Table 4-7. The FR-DP pairs are sorted in descending order of the differences between the evaluation scores.

Table 4-7. Comparison of external and internal MSDD evaluation scores

ID	FR	DP	MSDD Scores		
			Prof. Cochran	Internal	Difference
D12	Enable worker to operate more than one machine / station	Train the workers to operate multiple stations	4.3	4.3	0.0
T4	Reduce transportation delay	Material flow oriented layout design	3.0	3.5	0.5
T221	Ensure that automatic cycle time <= minimum desired production pace (or takt time)	Design of appropriate automatic work content at each station	1.7	2.4	0.8
T52	Ensure that production activities don't interfere with one another	Ensure coordination and separation of production work patterns	3.5	4.5	1.0
T53	Ensure that support activities (people/automation) don't interfere with one another	Ensure coordination and separation of support work patterns	3.0	4.0	1.0
D11	Reduce time operators spend on non-value added tasks at each station	Machines & stations designed to run autonomously	3.0	4.2	1.2
D21	Minimize wasted motion of operators between stations	Configure machines / stations to reduce walking distance	2.3	3.5	1.3
T32	Produce in sufficiently small run sizes	Design quick changeover for material handling and equipment	2.5	3.8	1.3
T51	Ensure that support activities do not interfere with production activities	Subsystems and equipment configured to separate support and production access req'ts	2.6	4.3	1.7

From Table 4-7, there is a varying range of agreement and disagreement over certain aspects of the new plant design. Of the nine scores, three 3 FR-DP pairs (D12, T4 and T221) have consistent results across both evaluations. Of these pairs, there is high agreement with one pair from each of the top and bottom performers of Table 4-6 (i.e. – D12 and T221). In fact, T221 scored the lowest across both the external and internal evaluations.

However, there are still disparities in the evaluations. The largest difference concerns FR-DP pair T51. For Professor Cochran, T51 is the 4th lowest scorer of 9 pairs, whereas T51 is Plant 2's 2nd highest overall scorer of 42 pairs. From the external viewpoint, this large difference can be further explained by the actual answers to the Questionnaire. The four respondents answers are reflected in Figure 4-29. Professor Cochran's answers are represented by the 'C' whereas the three internal respondents' answers are given by X, Y and Z. The ***R*** represents reverse scale questions.

T51 **Ensure that support activities do not interfere with production activities**

Subsystems and equipment configured to separate support and production access req'ts

		strongly disagree 1	2	3	4	strongly agree 5
- Delivery of material does not interrupt production				C	Y, Z	X
- Picking up outgoing material interrupts production (e.g. due to the need for forklifts to move large bins)	*R*	X	Y, Z	C		
- Material handling and transportation equipment does not limit the pace of production		C		Y	Z	X
- Operators have to leave their workstation to pick up new material	*R*	X	Y	C		
- Operators frequently perform activities, which disrupt the standardized work	*R*	Z	X, Y	C		

Figure 4-29. Answers from four respondents to FR-DP T51

Professor Cochran's answers are relatively moderate with the exception of the third question. As with previous experience in Plant 1, central scheduling coupled with large dunnage sizes have resulted in a push-style production planning that has not satisfactorily achieved the notion of system stability. Large dunnage sizes result in less-frequent movement of material and intermittent status review and control of production. Overhead monorails do not allow for easy information regarding material quantities, and control/adjustment of standard material between processes. As is even reflected in the internal evaluation, material availability is not ensured even though fallout exists, as parts are not moved downstream according to the pace of customer demand (P142). In Plant 2, as was the case in Plant 1, production is planned to be managed and operated under an MRP-environment.

4.4.6 Consequences of the Thinking

As is shown in this case study, the 'paradigm for success' used to create and 'improve' Plant 1 was used to design Plant 2. The consequence of the same thinking led to the creation of the same structure. The supposition is that the performance of Plant 2 will tend to be similar to that of the poor-performing Plant 1. If this hypothesis does indeed hold true, the two originally stated tactical and strategic goals would not be achieved.

4.5 Chapter Summary

The three case studies presented satisfied (in a practical manner) the three objectives of the chapter:

- Provide detailed illustrations of the general systems engineering model proposed in Section 2.3
- Illustrate a practical application of the 'chasm of paradox' model proposed in Section 2.6.

- Apply the MSDD to baseline, evaluate and draw insights into actual manufacturing systems (see Section 3.6).

Through these illustrations, the fallacy of Company A's 'paradigm for success'—thinking that piece part optimization can optimize the whole system—becomes apparent. As a result, Company A basically reincarnated the structure of Plant 1 in Plant 2. The consequence of the same paradigm was that Company A was not able to successfully cross the 'chasm of paradox' (Figure 4-30).

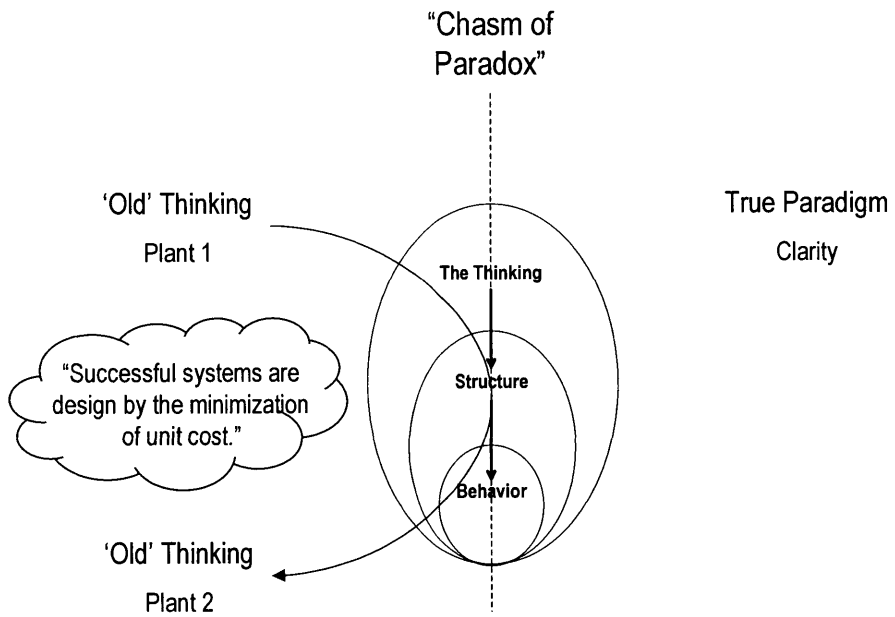


Figure 4-30. Trap of the Paradox

Chapter 5 Conclusions

5.1 Insights from the Thesis

Design approaches can be categorized into two broad, yet distinct, categories—design by philosophy and systems engineering [Duda, 2000]. Philosophy-based design is based on a general high-level thinking that is understood and communicated—explicitly or implicitly—with the goal of achieving a holistic impact on all phases of design. In contrast, a systems engineering approach is characterized as a more rigorous treatment of the design process. As reflected in this thesis, an ideal design approach requires an integrated effort from both approaches—the thinking of philosophy-based approaches and the explicit rigor of systems engineering approaches.

Chapter 2 created a model for an ideal systems engineering approach, and identified the combination of axiomatic design and system dynamics as a powerful unified approach. The development of the "Chasm of Paradox" model emphasized behavior is the result of the structure created by the thinking. Many fall into the paradox of trying to change the behavior by focusing on the behavior itself. The resulting policy resistance, and failure to change the behavior is an accepted paradox for many. The Chasm of Paradox model asserts that the paradox is revealed only through a paradigm shift. The shift in one's thinking begins with the recognition that the thinking creates the structure that results in the behavior. System dynamics is a powerful tool to shift the thinking of people. As a complement, axiomatic design is a powerful design approach that can design ideal systems.

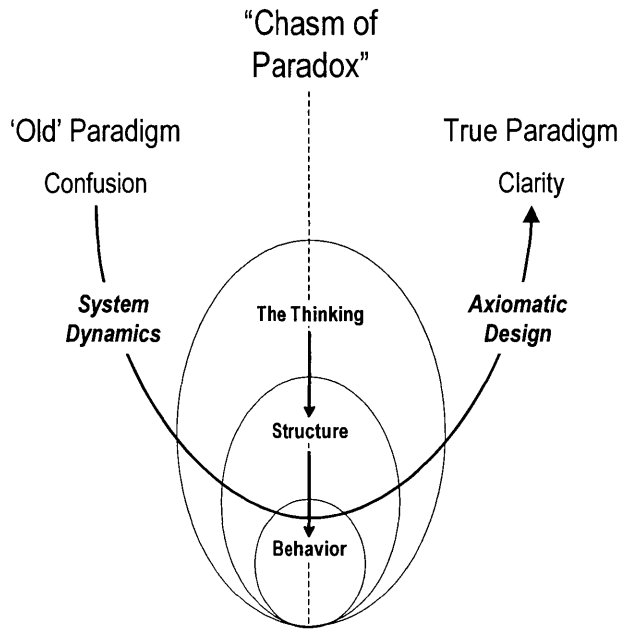


Figure 5-1. Crossing the "Chasm of Paradox"

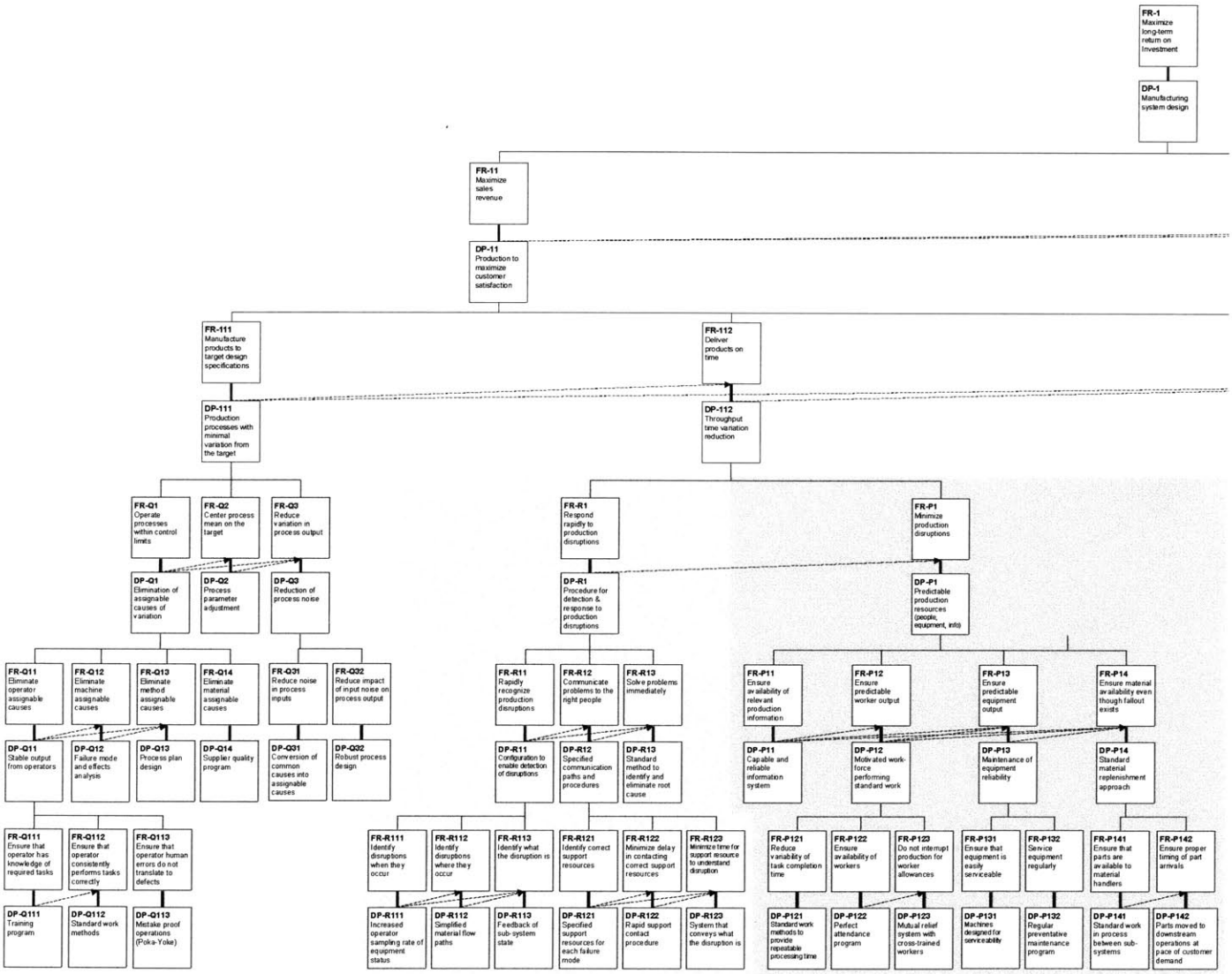
Chapter 3 introduced the MSDD as a manufacturing application of axiomatic design. The MSDD is fundamentally built upon the notion that the design of stable systems produces stable results. Once a stable system in designed and installed, then 'working on the work' results in systemic improvements to performance.

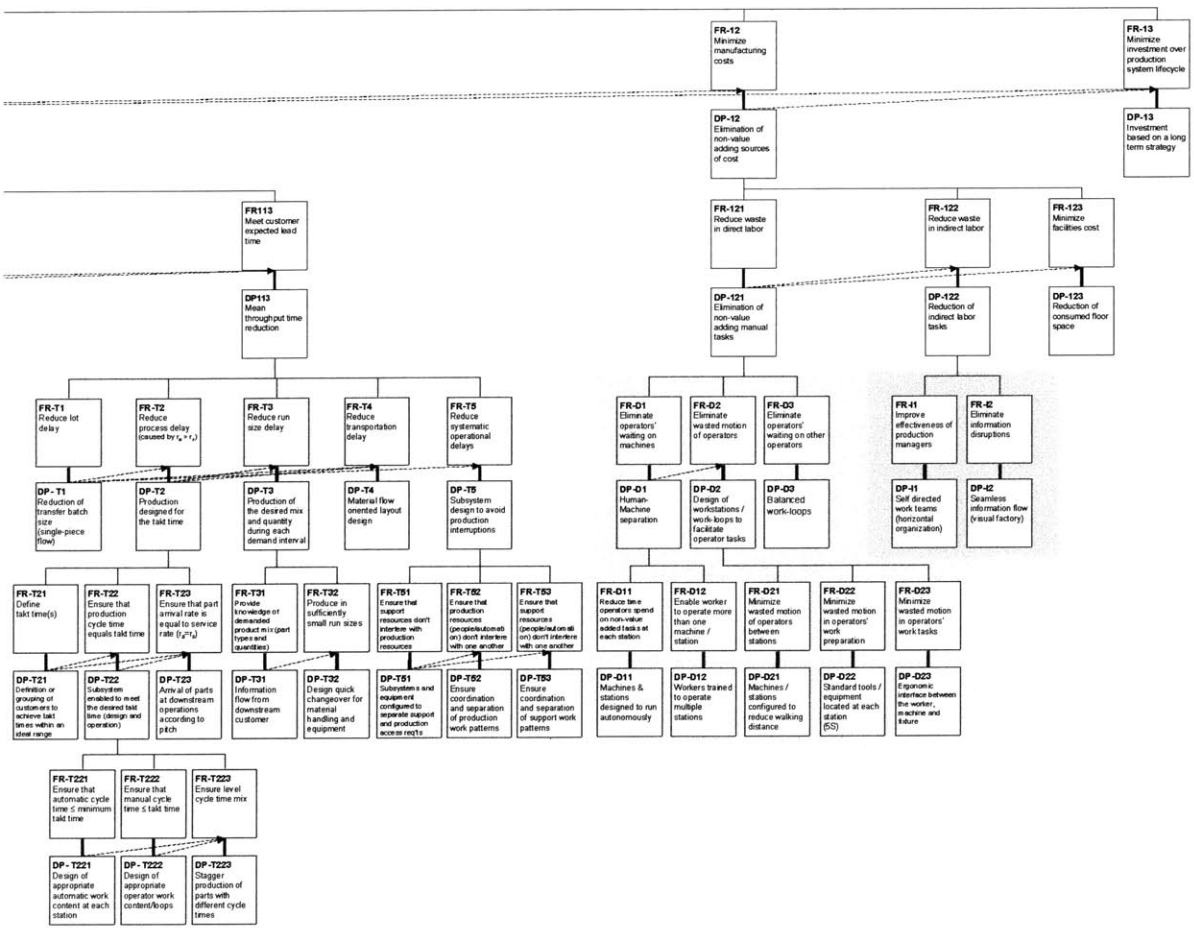
Chapter 4 built upon the results of the previous two chapters by applying the MSDD, and the concept of the Chasm of Paradox model. The case studies strongly supported the notion that the same thinking that resulted in poor system performance will reincarnate itself in another unstable system design that produces poor results—even in light of the opportunity for 'green field' design. Only when one recognizes that 'we are *part* of the system, and we *are* the system' will paradigms shift and the apparent chasm be crossable. The unified approach of axiomatic design and system dynamics is the bridge that enables a successful crossing.

Fundamental to this thesis is the acceptance of the notion that the thinking creates the structure that results in the behavior. In order for one to acknowledge the accomplishments of this thesis, one must come to an agreement with the underlying thinking. However, I am not convinced of a positive response from all, for I do not subscribe to the notion that "*where ignorance is bliss, 'tis folly to be wise*" [Grey, 1763]. But for yourself, I leave that to you to decide. As the famous German philosopher Nietzsche [1886] once proclaimed:

> *"When we have to change our mind about someone, we hold the inconvenience he has caused us very much against him."*

Appendix A: The Manufacturing System Design Decomposition (v 5.1)




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
FR-121
Reduce waste in direct labor
FR-122
Reduce waste in indirect labor
FR-123
Minimize facilities cost
DP113
Mean throughput time reduction
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 (caused by $r_e + r_v$)
FR-T3
Reduce run size delay
FR-T4
Reduce transportation delay
FR-T5
Reduce systematic operational delays
FR-D1
Eliminate operators' waiting on machines
FR-D2
Eliminate wasted motion of operators
FR-D3
Eliminate operators' waiting on other operators
FR-I1
Improve effectiveness of production managers
FR-I2
Eliminate information disruptions
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
DP-D1
Human-Machine separation
DP-D2
Design of workstations / work-loops to facilitate operator tasks
DP-D3
Balanced work-loops
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 seperate 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 future
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

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